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POTENTIAL AND RESULTS OF SUSTAINABLE RESIDENTIAL HEAT SUPPLY USING WASTEWATER HEAT RECOVERY

Summary. *Purpose. The purpose of this article is to substantiate a management approach for improving the energy efficiency of residential buildings in line with sustainable development principles. The study focuses on wastewater heat recovery as an alternative heat source for residential heating, aiming to evaluate its technical, economic, and environmental feasibility and contribution to energy transition and post-war reconstruction in Ukraine.*

Materials and Methods. The research applies a comparative and case-based analytical method to evaluate wastewater heat recovery potential for a residential building. The methodology includes thermodynamic and financial calculations, estimation of CO_2 emission reductions, and assessment of system performance based on seasonal heating demand. The analysis integrates sustainability criteria – economic (cost reduction), environmental (emission mitigation), and social (comfort and affordability) – to provide a holistic evaluation framework.

Results. The results confirm that wastewater heat recovery systems offer significant potential for energy efficiency improvement in the residential sector. The analyzed system covered heat demand, reduced heating costs, and decreased CO_2 emissions. In addition to measurable environmental and economic benefits, the system enhances residential comfort, affordability, and energy security – crucial for Ukraine's post-war recovery and EU integration.

Discussion. The findings highlight wastewater heat recovery as a viable, sustainable, and scalable energy solution for urban housing. However, the study's limitations include its single-case nature, simplified assumptions regarding tariffs and emission factors, and the absence of detailed consideration of maintenance, fouling, and operational challenges. Future research should expand to multi-building or district-scale systems, incorporating lifecycle cost-benefit analysis, monitoring of long-term performance, and integration with smart municipal energy management frameworks. Additionally, financing mechanisms and engineering optimization of heat exchangers and filtration systems warrant further exploration.

Conclusions. Developing wastewater heat recovery technologies represents an important step toward achieving energy efficiency and sustainability in the residential sector. The proposed case demonstrates that such systems can significantly contribute to reducing fossil fuel dependency and carbon emissions, while supporting local energy resilience. The integration of wastewater heat recovery into urban energy systems should therefore be prioritized within national energy efficiency programs and EU-aligned climate policies to accelerate Ukraine's transition to a low-carbon, resource-efficient, and socially inclusive energy model.

Key words: *recuperation, energy, efficiency, sustainable development, water waste, heat supply.*

Problem statement. Achieving a fair and rapid energy transition requires not only expanding the share of renewable energy sources (RES), but also increasing the efficiency of using existing energy resources in production, supply and consumption [1]. One of the key areas of such efficiency is the use of secondary energy resources, in particular waste water heat, which is often lost without benefit.

Empirical studies show that the introduction of renewable sources without a parallel increase in energy efficiency does not provide the expected effect — system costs increase, technological losses increase, and decarbonization slows down. Therefore, along with the development of solar, wind and bioenergy, it is important to use local low-potential heat sources — for example, wastewater, industrial waste heat, ventilation flows. Such solutions do not require significant areas and allow reducing fossil fuel consumption in heating systems of buildings and enterprises.

From the point of view of the energy system, resource efficiency is a tool for balancing supply and demand. Heat recovery technologies and waste water heat pumps can reduce peak loads on the power grid, stabilize consumption and reduce CO_2 emissions. This approach combines alternative energy with the principles of the circular economy, where energy from waste becomes part of the overall energy efficiency of a city or enterprise.

Therefore, the efficiency of energy consumption — in particular through the use of waste water heat — should be considered as an integral element of the energy transition. This not only reduces overall energy costs, but also ensures sustainable, locally oriented development of energy infrastructure, increasing energy security, accessibility and environmental friendliness.

Literature review. Today, the topic of energy efficiency in residential areas is widely covered in academic work. A bibliometric review of research on energy efficiency [2] concludes that achieving energy efficiency toward sustainable buildings is a hot topic in the sustainable development area, and underlines the need for future research in the field. Authors of article [3] examined sustainable building design and found that it is accompanied by the use of emerging energy sources such as solar, wind, hydrogen, and geothermal resources. Article [4] reported 25% higher energy savings and 46.8% lower CO_2 emissions for the green option by comparing a green-building model with a conventional one. Authors of the article [5] also address sustainable design and technologies that use alternative energy sources to enhance energy efficiency. Prospects for the deployment of alternative energy sources are framed in article [6,7] and normative documents [8].

