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Optimization of economic outcomes of energy saving actions taken throughout the entire lifecycle of a capital construction facility

The current consensus on the lack of alternatives to the energy-saving vector of economic development has led to the development of national and international energy saving programmes and numerous studies on improving the energy efficiency throughout the entire life cycle of projects in architecture, engineering, construction and operation of buildings. However, research projects have revealed a wide gap between projected and real energy consumption, which disrupts energy modernization strategies and policies. According to the recent studies, this gap is caused by social, technical and technology-related factors. The accuracy of assessing the economic efficiency of energy saving actions is also affected by macroeconomic uncertainties, which overcomplicate energy-focused economic modernization. Integration of technologies towards information modeling of the entire life cycle, energy saving, cost reduction can improve the state of affairs in architecture, engineering, construction and operation of buildings and structures. Methods used to increase the accuracy of prognosticated economic consequences of energy saving actions are the subject of this study. The authors have developed algorithms for the quantitative description of contributions, made by architectural/planning solutions, energy-saving technical and technology-focused solutions, and predictive macroeconomic conditions to the energy efficiency assessment throughout the entire life cycle of a construction project. The resulting information model of the project life cycle, available at the design stage, allows optimizing geometric parameters of architectural and planning solutions in terms of the energy consumption/cost ratio. At the reconstruction stage, information models optimize technical and technological solutions aimed at energy saving. At the stage of operation, planned energy-saving actions can be optimized using the results of dynamically monitored thermal properties of building envelopes and macroeconomic conditions. In addition, the information model of energy efficiency allows for the quantitative analysis of the economic effect of investments in the replacement of building envelope elements to optimize current management solutions in terms of the cost/effect ratio.

Keywords: *building information model, project lifecycle, energy saving, optimization, economic efficiency, capital construction facility*

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INTRODUCTION

According to various estimates, an increase in the energy efficiency of the Russian housing sector, that consumes one quarter to one third of primary energy, is an absolute must for the development of design, construction, architecture and building operation sectors, characterized by an increase in the negative environmental impact, depletion of non-renewable (primarily, hydrocarbon) natural resources, and the ever-growing price of energy from renewable sources, the integral economic and environmental efficiency of which is currently negative [1]. As a result, binding documents contain a wide range of energy saving actions for the housing and utilities sector. Hence, according to the state report, issued by the Ministry of Economic Development, the goal of the housing and utilities sector is to have energy savings worth 19.8 million tons of reference fuel by 2030. This goal is attainable by tightening the requirements for energy resources consumption in public areas and energy efficiency criteria for apartment buildings and other structures. To achieve this goal, the Fund for Assistance to the Reform of Housing and Utilities (hereinafter “the Fund”) resumed the provision of financial support of the overhaul of apartment buildings (OAB) suspended in 2018. The amount of resources in the housing and utilities sector is to reach its maximum value through the comprehensive overhaul of multi-apartment residential buildings coupled with the introduction of energy efficient technologies. However, these energy saving actions, planned for the housing and utilities sector, demonstrate extremely low efficiency. For example, in 2019, the total consumption of fuel and energy resources was down 5.16 million tons of reference fuel. However, the climatic factor had a positive affect on reduction of the energy intensity of the sector worth more than 7.28 million tons of reference fuel. Consequently, the contribution of technical, technological, organizational and other actions turned out to be negative.

MATERIALS AND METHODS

The application of technical and technological methods of boosting the energy efficiency of buildings is very costly, and as a result their payback period is quite long in most cases. The impossibility of projecting macroeconomic conditions even in the medium term gives rise to uncertainties in assessing the energy saving potential [2], which slows down decision-making on investments in energy modernization [3, 4]. To overcome this problem, numerous attempts were made to optimize methods of predicting the economic results of energy saving actions [5–7]. As a result of the research, two classes of reasons for major errors in the description of the economic potential of energy saving were identified [8, 9]. Firstly, these are the reasons associated with socio-economic factors and called the rebound effect [10] and the prebound effect [11, 12] that explains the productivity gap.

Errors in the economic forecast are also associated with errors in physical models of energy losses [13, 14] and errors in the data used to implement these models [15].

This work focuses on formation of an algorithm that describes the economic potential of energy saving free from these shortcomings.

The integral quantitative characteristic of efficiency can be represented as

$$EFF = \sum_{t=1}^{t_t} PB_t \Big/ PQ_{tot}. \qquad (1)$$

In formula (1), the following notations are used:

- t_t is the total number of periods (months, quarters, years, depending on the terms of assessment) in the total life cycle;
- t_t numbers the periods in the life cycle;
- PB_t is the price of technical and technological actions aimed at improving the energy efficiency in the t-th period;
- PQ_{tot} as the total savings accumulated through the implementation of energy saving actions.

