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Shaping cost-optimal and environmentally friendly strategies for household heating systems: case of Ukraine

Abstract: The heating processes of private residential buildings demand substantial fuel and energy resources and contribute to global warming, necessitating the transition to energy-efficient and eco-friendly heating. This study aims to develop a methodological approach for selecting cost-optimal strategies for household heating systems by assessing the environmental impacts and cost-effectiveness of available options of fossil fuels and renewable energy used in the residential sector during a heating season while ensuring homes' greening and energy efficiency. The research extends the existing methodology by considering climatic zones and their ambient air temperature fluctuations during a heating season, household energy efficiency, various energy carriers used for heating, household running and capital costs for heating, multi-zone electricity tariffs, and prospects of heating automation, aiding policymakers in shaping residential heating choices. Tested on a typical Ukra-

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inian household, the approach contributes to sectoral policy improvement by creating energy-efficient and decarbonization strategies for housing stock, with potential application in other countries. The results show that the most cost-optimal options for heating in Ukraine are firewood and natural gas use under the current energy policy. Based on the findings, the study suggests recommendations within Ukraine's regional context and carbon neutrality goals. They provide a transition to renewables (wood pellets and heat pumps) by developing a market infrastructure for servicing boiler equipment and logistics for biofuel supply, state economic support to local boiler equipment manufacturers, and partial reimbursement of investments in pellet boilers and heat pumps for households, electricity tariff adjustments, etc.

Keywords: household, heating, cost-optimal strategy, decarbonization, Ukraine

Introduction

The heating processes of residential buildings in countries of the northern hemisphere during the cold season not only require significant fuel and energy resources but also have a serious impact on the environment and climate change. A significant portion of the power used for heating comes from coal, natural gas, and other hydrocarbons, the combustion of which releases substantial amounts of carbon dioxide and other harmful emissions into the atmosphere, contributing to global warming. According to the International Sustainable Development Goals (United Nations 2015), one of the priority tasks is to reduce greenhouse gas emissions and decrease the carbon footprint of national economies (Bilan et al. 2020; Prokopenko et al. 2021; Chygryn and Shevchenko 2023). Considering this, the need to transition to energy-efficient and environmentally friendly heating systems that minimize the negative impact on the environment becomes evident (Chygryn et al. 2023; Vakulenko et al. 2023).

The focus on achieving decarbonization goals in the residential sector requires the development and implementation of heating strategies based on renewable energy sources such as geothermal systems, biomass, solar, wind energy, etc., and also energy from municipal solid waste (Matvieieva et al. 2023; Ziabina and Acheampong 2023; Ziabina et al. 2023a; Ziabina et al. 2023b). It is crucial to ensure not only a reduction in greenhouse gas emissions but also the preservation of comfort and heating quality for building residents (Grieze and Miķelsone 2021). Thus, forming cost-optimal and environmentally friendly strategies for household heating systems becomes a key task that meets the requirements of sustainable development and promotes energy efficiency and environmental conservation for future generations, extending far beyond local and national contexts (Letunovska et al. 2021; Kuzmynchuk et al. 2024).

In the case of Ukraine, optimizing heating processes in private residential buildings is particularly relevant. Members of over 50% of Ukrainian households (51.2% in 2021) live in private houses or parts of private houses. More than 45% of households (45.9% in 2021) have individual heating systems. Most private homes (65–70%) were built in the 1960s–1980s and are characterized by low energy efficiency levels (State Statistics Service of Ukraine 2021). As a result, heating costs account for at least 50–60% of homes' utilities during the heating season. Since the latter lasts about 5–6 months, significant energy losses and overspending on utilities lead to energy poverty of the population (Pysar et al. 2018; Li Rui et al. 2022) alongside excessive environmental pollution. Addressing these issues can be achieved by forming and implementing approaches to defining optimal heating strategies for households. They will help identify the most economically viable patterns of households' behavior while developing adequate national and regional policies to adjust them in the context of increasing energy efficiency, decarbonization, and the utilization of renewable power, which will ensure both the eradication of energy poverty and the implementation of green energy transition in the residential sector (Arsawan et al. 2021).