Practical applications of alternative energy for building heating are likewise covered in the literature. Voloshchuk V. and Hrytsyna O. [9] discuss the concept of fourth-generation district heating, including technologies that use energy from wastewater, and view sewerage and heat supply systems as components of a single urban life-support complex. Author's team of article [10] present the potential of wastewater heat recovery at different points in the water cycle (heat exchangers and/or heat pumps) to reduce heating demand. They show that, at the individual-building level, economic feasibility is limited and that studies jointly addressing energy, economic, and environmental aspects remain scarce. Łokietek et al. (2023) [11] present the heat-recovery potential at a Polish wastewater treatment plant as a case study. Thus, one promising area is the use of heat from sewage, which is typically discharged without beneficial use.

The relevance of this topic is supported by international data. According to the International Energy Agency [12], district heating accounts for around 10% of building heating worldwide. Fuels and sources used include fossil fuels, waste heat from power generation and industry, sewage, data centres, and renewable energy. In Europe, there are over 6,000 district-heating networks, covering about 11% of heating demand. Many countries have already implemented sewage heat-recovery technologies in municipal and public sectors. For example, in Switzerland, a heat-pump system uses sewage heat for district heating of apartment buildings and schools [13], reducing natural-gas consumption by 70% and CO_2 emissions by 40% [14]. In Stockholm, about 98% of heating is provided from renewable or recovered waste heat using large-scale heat pumps. In Paris, under the Seine Amont project, heat exchangers installed in sewers supply heat to municipal buildings, including schools and swimming pools [15]. In the Netherlands (Amsterdam), a large-scale sewage heat-recovery system supplies heat to entire residential areas as part of the city's 2050 climate-neutral strategy; wastewater at around 20 °C can be used, and separating hot and cold streams can improve efficiency [16]. In Tokyo, a system recovers heat from sewage to warm subway stations and municipal buildings, supported by a government energy-efficiency program [17].

Research on existing wastewater heat-recovery (WWHR) systems worldwide also shows substantial savings potential — primary energy consumption can be reduced by up to 50% [18]. Studies in low-carbon neighborhoods on the outskirts of Paris found that a heat-pump system covered about 75% of annual heating needs, with recovered energy accounting for 30–40% of monthly primary energy consumption, and four-times lower CO_2 emissions versus a gas-only system [19]. In sum, using sewage for heating is innovative but already proven in developed countries. For Ukraine, especially amid ongoing conflict and constrained access to traditional fuels, the approach is relevant, economically viable, and environmentally safe. Its implementation would strengthen energy independence, reduce CO_2 emissions, and lower operating costs for building heating.

Recent scholarship demonstrates how the sustainability lens has reshaped energy-efficiency management from a purely technical focus (e.g., kWh/m² via insulation and equipment upgrades) to a strategic lever for sustainable development [20–22]. An improved management view integrates organizational, financial, and behavioral drivers [23]. Within this framework, we assess the technical, economic, energy, and environmental performance of wastewater heat recovery for space heating as an alternative source consistent with sustainability criteria [24]. Because implementing sustainability principles entails change, it is important to study readiness — drawing on international experience and evaluating domestic potential, including in Ukraine.

Thus, recent scientific research is increasingly focused on identifying and applying alternative energy sources to enhance energy security and sustainability.

Among these, the use of recovered heat from wastewater in urban sewer systems has become a rapidly developing practice in many foreign countries. This highlights both the relevance and novelty of the investigated topic, as in domestic practice such applications remain relatively rare. The issue of utilizing thermal energy from wastewater requires a deeper technical and economic analysis. However, considering a specific case study will allow for demonstrating the tangible results and potential of this alternative energy asset for decentralized energy supply.

The purpose of the article is to substantiate the management approach for improving the energy efficiency of residential premises, considering the criteria of sustainable development, based on a study of the use of wastewater heat recovery for heating residential premises. To achieve this goal, the article substantiates the relevance of using alternative sources of heat supply in residential buildings and describes a method for determining the amount of energy required to heat a residential building based on the use of heat from municipal sewage wastewater, and demonstrates the impact on achieving sustainable development goals and the potential for developing this direction of energy supply for heating residential buildings.

Material and Methods. The study's materials include the regulatory and legal framework governing the management of energy resource generation and delivery to customers, as well as the scientific and practical works of domestic and international scholars who conduct research in the field of investigation, including the implementation of alternative energy resources and their delivery to customers.

To achieve the set goal, it is planned to conduct a content analysis of the concept of energy efficiency in the residential area, highlight the differences between traditional and sustainable approaches to energy efficiency management, and justify the sustainability of management decisions.

The energy balance of the building gained by renewable sources is determined based on the calculation of the amount of heat obtained through wastewater heat recovery and the calculation of the amount of heat required to heat the premises. The heat demand is calculated using the formula:

$$Q_1 = v \cdot q \cdot \Delta T, \quad (1)$$

where are:

Q_1 — heat demand;

v — house volume (500 m^2);

q — specific heat load per 1 m^2 (50 W/m^2);

ΔT — temperature difference (income — outcome in °C = 20 °C – 12 °C = 8 °C).