The value of selling price PB_t is determined in accordance with the construction or reconstruction project, whose matrix is presented in Table as part of the information model of the whole life cycle.

The maximum number of modifiable elements is determined as the sum of $J_{max} = J_d + J_w$ attainable in the case of complete simultaneous replacement of elements. In the case of successive performance of activities in each interval, condition $J < J_d + J_w$ is fulfilled. The implementation cost of actions, aimed at improving the energy efficiency in the t-th period, can be calculated by summing up the purchase cost of elements, their dismantling and installation, insulation of walls, roofs and floors:

$$PB_t = \sum_{i=1}^{J_t^w} n_i^t \left(c_i + c_i^m + c_i^d\right) + \sum_{i=1}^{J_t^d} n_i^t \left(c_i + c_i^m + c_i^d\right) + \\ + \sum_{i=1}^{J_t^c} n_i^t \left(c_i + c_i^m + c_i^d\right) + S_t^{wall} C_{wall}^t + S_t^{roof} C_{roof}^t + S_t^{base} C_{base}^t. \qquad (2)$$

In formula (2), the first three sums take into account the shares of windows, doors and air conditioning units in the implementation cost of technical and technological actions, respectively. The number of addends in these sums (J_t^w, J_t^d and J_t^c) is determined by the number of elements modified in the t-th period. The cost of elements and work items is determined during the same period, which requires an ongoing update of the library of standard sizes. In the course of construction periods, when condition $t < t_{bild}$ is fulfilled, if t_{bild} is the term of construction, dismantling and reclamation costs c_i^d are equal to zero. Same as in the case of individual elements, characteristics (areas and modification costs) of walls, roofs and basements are determined for each period, which requires an update of basic structures of an information model.

Unlike energy-saving costs that are limited in time, the savings that they ensure are accumulated in the course of the life cycle.

Matrix of the information model of the whole life cycle, that determines the implementation price of technical and technological actions aimed at improving the energy efficiency of windows and doors

Implementation period	Size number	Number of elements	Reconstructed areas
t_1	k_1	$n_{k_1}^1$	S_1^{wall} S_1^{bas} S_1^{roof}
	k_2	$n_{k_2}^1$	
	…	…	
	k_{J_1}	$n_{k_{J_1}}^1$	
t_2	k_1	$n_{k_1}^2$	S_2^{wall} S_2^{roof} S_2^{bas}
	k_2	$n_{k_2}^2$	
	…	…	
	k_{J_2}	$n_{k_{J_2}}^2$	
…	…	…	
t_m	k_1	$n_{k_1}^m$	S_m^{wall} S_m^{roof} S_m^{base}
	k_2	$n_{k_2}^m$	
	…	…	
	k_{J_m}	$n_{k_{Jm}}^m$	

Assuming that the macroeconomic situation is stable and energy saving amounts are invested in full, the time dependence of specific accumulated savings per unit area of an enclosing structure was studied in [16], and the energy efficiency criteria in [17–20].

Let's consider the benefits of energy saving actions for a set of individual elements in a dynamically changing macroeconomic environment (windows, doors, air conditioning units, walls, etc.), which can be represented as:

$$PQ_i(t_0) = PQ_i(0)\sum_{j=0}^{j_{\max}}\prod_{m=1}^{j}(1+k_m). \tag{3}$$

In formula (3), the following notations are used:

- t_0 is the time period for energy saving work (construction of a structure, replacement of individual elements, overhaul, etc.);
- $PQ_i(t_0)$ is the benefit of energy saving actions accumulated during the following period $\Delta t = t_{fin} - t_0$ where $t_{fin} = min[t_{tot}, t_{elem}]$ is the smaller of the following time periods: t_{tot} as the complete project life cycle and t_{elem} as the life cycle of a modified element;
- $PQ_i(0)$ is the basic benefit of energy saving actions obtained during the initial period;
- $j_{\max}$ is the number of scheduled periods within Δt, the term of benefits accumulated by energy saving actions;
- k_m is the inflation rate for scheduled periods of benefit accumulation.