Therefore, this study aims to develop a methodological approach for selecting cost-optimal strategies for operating household heating systems based on comparing the total seasonal costs of using different types of energy carriers (or combinations thereof) for heating, as well as form sectoral policy recommendations for adjusting strategies in the decarbonization context. The approach will be tested on an example of a typical Ukrainian household. The findings will contribute to (1) improving existing management tools in the field of increasing energy efficiency and decarbonization of Ukraine's housing stock and (2) scaling this approach for application in other countries in the northern hemisphere.

This paper is structured as follows. Section 1 presents a literature review of the field. Section 2 covers the research methodology and data. Section 3 verifies the developed methodological approach by estimating the environmental impacts and cost-effectiveness of available options of fossil fuels and renewable energy used in the residential sector during a heating season. It considers the influence of different factors and provides cost-optimal heating strategies on the example of a typical Ukrainian private household. In addition, the section offers recommendations to improve government sectoral policy within regional and decarbonization contexts. The last section draws general conclusions and policy implications from the study, its limitations, and prospects for further research.

1. Literature review

Within the growing imperative of carbon neutrality and energy efficiency in the residential sector, many recent papers investigate cost-effective and environmentally sustainable heating strategies for households. The majority of publications are focused on national policies to guide greening household heating systems concerning decarbonization targets (Esmat et al. 2023; Meng et al. 2023; De Mel et al. 2023; Kurbatova et al. 2023a), electrification of household heating (Meng et al. 2023; Yu et al. 2023), energy prices (Mentel at al. 2018; Esmat at al. 2023), heating costs (Wang et al. 2023), social attitudes (Baborska-Narożny et al. 2020; Zimmermannova et al. 2023), energy efficiency (Pimonenko et al. 2017), etc. Far fewer articles explore heating strategies at the micro level regarding a smart home concept (Gao et al. 2018), inputting building and weather data (Mazhar et al. 2022), energy-saving potential of heating (Becker et al. 2018), price signals and thermal comfort (Dong et al. 2023), etc.

For example, Esmat et al. (2023) developed a comprehensive decision support system to guide optimal household heating strategies, taking into consideration uncertainties in heat demand, fuel prices, investment, and operational expenses. These strategies determine the most suitable type, capacity, and timing of investment for decentralized heat source technologies, along with their projected annual heat generation. Applied to a typical household in Lyngby-Tarbæk, Denmark, the decision support system revealed a small cost disparity between the most environmentally friendly and cost-efficient solutions, highlighting the importance of policy adjustments in promoting sustainable heating technologies.

Meng et al. (2023) examine household heating approaches within the context of cost-efficiency and air pollution in China. Their findings suggest that transitioning to electricity or gas would result in a more significant reduction in air pollution and premature mortality. However, they also note that the adoption of clean coal or biomass pellet systems, despite their relatively low initial costs, could yield a larger benefit-cost ratio, indicating greater cost efficiency. Consequently, clean coal or biomass pellet technologies might serve as transitional alternatives for less developed or remote regions that may not have the immediate resources for a complete shift to electricity or natural gas heating methods.

Yu et al. (2023) investigate residential heating strategies to minimize expenses and curb greenhouse gas emissions in both China and Europe. Their findings indicate that electrifying heating systems utilizing heat pumps could lower household heating expenses and alleviate European urban reliance on natural gas. Nonetheless, the substantial initial investment might impede the practical adoption of high-efficiency heat pump systems. Hence, providing financial incentives is crucial to guarantee feasible energy savings despite the extended payback periods.

Wang et al. (2023) analyze the impact of transitioning from coal-fired power plants to cleaner alternatives on household heating expenses in the example of northern urban China under various climate goal scenarios. Their analysis reveals that replacing combined heat and power heating with cleaner options could substantially raise residential heating costs, particularly in economically disadvantaged regions. These findings highlight the potential social risks and injustices associated with implementing coal retirement strategies.

De Mel et al. (2023) explore a new optimization framework to assist in decarbonizing residential heating in the United Kingdom. They integrate technology-driven decision support with policy decisions and evaluate three scenarios to gauge the effectiveness of current technology and policy mixes in achieving local emission reduction goals. These scenarios are compared to emissions from current gas-based heating systems and insulation measures. The findings highlight the necessity of operational assistance to manage increased energy costs, particularly impacting low-income or fuel-poor households during the transition to electrified heating systems.