To quantify the heat that can be harvested from a wastewater flow, we use formula (2):

$$Q_2 = \frac{Q_2}{t} = \dot{m} \cdot c \cdot \Delta T, \quad (2)$$

where are:

$\dot{m}$ — is the mass flow rate of wastewater, kg/h; in our case 10 m^3/h ≈ 10 000 кg/h;

c — is the specific heat capacity of water [~4.18 kJ/(kg · K)];

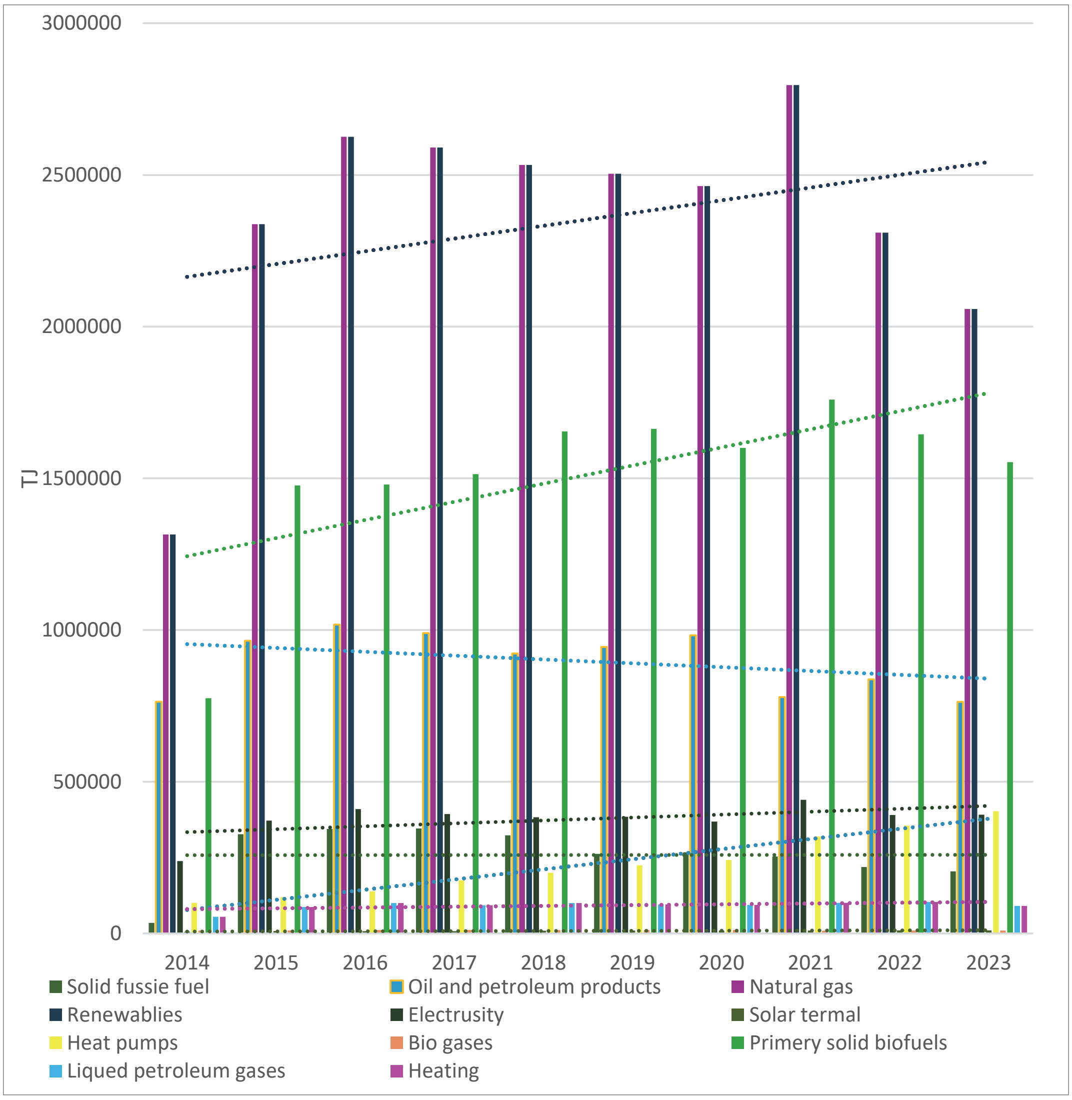
ΔT — is the temperature difference between the wastewater and the heat carrier in the heating system.