In formula (3), multiplier

$$G = \sum_{j=0}^{j_{\max}}\prod_{m=1}^{j}(1+k_m)$$

is determined both by the macroeconomic environment and the period of energy saving benefit accumulation. In contrast, multiplier $PQ_i(0)$ is only determined by the nature of engineering solutions used to improve energy efficiency. If the macroeconomic situation is stable, approximation of the constant inflation rate is valid $k_m = k$ = const. In this case, formula (3) can be substantially simplified. We take into account that in this case equation (4) is true

$$\begin{aligned}\prod_{m=1}^{j}(1+k_m) &= (1+k_{m_1})\times \\ &\times(1+k_{m_2})\ldots(1+k_{m_j}) = (1+k)^j.\end{aligned} \tag{4}$$

Hence, in equation (4), the result of summation, which is reduced to calculating the sum of geometric progression, will be as follows in case of non-zero inflation:

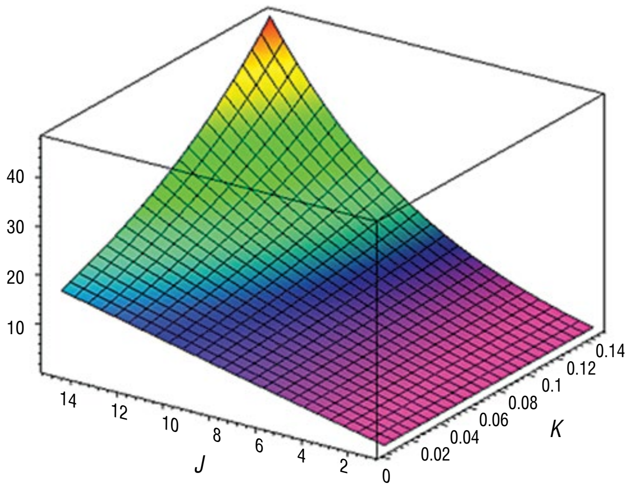
$$PQ_i(t_0) = PQ_i(0)\frac{(1+k)^{j_{\max}} - 1}{k}. \tag{5}$$

In zero inflation intervals, the passage to the limit $k \to 0$ in formula (5) generates the following result $PQ_i(t_0) = PQ_i(0)\cdot j_{\max}$. By expanding the left side of formula (5) into McLaurin series with respect to k parameter within the accuracy of first-order members, we obtain

$$PQ_i(t_0) \approx PQ_i(0)\cdot j_{\max}\left[1 + k\cdot(j_{\max} - 1)/2\right]. \tag{6}$$

Hence, in conditions of moderate inflation and/or short-term plans, when inequality $k \cdot j_{\max} \ll 1$ is fulfilled, the benefit, accumulated by energy saving actions, can be considered linear in terms of the inflation index and quadratic in terms of time. This fact is illustrated in Figure.

Figure clearly demonstrates that at low inflation this dependence is close to linear regardless of duration. For values of $k > 0.02$ there is a sharp increase in G for $j > 10$, and at k > 0.1 a sharp increase is implemented for $j > 5$.



Graph of dependence between the multiplier (the applicate axis) and the rate of inflation (the abscissa axis), between the benefit accumulation period and energy saving actions (the ordinate axis)

Let's consider methods used to describe the contribution of technical and engineering solutions to an increase in energy efficiency, determined by multiplier $PQ_i(0)$ in formula (6). The cost of consumed thermal resources is determined by heat losses P_T, heating season duration Δt, heat losses and regional or local price of heat energy C_Q, rubles/J:

$$PQ_i(0) = C_Q\cdot\left[P_T\cdot\left(T_0 - \langle T\rangle\right)\cdot\Delta t + \Delta Q_{\text{macro}}\right]. \tag{7}$$

If the heat agent temperature difference at the inlet and outlet is proportional to the indoor and outdoor temperature difference $\Delta T^{w}_{j} = \alpha\cdot\Delta T^{w}_{j}$, the heat loss equation can be formulated as follows:

$$\begin{aligned}\Delta Q_{\text{macro}} &= \left[c_{\text{gas}}\cdot\sum_{i=1}^{N_{\text{con}}} n_i P_i + c_{\text{water}}\cdot P_{\text{water}}\cdot\alpha\right]\cdot\sum_{j=1}^{N_t}\Delta t_j \Delta T_j = \\ &= \left[c_{\text{gas}}\cdot\sum_{i=1}^{N_{\text{con}}} n_i P_i + c_{\text{water}}\cdot P_{\text{water}}\cdot\alpha\right]\cdot\left(T_0 - \langle T\rangle\right)\cdot\Delta t.\end{aligned} \tag{8}$$

By substituting formula (8) into expression (7) we obtain

$$\begin{aligned}PQ_i(0) &= C_Q\cdot\left(T_0 - \langle T\rangle\right)\cdot\Delta t\times \\ &\times\left[P_T + c_{\text{gas}}\cdot\sum_{i=1}^{N_{\text{con}}} n_i P_i + c_{\text{water}}\cdot P_{\text{water}}\cdot\alpha\right].\end{aligned} \tag{9}$$

