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INTERNAL ENERGY CIRCULATION SOLUTIONS IN HEATING, VENTILATION AND AIR-CONDITIONING SYSTEMS: ASSESSMENT METHOD AND COMPARATIVE ANALYSIS

Abstract. *The paper presents an approach for assessing the sustainability of energy-saving measures in buildings based on the integral Sustainability Impact Index (SII), which incorporates the energy, environmental and circulatory characteristics of each solution. The methodology was tested on a case study of an office building, where energy-saving measures were structured into three groups and evaluated through a comparative analysis. The study also included the development of a circulatory solution based on the reuse of condenser heat from the building's chiller units. The results demonstrate that the application of the SII clearly reflects the increasing importance of measures related to internal energy circulation. The SII value for the circulatory measure was found to be approximately twice as high as for the technical and operational groups, indicating its concentrated impact and potential to replace external energy resources. The proposed approach allows for a more accurate prioritization of sustainable solutions and can be applied in planning HVAC system modernization and developing building decarbonization strategies.*

Keywords: *building energy efficiency, HVAC systems, circulatory solutions, heat recovery, sustainability index, multi-criteria assessment.*

Introduction. Heating, ventilation and air conditioning systems are among the main energy consumers in buildings and contribute significantly to their operational carbon footprint. Traditional approaches to improving their performance usually rely on local technical or control measures and do not take into account the potential of internal energy flows. As a result, considerable amounts of low grade heat from chiller units, server rooms, data processing centres, telecommunication equipment, pumping units and auxiliary cooling systems continue to be released into the environment. Growing requirements for the energy resilience of buildings and the tightening of environmental standards create a need for evaluation approaches that consider not only the local efficiency of individual measures but also their contribution to internal circulatory energy flows.

Research relevance. Circulatory energy solutions play an important role in current building decarbonization strategies because they support the reuse of internal thermal streams and reduce the dependence on external energy sources [1,2]. The algorithm for the transition to sustainable energy systems (Fig. 1) includes a consistent introduction of energy efficiency measures, the modernization of technological processes and the transformation of heat supply sources. Within this structure, circulatory solutions take an intermediate position and generate a system level effect that cannot be fully reflected by traditional energy or economic performance indicators.

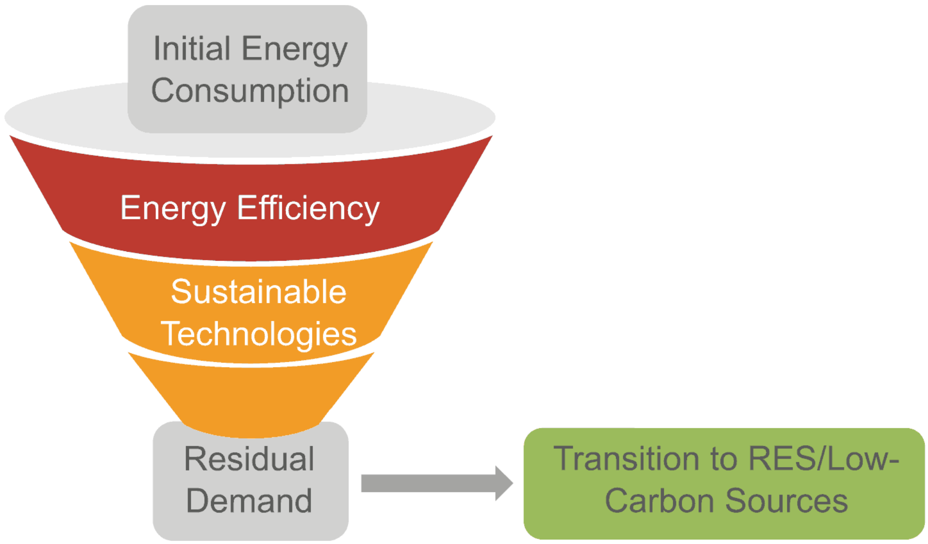

Fig. 1. Algorithm for Ensuring the Decarbonisation of Building Energy Systems incl. Renewable Energy Sources (RES)

Although considerable attention has been given to the technical aspects of heat recovery technologies and to the evaluation of their economic performance, the methodology for comparing such solutions with other energy saving measures remains insufficiently explored. This gap determines the relevance of the present study.