Based on the data obtained, an energy balance was constructed and the resource deficit was determined, which allows identifying additional reserves of energy supply and energy efficiency. To justify the sustainability of the solution, the sustainable efficiency of using alternative resources to obtain thermal energy from wastewater was determined by calculating the environmental, ecological, and social efficiency.

Results. According to the annual statistics on final energy consumption of households [25], energy consumption for heating has been showing a slow upward trend since 2014, peaking around 2021, after which there was a significant decline in 2022–2023. This trajectory is well consistent with the post-pandemic recovery in demand, and later with the response of households to the price shock and energy saving policies resulting from the war in Ukraine.

The fuel structure shows a shift from traditional fossil fuels to electrification and renewable sources. Petroleum products for domestic stoves and boilers have been steadily losing ground throughout the period, the longest and most consistent decline among all fuels. Coal and briquettes are also decreasing, although in some years there has been a temporary stabilization: current levels are significantly lower than ten years ago. Natural gas grew until 2021, but declined during the 2022–2023 crisis, reflecting both price risks and the accelerated replacement of gas systems with alternatives. LPG has generally fluctuated around a relatively stable level, with no clear long-term trend. Renewables, on the other hand, have shown steady growth. The combined category of "renewables and biofuels" has strengthened significantly, having grown most significantly since 2018. Biogas is being added slowly, from a small base. Solar heat is growing gradually and remains a small contribution so far. The key story of the period is the electrification of heating: electricity consumption for heating has been growing throughout the period, and the use of heat pumps has accelerated sharply since 2019–20. Heat pumps have provided the most rapid growth in recent years, becoming the main driver of structural changes towards cleaner and more efficient heating. As a result, we see a gradual shift away from oil and coal, a wave-like gas dynamics, the stability of liquefied gas, and a systemic transition to renewable solutions and electrification, the culmination of which was heat pumps. After the peak in 2021, total heating consumption decreased, but the structural trends — "less fossil, more electricity and renewables" — have persisted. For policymakers, this means the need to support the modernization of buildings, accelerate the connection of heat pumps, and provide affordable, low-carbon electricity. This combination of measures simultaneously reduces emissions, increases the energy efficiency of housing, and reduces the vulnerability of households to price shocks. Fig. 1 graphically presents the trends in the change in the energy mix for heating purposes.

Thus, the dashed lines in the figure confirm a shift in the heating mix away from oil products and coal toward electrification and renewable solutions (especially heat pumps), against a backdrop of a moderate overall increase in heat demand over the decade. Therefore, it is important and timely to study how this energy transformation can be practically implemented.



Notes: The dashed lines on the chart are linear trends. They show where each data series is "pulling" despite year-to-year fluctuations.
Total "Heating" (space heating) — upward trend: overall heat demand increased, though there is a decline after the 2021 peak.
Renewables (aggregate) — upward trend.
Primary solid biofuels — upward trend (the most pronounced growth among fuels).
Electricity for heating — steady upward trend.
Heat pumps — sharply upward trend (acceleration since 2019–2020).
Biogases — slightly upward trend (from a low base).
Solar thermal — moderately upward trend (small contribution).
Natural gas — mostly upward until 2021, then a decline; overall, the trend is nearly flat/slightly upward over the whole period.
Oil and petroleum products (heating oil/kerosene/diesel) — steadily downward trend.
Solid fossil fuels (coal/briquettes) — downward trend (current levels are markedly lower than in 2014).
Liquefied petroleum gas (LPG) — slightly downward/stable trend.

Fig. 1. Structure and dynamics of energy consumption for space heating, TJ.
Source: formed based on [25]

Research on utilizing wastewater as a source for enhancing energy efficiency is conducted within the framework of energy-efficiency policies at both national and international levels. In Ukraine, one of the goals under the National Renewable Energy Action Plan to 2030 is to increase the share of renewable energy in gross final energy consumption for heating and cooling systems from 20.8% in 2025 to 32.5% in 2030 [26]. Among the projects in the national programme for the recovery and modernization of housing and regional infrastructure is the initiative titled "Creation of energy–environmental complexes that use gas from organic waste and from municipal wastewater treatment plants in cities with populations over 100,000" [27].

In the EU, the REPowerEU plan [28] aims to rapidly reduce dependence on Russian fossil fuels and to accelerate the green transition through three pillars: prioritizing energy efficiency, diversifying supplies, and scaling up clean energy. For urban heat supply, this translates into support for heat pumps, streamlined permitting, network modernization, and the deployment of low-grade heat sources. In this context, wastewater becomes a strategic resource, as its stable temperature enables the supply of district heating systems for buildings via heat exchangers and large heat pumps. This reduces the consumption of gas and heating oil, cuts emissions, and mitigates price risks. REPowerEU opens access to financing, simplifies procedures, and facilitates integration into heat networks for such projects, making energy from wastewater a practical tool for both decarbonization and strengthening the resilience of municipal heat supply.