Hence, in accordance with expression (9), the basic benefit of energy saving actions $PQ_i(0)$ is completely determined by the regional coefficient

$$C_R = C_Q\cdot\left(T_0 - \langle T\rangle\right)\cdot\Delta t, \tag{10}$$

depending on climate factors and the price of thermal energy, technical and engineering characteristics of the structure, that are quantitatively described by the multiplier

$$C_B = P_T + c_{\text{gas}}\cdot\sum_{i=1}^{N_{\text{con}}} n_i P_i + c_{\text{water}}\cdot P_{\text{water}}\cdot\alpha. \tag{11}$$

CONCLUSIONS AND RESEARCH PERSPECTIVES

The following conclusions can be drawn as a result of the research. Lengthy payback periods, typical for technical and engineering methods used to improve the energy efficiency of buildings, and

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the unfeasibility of a reasonable forecast of macroeconomic conditions for the payback period lead to diverse assessments of economic efficiency of energy savings. The analysis and dynamic adjustment of the forecast is only feasible within the framework of energy efficiency information models developed for the whole life cycle of the project. The algorithm of quantitative description of the contribution of energy-saving solutions and predictive macroeconomic conditions to the energy efficiency improvement of buildings and the information modeling of the whole life cycle of the project, formulated in the paper, solves a number of practical problems. First of all, at the design stage, this algorithm allows for the energy optimization of geometric parameters of architectural planning solutions. Further, at the reconstruction stage strategic energy-saving solutions can be formulated. The dynamic adjustment Energy-saving actions can be adjusted on the basis of monitored thermos-physical properties of building envelopes and macroeconomic conditions. In terms of short-term planning, the energy efficiency information model, developed by the authors, makes it possible to perform the quantitative analysis of investments in the replacement of building envelope elements to optimize management decisions in terms of the cost/return ratio. The research needs to be continued to consolidate the algorithms, developed for capital construction projects, whose architectural planning solutions contain modules having spherical, conical and pyramidal shapes. Also of considerable practical interest is the software implementation of developed algorithms in relational database shells and the formation of dynamic libraries of thermo-physical and geometric parameters of building envelope elements for standard construction facilities.

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Оптимизация экономических результатов внедрения энергосберегающих мероприятий в течение полного жизненного цикла объекта капитального строительства

Сложившийся консенсус о безальтернативности энергосберегающего вектора развития экономики привел к формированию национальных и международных программ энергосбережения и многочисленным исследованиям методов повышения энергоэффективности полного жизненного цикла проектов сектора архитектуры, инжиниринга, строительства и эксплуатации. Однако при этом выявили значительный разрыв между прогнозируемым и фактическим потреблением энергии, что подрывает стратегии и политику энергетической модернизации. И причины этого разрыва определяются как социальными, так и технико-технологическими факторами. На точность оценки экономической эффективности энергосберегающих мероприятий оказывает влияние также и неопределенность макроэкономической ситуации. Такое положение значительно затрудняет энергетическую модернизацию экономики. В сфере архитектуры, инжиниринга, строительства и эксплуатации улучшить ситуацию позволяет интеграция технологий информационного моделирования полного жизненного цикла, энергосбережения и дисконтирования затрат и прибыли. Методам увеличения точности прогнозирования экономических последствий мер энергосбережения и посвящена данная работа. Здесь получены алгоритмы количественного описания вклада архитектурно-планировочных решений и энергосберегающих технико-технологических решений и прогнозных макроэкономических условий в оценку энергоэффективности полного жизненного цикла проекта. Полученная информационная модель полного жизненного цикла проекта на этапе проектирования позволяет оптимизировать геометрические параметры архитектурно-планировочных решений по соотношению энергопотребление/затраты. На этапе реконструкции информационная модель позволяет оптимизировать технико-технологические решения, направленные на энергосбережение. На этапе эксплуатации по результатам динамического мониторинга теплофизических свойств ограждающих конструкций и макроэкономических условий может быть выполнена оптимизация планируемых мер энергосбережения. Кроме того, информационная модель энергоэффективности позволяет выполнить количественный анализ экономических последствий вложения средств в замену элементов ограждающих конструкций, что дает возможность оптимизировать текущие управленческие решения по соотношению затраты/отдача.

Ключевые слова: *информационная модель строительства, жизненный цикл проекта, энергосбережение, оптимизация, экономическая эффективность, объект капитального строительства*

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