Recent studies and publications. The issues of improving the performance of HVAC systems are widely represented in contemporary literature. A substantial body of research focuses on the enhancement of equipment, the optimisation of operating modes and the implementation of intelligent control algorithms [3–4]. International organisations and professional associations define key directions for the development of energy efficient technologies and provide corresponding recommendations for the building sector [5–7]. These studies confirm that traditional technical and control based measures remain a fundamental tool for system optimisation.

Various approaches to heat reuse in buildings are examined in recent research. These include systems for the extraction and transfer of low grade thermal energy (heat recovery) [8–10], integrated cooling and heating schemes that combine the operation of the cooling and heating parts of the system [11–13], and internal closed energy loops that support the redistribution of thermal flows within a building [14,15]. It has been shown that heat recovery solutions can significantly reduce thermal energy consumption and CO_2 emissions in large office buildings [16–17]. At the same time, existing research mainly concentrates on the technical aspects of integrating such modules, while the methodological comparison of these solutions with other energy saving measures remains insufficiently addressed.

Current approaches to the analysis of the sustainability of energy solutions often employ multi criteria decision making methods that allow simultaneous consideration of energy, environmental, economic and operational factors [18]. The study in [19] proposes the use of normalised weighting coefficients for comparing HVAC modernisation options, which aligns with trends in building energy research. However, the available literature contains virtually no studies in which the criterion of internal energy circulation is considered separately and its system level role within the structure of energy effective measures is explicitly evaluated.

Therefore, despite the large number of studies devoted to HVAC optimisation and heat recovery technologies, the development of an evaluation method that correctly identifies the priority of circulatory solutions in the context of long term energy resilience of buildings remains an open task. The present study addresses this gap.

The aim of the paper is to develop a method for multi criteria assessment of circulatory energy solutions in building HVAC systems and to test this method for determining the relative effectiveness of a condenser heat recovery scheme in comparison with traditional energy saving measures.

Main part. Modern strategies for improving the sustainability and decarbonisation of building energy systems are often associated with the transition to renewable energy sources. At the same time, the effectiveness of such solutions largely depends on the quality of the preceding stages, which include the optimisation of energy consumption and the modernisation of technological processes. The three-component approach shown in Fig. 1 supports the reduction of resource losses and forms a basis for long-term decarbonisation [20]. In building systems these three blocks include the following directions.

- **Block 1. Optimisation of energy consumption.** Measures that reduce the initial energy demand of a building through improved performance of engineering systems, a decrease in losses and the use of precise and adaptive control.
- **Block 2. Adoption of sustainable technologies**. Measures that change or enhance the operating principles of HVAC systems. This includes the modernisation of energy intensive components, the introduction of advanced heating and cooling

technologies, the implementation of zonal transformations of the system and the development of circulatory solutions that enable the return and reuse of internal thermal flows.

- **Block 3. Transition to renewable energy sources.** Integration of low carbon and renewable energy systems to cover the remaining load after the implementation of the previous stages.

The subsequent analysis addresses a practical case study developed during the energy audit of an office building in Kyiv. Since the solutions belonging to the second block of sustainable technologies are technically complex and require careful justification, the audit included the search for an option that is rational, economically feasible and suitable for implementation under real operating conditions.

The evaluation of circulatory solutions requires prior identification of all thermal flows within the building. The zonal distribution of engineering systems by floor, presented in Fig. 2, provides the basis for further analysis of their interactions.