From a practical perspective in the housing and utilities sector, wastewater is a by-product of the activities of households and enterprises connected to sewerage systems. It is generated because of water use for domestic, industrial, stormwater, and other purposes. Therefore, it can be regarded as a component of municipal waste, specifically as water-use waste. From a legal perspective, under Ukrainian legislation, in particular the Law of Ukraine "On Housing and Communal Services," [29] wastewater is not defined as "solid household waste," yet it is an object of management within water supply and sewerage, which form part of municipal services. The Waste Law [30] defines waste as substances or items that no longer have any useful application at their place of origin and are subject to disposal or neutralization. EU Directive 2018/2001 [31] recognizes wastewater as a source of renewable heat. Accordingly, wastewater may be considered waste — namely, water-use waste — that is subject to treatment, disposal, or the recovery of secondary heat, as in the case of heat pumps. Thus, sewage is a specific type of municipal waste that, thanks to innovative technologies, can serve as a source of secondary resources, including thermal energy. This enables its integration into circular-economy models and sustainable development, and helps address the efficient use of energy resources and their potential. In the Ukrainian context, it is also appropriate to add that unforeseen disruptions to energy supply during conflicts encourage a shift to alternative energy sources, while the depletion and destruction of territories are seen as an opportunity to restore environmental standards or to create a new national legal framework for sustainable resource management [32].

The traditional definition of energy efficiency in residential are, which is often used in technical, economic, and regulatory literature, characterizes the relationship between the useful result obtained (service, product, comfort, etc.) and the amount of energy consumed to achieve it. European documents state that energy efficiency means using less energy to achieve the same output or service [33]. Ukrainian official sources also provide a similar definition of energy efficiency as achieving a specified level of useful energy consumption with minimal energy expenditure [34]

We propose to deepen the definition of energy efficiency in the residential sector. We define energy efficiency as the ability of a building to provide an adequate level of comfort and functionality with minimal energy consumption, achieved through the systematic implementation of managerial, technological, financial, and regulatory-strategic measures focused on sustainable development and adaptation to post-war recovery conditions. One source of energy efficiency is displaced energy — the amount of thermal energy that can be obtained from wastewater heat and which would otherwise be obtained from traditional sources (gas, coal, electricity). It is calculated in Gcal/year or kWh/year. Sewage is a specific type of municipal waste that, thanks to innovative technologies, can be a source of secondary resources, such as thermal energy. This allows it to be integrated into circular economy and sustainable development models (Directive (EU) 2018/2001).

We consider a house with a volume of 500 m2 to calculate the potential of residential heating from wastewater obtained from a municipal sewer system. The calculation of wastewater mass per second is as follows:

Calculation of wastewater mass per second:

$$m = 10\ \text{m}^3/\text{hour} \times 1000\ \text{kg/m}^3\ (\text{density}) =$$
$$= 0.00278\ \text{m}^3/\text{sec} \times 1000\ \text{kg/m}^3 = 2.78\ \text{kg/sec};$$
$$\Delta T = 20 - 12 = 8\ °\text{C}.$$

The heat demand is:

$$Q_1 = 500 \cdot 50 \cdot 8 = 80000\,W = 80\,kW\,,$$

The thermal power extracted from the water is:

$$Q_2 = 2.78\,kg/m^3 \times 4.18\,kJ/\left(kg \cdot K\right) \times 8 = 92.96\ \ kW/m^3$$

Thus, the thermal energy that can be obtained from wastewater is equal to 92.96 kW ~ 93 kW. Taking into account the efficiency of the heat exchanger (the heat that will actually be transferred). Taking into account the efficiency of the heat pump (85%), the thermal energy is equal to:

$$Q_{2'} = 92.96 \times 0.85 = 79.02\,kW.$$

Therefore, the adjusted thermal energy is equal to 79.02 kW. Based on the above data, we can form an energy balance for the building, which allows us to assess whether the thermal energy obtained from wastewater is sufficient to meet the heating needs of the premises (Table 1).

Table 1

Energy balance

Parameter	Value
Building heat demand	80.00 kW
Available heat from wastewater	79.02 kW
The difference	–0.98 kW

The thermal energy obtained from wastewater almost completely covers the building's heating needs. With an optimal design of the heat exchanger, underfloor heating, or other storage systems, such a system can be self-sufficient, environmentally friendly, and energy efficient. It is essential to consider actual heat losses, which also depend on heat loss through the building envelope (walls, roof, and floor), air infiltration (drafts), ventilation, and uneven heat supply from wastewater (such as during peak hours). Therefore, it is advisable to include a 10–15% reserve in the heat source or combine it with an auxiliary source (e.g., a heat pump) (Table 2).