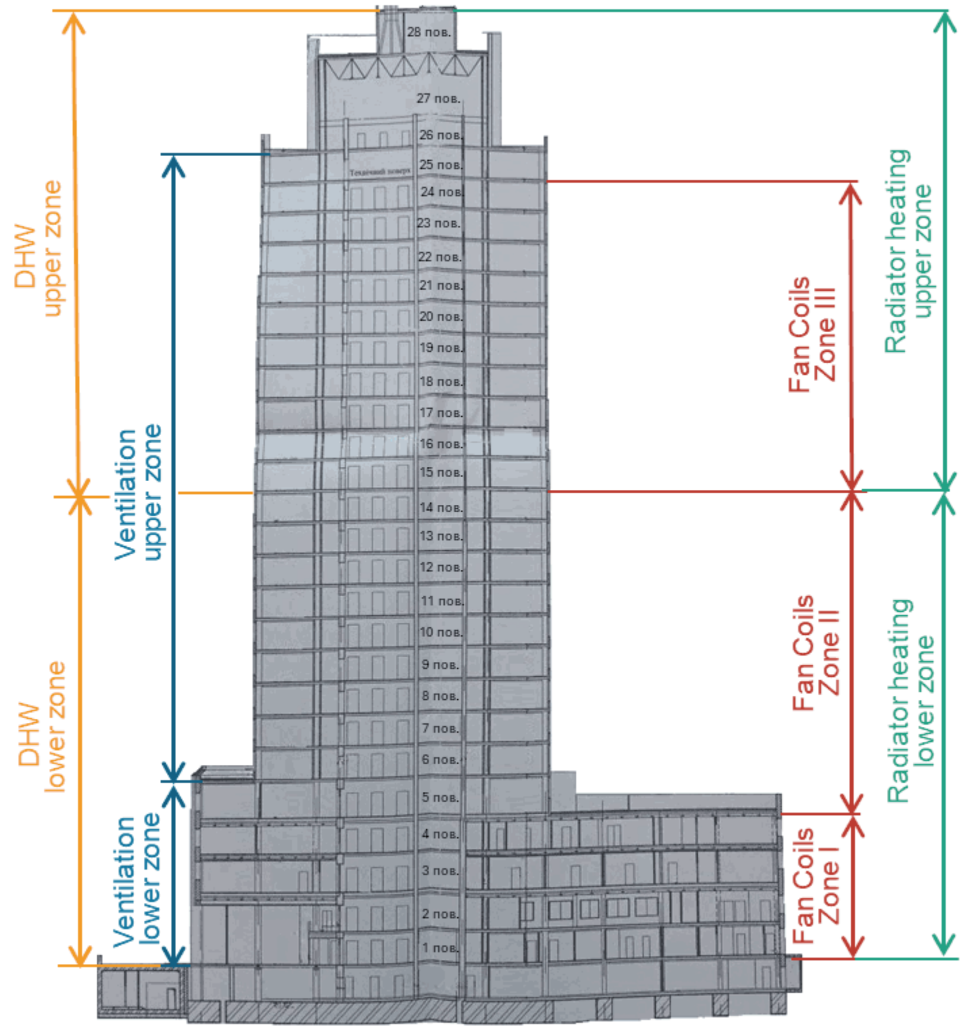

Fig. 2. Zonal distribution of building engineering systems by floors

Cooling in the building is provided by two chiller units operating with dry coolers, while heat supply, preheating of supply air and domestic hot water preparation are ensured by the central heating station equipped with nine heat exchanger modules. The internal spaces are fitted with fan coil units that operate in both cooling and heating modes.

During the cooling season, heat from the condenser circuits is discharged through the dry coolers, which leads to a substantial amount of waste heat being released into the atmosphere. Considering the duration of the summer period and the intensity of cooling system operation, these losses are considerable.

At the same time, the building includes a domestic hot water system with a stable thermal load, which creates a natural demand side loop capable of utilising part of this heat. The combination of a significant source of waste heat and a constant thermal demand creates favourable technical conditions for the integration of a heat recovery module into the chiller plant.

The measure involves the inclusion of a factory produced heat recovery module in the condenser circuit of the chiller system. The module is manufactured and supplied by the chiller producer as a standard modernisation option, which ensures complete compatibility and reliable system operation.

According to the manufacturer, the heat recovery module can extract approximately 70 to 80 percent of the condenser heat, which is then used for preheating cold water in a buffer tank before the domestic hot water system. The main heat exchangers of the heating station continue to maintain the required temperature parameters, while the recovery module only reduces their load without altering the configuration of the existing system. The operation of the integrated system is shown in Fig. 3, which presents the general principle of connecting the heat recovery module to the hydraulic circuit of the chiller plant and the domestic hot water system.

The heat recovery module operates in parallel with the existing condensers and performs the following functions:

1. When there is a demand from the domestic hot water system, the module provides preliminary heating of cold water in the buffer tank before it enters the main heat exchangers of the heating station.
2. When the amount of available heat exceeds the demand for water preheating, the excess is automatically discharged to the dry coolers, which corresponds to the normal operating mode of the system.
3. The operating mode of the chiller units remains unchanged, since the module automatically regulates the condensation pressure and adjusts to the actual thermal load.