Table 2

Energy balance

Parameter	Value
Building heat demand	80.00 kW
Reserve for losses (15%)	0.15 × 80 = 12.00 kW
Total demand, taking into account losses	92.00 kW
Heat from wastewater (considering efficiency)	79.02 kW
Heat deficit	92–79.02 = 12.98 kW

Thus, considering the reserve, the wastewater heat recovery system covers ~86% of the building's heating needs. It is recommended to combine the wastewater system with an auxiliary heat source, such as an air-to-water heat pump or a gas boiler. Let's calculate the economic effect of using a wastewater heat recovery system compared to the cost of conventional electric heating. The calculation of the costs of full electric heating (at 16 hours of heating during a heating period of 150 days) is based on the electricity price of about 4,32 UAH per kWh.

$$Q = 92\,kW \times 16\,hours\,/\,day \times 150\,days = 220{,}800\,kWh\ ,$$

$$Value = 220{,}800 \times 4.32\,UAH = 954{,}057.60\,UAH\ ,$$

Let's calculate the costs of using heat from wastewater:

$$Q = 12.98\,kW \times 16\,hours \times 150\,days = 31{,}152\,kWh\ ,$$

$$Value = 31{,}152 \times 4.32\,UAH = 134{,}578.00\,UAH$$

The Table 3 shows the steady results of wastewater heat recovery for heating buildings. The results confirm that wastewater heat recovery systems have significant technical, economic, and environmental potential for improving energy efficiency in residential buildings.

The system provided about 86% of total heat demand, reducing heating costs by over 85% and cutting CO_2 emissions by around 13.5 tons per season for a 200 m² house. In addition to economic and environmental benefits, such systems improve living comfort, affordability, and energy security — key priorities for Ukraine's post-war reconstruction and EU integration.

The main advantages of this study are the practical demonstration of a real case, clear calculations of savings and emissions, and a multidimensional assessment combining technical, financial, and social effects. The limitations include its single-case nature, assumptions about tariffs and emission factors, and lack of detailed analysis of installation, maintenance, and fouling effects. Future research should focus on

Table 3

Effects of energy efficiency measures

Elements of efficiency	Calculation	Explanation
Economic effect	954,057.60 – 134,578.00 = = 819,479.60 UAH per season	The use of a heat recovery system reduces heating costs by approximately 820,000 UAH per season, which is more than 85% savings compared to full electric heating
Environmental effect	(220,800 – 31,152) × 0.432* = = 13,464.6 kg CO_2 ≈ 13.46 *t* CO_2	The use of a wastewater heat recovery system reduces greenhouse gas emissions by ~14 tons of CO_2 per year for a single 200 m² house.
Social impact	Reduction in household energy costs: 819 479,60/12/15 000** ≈ 4.5 people	The social impact is an indirect result that reflects the quality of life, comfort, accessibility of resources, health care, and well-being of the population.

Notes: *Conditional CO_2 emissions per 1 kWh of electricity in Ukraine: 0.432 kg CO_2/kWh
**Average salary in Ukraine

large-scale applications in residential complexes, long-term performance monitoring, and cost-benefit analysis including lifecycle impacts. Attention should also be given to engineering optimization, financing models, and integration into municipal energy systems to strengthen the transition toward sustainable, low-carbon urban heating solutions.

Conclusion. Developing the issue of Energy Efficiency in the residential sector, it is essential to determine how to enhance a building's ability to provide the necessary comfort and functionality with minimal energy consumption through targeted changes (management, technological, financial, and regulatory). The relevance of this issue arises from the need to establish secure energy supply conditions in the context of energy infrastructure destruction, as well as Ukraine's desire to meet EU requirements for energy transition during post-war reconstruction.

Using a comparative approach to justify management principles for improving building energy efficiency — while accounting for sustainability criteria — we find that wastewater heat recovery for residential heating aligns with sustainable development and delivers economic, environmental, and social benefits. In our case study, a sewer heat-exchanger system reduced CO_2 emissions by more than 12 tons per heating season and supplied approximately 86% of the building's heat demand. Social co-benefits include improved comfort, resource affordability, and public health and well-being. These results substantiate the decision to deploy wastewater heat recovery for space heating and form the potential for energy transition and sustainable making decision. Implementation of investigated case still requires careful consideration of building design, sewer hydraulics and thermal conditions, infrastructure readiness, operations and maintenance capacity, and personnel skills. Further research should address infrastructure needs for specialized heat-pump systems and pipelines, and tackle fouling from suspended solids and chemical contaminants in wastewater through appropriate pretreatment, filtration, and cleaning to avoid equipment damage.

References

1. Mykhailyshyn, K., Polyanska, A., Psyuk, V., Antoniuk. How to achieve the energy transition taking into account the efficiency of energy resources consumption. *E3s Web of Conferences,* 2024, 67, 01026. https://doi.org/10.1051/e3sconf/202456701026

2. Hafez, F. S., Sa'di, B., Safa-Gamal, M., Taufiq-Yap, Y. H., Alrifaey, M., Seyedmahmoudian, M., Stojcevski, A., Horan, B., & Mekhilef, S. Energy Efficiency in Sustainable Buildings: A Systematic Review with Taxonomy, Challenges, Motivations, Methodological Aspects, Recommendations, and Pathways for Future Research. *Energy Strategy Reviews*, 2023, 45. https://doi.org/10.1016/j.esr.2022.101013

3. Wang, N., Adeli, H. Sustainable building design. *Journal of civil engineering and management*, 2024, 20(1), 1–10. http://doi.org/10.3846/13923730.2013.871330

4. Kusi, E., Boateng, I., & Danso, H. Energy consumption and carbon emission of conventional and green buildings using building information modelling (BIM). *International Journal of Building Pathology and Adaptation*, 2025, 43(4), 826–854. https://doi.org/10.1108/IJBPA-09-2023-0127

5. Shahee, A., Abdoos, M., Aslani, A. et al. Reducing the energy consumption of buildings by implementing insulation scenarios and using renewable energies. *Energy Inform,* 2024, 7, 18. https://doi.org/10.1186/s42162-024-00311-9

6. Oriekhova A., Khorolets B., Klymenko M. Alternative energy in the context of innovative restructuring of the energy sector of Ukraine: management aspect. *Ukrainian Journal of Applied Economics and Technology,* 2024, 9(2), 214–218. https://doi.org/10.36887/2415-8453-2024-2-36 [in Ukrainian].

7. Kasych A. O., Lytvtnenko Ya. O. Factors of development of alternative energy in modern conditions. *Economy and Society,* 2017, 12, 93–99 [in Ukrainian].

8. European Commission: Directorate-General for Energy, E-Think, Fraunhofer ISI, TU Wien, Viegand Maagoe, Öko-Institut e.V, Kranzl, L., Fallahnejad, M., Büchele, R., Müller, A., Hummel, M., Fleiter, T., Mandel, T., Bagheri, M., Deac, G., Bernath, C., Miosga, J., Kiefer, C., Fragoso, J., Braungardt, S., Bürger, V., Spasova, D., Viegand, J., Naeraa, R.Forthuber, S. (2022). Renewable space heating under the revised Renewable Energy Directive — ENER/C1/2018-494 — Final report, Publications Office of the European Union. URL: https://data.europa.eu/doi/10.2833/525486 (Retrieved August 16, 2025).

9. Voloshchuk, V. A., Hrytsyna, O. O. Wastewater as a source of energy in a new generation of heat supply systems. *Problems of water supply, sewerage, and hydraulics.* KNUCA (Kyiv National University of Construction and Architecture), 2016, 19, 63–70 [in Ukrainian].

10. Nagpal, H., Spriet, J., Murali, M. K., McNabola, A. Heat Recovery from Wastewater — A Review of Available Resource. *Water*, 2021, 13, 1274. https://doi.org/10.3390/w13091274

11. Łokietek, T., Tuchowski, W., Leciej-Pirczewska, D., Głowacka, A. Heat Recovery from a Wastewater Treatment Process — Case Study. *Energies,* 2023, 16, 44. https://doi.org/10.3390/en16010044

12. International Energy Agency (IEA). Energy Efficiency 2022. URL: https://iea.blob.core.windows.net/assets/7741739e-8e7f-4afa-a77f-49dadd51cb52/EnergyEfficiency2022.pdf (Retrieved August 16, 2025).

13. Hadengue, B., Joshi, P., Figueroa, A., Larsen, T. A., Blumensaat, F. In-building heat recovery mitigates adverse temperature effects on biological wastewater treatment: a network-scale analysis of thermal-hydraulics in sewers, *Water Research,* 2021, 204, 117552. https://doi.org/10.1016/j.watres.2021.117552

14. Meuli, K., Bryner, A. Reusing shower water. Eawag: Swiss Federal Institute of Aquatic Science and Technology. (2021, september 9). URL: https://www.eawag.ch/en/info/portal/news/news-detail/reusing-shower-water/ (Retrieved August 16, 2025).

15. SIAAP. The SIAAP's strategy for an ecological transition towards sustainable development. *SIAAP,* 2017. URL: https://www.siaap.fr/fileadmin/user_upload/Siaap/1_Le_SIAAP/SIAAP_en_anglais/SIAAP-STRAT-DD_EXE-GB.pdf (Retrieved August 16, 2025).