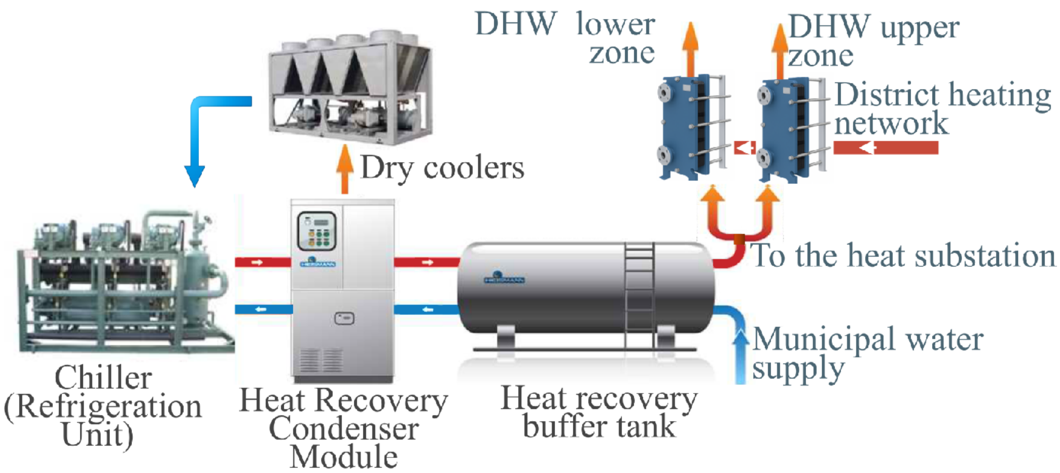

Fig. 3. Diagram of condenser heat recovery in the building's cooling system

The proposed heat recovery solution enables the utilisation of a portion of the condenser heat that was previously entirely discharged to the dry coolers. According to the analysis, the amount of heat available for reuse reaches approximately 301.9 MWh per year. In addition, the reduction in the thermal load on the dry coolers decreases their electricity consumption by about 17.8 MWh per year, which provides a noticeable energy benefit during the summer period. Owing to the reduced consumption of energy resources, the total annual environmental effect is estimated at approximately 85.7 tonnes of CO_2 per year.

For a correct determination of the priority of the heat recovery solution, its energy and environmental indicators must be compared with those of other energy-efficient measures identified during the building audit. For this purpose, the measures were organised into structured groups and an integral sustainability assessment method was applied, which makes it possible to compare heterogeneous solutions using consistent criteria.

Within the energy audit of the office building, sixteen energy saving measures were identified, each characterised by a different type of influence on HVAC system performance. To ensure a structured analysis and a consistent comparison of their contribution to sustainability improvement, these measures were consolidated into three groups, namely technical (engineering), operational and managerial, as well as circulatory energy solutions. Table 1 presents the content of each group, the corresponding energy and environmental indicators and the values of the Sustainability Impact Index (SII), which is used for the comparative assessment.

The calculation of the SII sustainability index for each solution ***i*** is based on a combination of four criteria and is formally expressed as follows:

$$SII_i = F\left(\Delta E_i + \Delta CO_{2,i} + \Delta B_{losses,i} + \Delta R_{circ,i}\right) \quad (1)$$

Table 1

Energy and environmental performance of energy-saving solutions and their sustainability index

№	Groups of Measures and Their Content	Number of measures	Energy effect, MWh/year	Environmental effect t CO_2-eq/year*	SII
1	**Technical (engineering) solutions** Hydraulic balancing of heating systems, improvement of connection nodes, replacement of outdated equipment with modern units, enhancement of filtration and heat-transfer efficiency, reduction of airflow resistance in ventilation ducts	7	222, 3	75,7	0,54
2	**Operational and managerial measures** Implementation of weather-based control, zonal temperature management protocols, adjustment of HVAC operating parameters, improvement of monitoring and control functions (metering, sensors, SCADA), enhancement of user interaction with the systems	8	392,0	105,5	0,73
3	**Circulatory energy solutions** Installation of an integrated condenser-heat recovery module	1	319,8	85,7	0,86

* *The environmental effect was calculated using the national CO_2 emission factors in accordance with Annex 10 of the Methodology for the Energy Performance of Buildings (MinRegion Order No. 169 of 11.07.2018): 0.42 t CO_2/MWh for electricity and 0.2598 t CO_2/MWh for district heating.*

where ΔE_i is the annual energy savings; $\Delta CO_{2,i}$ is the reduction of greenhouse gas emissions; $\Delta B_{losses,i}$ is the decrease in avoidable energy losses; $\Delta R_{circ,i}$ is the increase in the share of internal energy reuse.

Since these criteria have different physical nature and units of measurement, the method of normalised weights was applied to integrate them into a unified evaluation model, which is widely used in multi-criteria analysis of energy systems. This approach is applied in MCDM methodologies and in composite sustainability indices described in a number of international reviews [18] and studies on comprehensive HVAC modernisation [19].

The method requires expert determination of the relative importance of the criteria followed by weight normalisation. The sum of the weights for the four criteria is equal to one:

$$w_1 + w_2 + w_3 + w_4 = 1 \qquad (2)$$

Such a choice reflects the priority assigned to the circulatory component (internal reuse of energy), which is a key element of the proposed solution and corresponds to contemporary approaches to the energy sustainability of building systems.

To ensure the comparability of the criteria, the numerical values of the annual energy savings ΔE_i and the reduction in emissions $\Delta CO_{2,i}$ were converted into dimensionless form by normalising them within the interval [0;1]. Normalisation was performed using the relative maximum among all three groups of solutions:

$$\widetilde{E}_i = \frac{\Delta E_i}{\max\left(\Delta E\right)}, \quad \widetilde{CO}_{2,i} = \frac{\Delta E_{CO_{2i}}}{\max\left(\Delta E_{CO_2}\right)} \qquad (3)$$

The criteria are then included in the calculation of the sustainability index with the corresponding weighting coefficients. The SII value for solution *i* is determined as:

$$SII = w_1 \widetilde{E}_i + w_2 \widetilde{CO}_{2,i} + w_3 \Delta B_{loss,i} + w_4 \Delta R_{circ,i} \qquad (4)$$

The values of the normalised criteria and the adopted weighting coefficients for the three groups of solutions are presented in Table 2, and the calculated sustainability index values are shown in Table 1.

The analysis of the results in Fig. 4 shows that the use of the SII index changes the perception of the effectiveness of different groups of energy saving measures.

Table 2. Normalized criteria and weighting coefficients for calculating the SII

no	Group of measures	$\widetilde{E}$	$\widetilde{CO_2}$	ΔB_{loss}	ΔR_{circ}	w_1	w_2	w_3	w_4
1	Technical (engineering) measures	0,57	0,72	1,0	0,3	0,25	0,25	0,1	0,4
2	Operational and managerial measures	1,00	1,00	0,7	0,4	0,25	0,25	0,1	0,4
3	Circulatory energy solutions	0,82	0,81	0,5	1,0	0,25	0,25	0,1	0,4

For further comparison, the results from Table 1 were brought to a common scale by converting indicators into relative values. This made possible to present the three groups of measures in a comparable form and to perform their aggregated evaluation. Based on these data, Fig. 4 was constructed to show the energy effect, the environmental effect and the sustainability index SII for each group of measures.

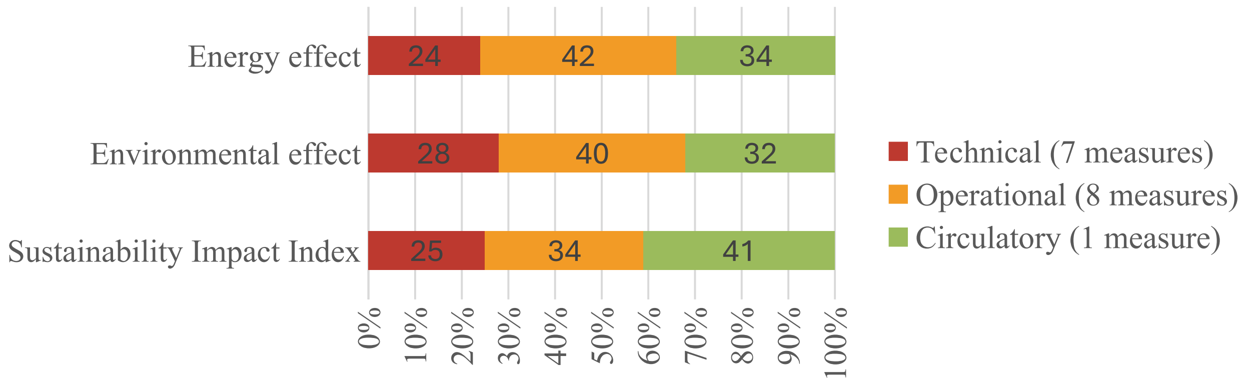

Fig. 4. Comparison of Energy-Saving Measures and Their Contribution to System Sustainability