16. RES. The offer from the Amsterdam sub-region [Draft 2020]. URL: https://www.amsterdam.nl/en/policy/sustainability/renewable-energy/ (Retrieved August 12, 2025).

17. Tokyo Metropolitan Government. Tokyo Sustainability Action 2023. URL: https://gold.uclg.org/sites/default/files/uploaded/tokyo_2023.pdf (Retrieved August 15, 2025).

18. Liu, Z., Ma, L., Zhang, J. Application of a heat pump system using untreated urban sewage as a heat source. *Applied Thermal Engineering*, 2014, 62, 747–757. https://doi.org/10.1016/j.applthermaleng.2013.08.028

19. Sievers, J., Londong, J., Stübler, A., Bestenlehner, D., Drück, H., Schönfelder, W. Heat recovery potential of domestic grey water in the pilot project Jenfelder Au in Hamburg. In Proceedings of the 17th International EWA Symposium "WatEnergyResources-Water, Energy and Resources: Innovative Options and Sustainable Solutions", Munich, Germany, 5–9 May 2014.

20. Mikučionienė R., V. Martinaitis. The model of sustainable management of building energy performance. The 9th International Conference "Environmental engineering" 22–23 May 2014, Vilnius, Lithuania. 272. https://doi.org/10.3846/enviro.2014.272

21. Kosenko, A., Khomenko, O., Kononenko, M., Polyanska, A., Buketov, V., Dychkovskyi, R., Polański, J., Howaniec, N., & Smolinski, A. Sustainable management of iron ore extraction processes using methods of borehole hydro technology. *International Journal of Mining and Mineral Engineering*, 2025, 16 (1), pp.92–112. https://doi.org/10.1504/IJMME.2025.145592

22. Polyanska, A.S., Martynets, V.O., Psyuk, V.R., Kashchenko, Y.R., Maksymchuk, A. O. Transformation of the business ecosystem model into energy enterprise's strategy. *IOP Conference Series: Earth and Environmental Science Conference Paper*, May 2024. http://doi.org/10.1088/1755–1315/1415/1/012055

23. Polyanska, A., Pazynich, Yu., Petinova, O., Nesterova, O., Mykytiuk, N., Bodnar, G. Formation of a Culture of Frugal Energy Consumption in the Context of Social Security. *ICOHTEC*, 2024, 29 (2), 60–87. https://doi.org/10.11590/icon.2024.2.03

24. Akinsulire, A., Adewale, A., Idemudia, C., Okwandu, A. C., & Iwuanyanwu, O. Sustainable development in affordable housing: Policy innovations and challenges. *Magna Scientia Advanced Research and Reviews*, 2024, 11(02), 90–104. https://doi.org/10.30574/msarr.2024.11.2.0112

25. Eurostat. Disaggregated final energy consumption in households — quantities. *Eurostat.* URL: https://ec.europa.eu/eurostat/databrowser/view/nrg_d_hhq__custom_17730621/default/table (Retrieved August 14, 2025).

26. National Action Plan on Renewable Energy until 2030. Approved by the Resolution of the Cabinet of Ministers of Ukraine dated August 13, 2024, No. 761-r URL: https://zakon.rada.gov.ua/laws/show/761-2024-%D1%80#Text [in Ukrainian].

27. National indicative target for renewable energy in gross final energy consumption by 2030 in heating and cooling systems, in electricity generation, and in the transport sector. URL: https://recovery.gov.ua/project/program/recovery-and-upgrade-of-housing-and-regions-infrastructure?page=10 [in Ukrainian].

28. REPowerEU: A plan to rapidly reduce dependence on Russian fossil fuels and fast forward the green transition. URL: https://ec.europa.eu/commission/presscorner/detail/en/ip_22_3131 (Retrieved August 16, 2025).

29. On Housing and Communal Services: The Law of Ukraine [in Ukrainian].

30. On Waste: The Law of Ukraine [in Ukrainian].

31. Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources. *Off. J. Eur. Union,* 2018, 5, 82–209.

32. Polyanska, A., Cichon, D., Verbovska, L., Dudek, M., Sala, D., Martynets, V. Developing Waste Management Skills in Modern Conditions: The Case of Ukraine. *Financial and Credit Activity Problems of Theory and Practice*, 2022, 4(45), 322–334. https://doi.org/10.55643/fcaptp.4.45.2022.3814

33. Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 006/32/EC. Directive — 2012/27 — EN — EUR-Lex.

34. On energy efficiency: The Law of Ukraine № 1817-IX from 21.10.2021.