The technical and operational groups have comparable energy and environmental indicators, although their overall effect is formed by numerous individual actions, each of which provides only a limited contribution. At the same time, the circulatory group contains only one measure, yet its aggregated SII value is the highest among the three groups.

The obtained relationship shows that traditional indicators do not fully reflect the potential of solutions that enable the reuse of internal energy flows and reduce the building's dependence on external resources. The use of the SII makes it possible to evaluate such solutions more comprehensively and to justify their priority in the development of modernisation plans and the enhancement of the resilience of building systems.

Conclusions. The energy audit of the office building resulted in the formation of a set of energy saving measures that included technical, operational and circulatory solutions, among them the reuse of condenser heat from the chiller units. The analysis showed that the technical and operational groups generate their effect through numerous local improvements, while a single circulatory measure achieved the highest sustainability score. This confirms its considerably stronger influence on the energy resilience of the building and demonstrates that solutions aimed at forming internal energy flows can play a decisive role in the overall outcome of system modernisation. The proposed Sustainability Impact Index made it possible to compare measures with different characteristics and scales of influence in a consistent way. The method demonstrated that traditional energy saving indicators do not fully capture the potential of circulatory solutions and may underestimate their priority within a classical energy audit. The use of the SII provides a more accurate identification of measures that support the long term sustainable performance of HVAC systems and deliver the highest overall effect.

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ЦИРКУЛЯЦІЙНІ ЕНЕРГЕТИЧНІ РІШЕННЯ В СИСТЕМАХ ОПАЛЕННЯ, ВЕНТИЛЯЦІЇ ТА КОНДИЦІОНУВАННЯ ПОВІТРЯ: МЕТОД ОЦІНЮВАННЯ ТА ПОРІВНЯЛЬНИЙ АНАЛІЗ

Анотація. *У статті розглянуто підхід до комплексного оцінювання сталості енергоощадних рішень у будівлях на основі інтегрального індексу SII (Sustainability Impact Index). Індекс об'єднує енергетичні, екологічні та циркулярні характеристики рішень і дає змогу порівнювати заходи з різною природою та масштабом впливу. Методика апробована на прикладі офісної будівлі, для якої в межах енергетичного аудиту сформовано перелік потенційних заходів і згруповано їх у технічні, операційні та циркулярні рішення, після чого виконано їх оцінювання за критеріями сталості. Особливу увагу приділено циркулярному рішенню, що передбачає використання теплоти конденсаторів холодильних машин для покриття потреб системи гарячого водопостачання. Такий підхід формує внутрішній енергетичний контур будівлі та зменшує залежність від зовнішніх ресурсів. Аналіз виконано на прикладі енергетичного аудиту офісної будівлі в Києві, обладнаної системами опалення, вентиляції, кондиціювання повітря та гарячого водопостачання. Результати показали, що технічні та операційні заходи забезпечують переважно локальні покращення, тоді як один циркулярний захід має найбільший інтегральний ефект. Значення SII для рекупераційного рішення майже вдвічі перевищує показники інших груп, що підтверджує його системну значущість.*

Використання індексу SII дозволяє визначати пріоритетність заходів з урахуванням їхнього внеску у формування сталих енергетичних потоків, а не лише у зменшення поточного споживання енергії. Такий підхід є корисним для підготовки планів модернізації систем опалення, вентиляції та кондиціювання повітря, інвестиційних обґрунтувань і стратегій декарбонізації будівель. Отримані результати підтверджують, що залучення циркулярних рішень до переліку першочергових заходів може суттєво підвищити енергетичну сталість будівельних систем у довгостроковій перспективі.

Ключові слова: *енергоефективність будівель, HVAC-системи, циркуляційні рішення, рекуперація теплоти, індекс сталості, багатокритеріальна оцінка.*

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