Baborska-Narożny et al. (2020) investigate the challenge of high emissions from residential heating in Polish cities, emphasizing uncertainties in transitioning to eco-friendly heating. Their field research in Wroclav examines heating systems in 422 dwellings, revealing solid fuel's dominance among solid fuel-based, gas, electric, and district heating and residents' readiness to switch. Thermal comfort and mold issues, fuel transport issues, and the high operational cost of water heating emerge as concerns, suggesting the need to address barriers beyond social attitudes in promoting heating system changes. While the study advocates for reshaping narratives to encourage solid fuel substitution, it does not offer cost-effective heating strategies for homes.

Zimmermannova et al. (2023) assess household energy consumption for heating in the Czech Republic, noting a shift from coal to biomass with stable environmental impacts. They recommend applying technological upgrades in combustion boilers to accompany fuel transitions and targeting pensioner households to promote biomass usage to support eco-friendly heating systems.

Gao et al. (2018) introduce a smart home heating model designed to address temperature fluctuations in Xinjiang, China. The model manages peak loads, enhances temperature control for users, and ensures lower electricity costs. While simulation results confirm the model's efficacy, the study does not provide extensive policy adjustments for the sector, focusing on the micro level.

Mazhar et al. (2022) developed an algorithm using the ISO 13790 standard to determine buildings' heating load and indoor temperatures across various heating strategies. While this tool offers flexibility in inputting building and weather data, it does not consider the use of different energy source options. A case study evaluating three common domestic heating strategies across nine residential buildings in Germany's typical cold winter conditions demonstrates the algorithm's efficacy in terms of energy load but does not provide insights into cost-optimal and environmentally friendly choices of power sources for household heating systems.

Becker et al. (2018) explore the energy-saving potential of different household heating strategies. They take into account the occupancy level in a household, characteristics of the dwelling, local weather, and heating modes to develop the occupancy detection algorithm based on smart electricity meter data and a building heating simulation. However, the research considers only electricity as a single resource for heating ignoring other options.

Dong et al. (2023) present a novel space heating coordination strategy for large populations of households with electrified heating appliances. This strategy addresses heterogeneous technical parameters and time-dependent thermal comfort requirements in residential buildings. Modeling space heating as a cost-responsive load, allows homes to adjust heating schedules based on updated price signals to achieve cost savings while maintaining thermal comfort. Through case studies, the strategy demonstrates peak shaving and cost-saving capabilities, particularly in day-ahead heating scheduling. The developed approach enables the enhancement of sectoral policy aimed at furthering the electrification of heating systems in the residential sector; however, like Becker et al. (2018), it overlooks the possibilities of using other types of energy carriers.

Nekrasenko et al. (2015) emphasize the role of carbon taxation as an effective environmental management tool in Ukraine. Their study highlights how carbon taxes can incentivize reductions in greenhouse gas emissions, a key consideration when transitioning to environmentally friendly heating systems. Implementing such fiscal measures can make renewable heating options more attractive and economically viable. Kurbatova et al. (2021) discuss the challenges of integrating high levels of renewable energy into Ukraine's energy system, exacerbated by the COVID-19 pandemic. Their insights are crucial for understanding the systemic adjustments needed to accommodate renewable heating technologies. This study underscores the importance of strategic planning in achieving a stable and resilient energy system that supports sustainable heating solutions.

Li Rui et al. (2022) explore the intersection of energy poverty and energy efficiency in emerging economies, including Ukraine. Addressing energy poverty is vital for ensuring that cost-optimal heating solutions are accessible to all households. Enhancing energy efficiency measures can reduce overall heating costs and improve affordability, making sustainable heating options more attainable for low-income families. Prokopenko et al. (2023) examine the potential of public-private partnerships (PPPs) to mitigate greenhouse gas emissions at national and local levels. Their findings suggest that PPPs can play a significant role in financing and implementing eco-friendly heating systems. Collaborative efforts between public authorities and private enterprises can drive innovation and investment in green heating technologies.

Sotnyk et al. (2023) conducted a bibliometric study on managing energy efficiency and renewable energy in the residential sector. Their research provides a comprehensive overview of the current trends and challenges in this area, offering valuable insights into best practices for enhancing household energy efficiency. The study highlights the importance of adopting energy-efficient heating technologies and practices to reduce environmental impact. Sotnyk et al. (2021) address the broader context of energy security in emerging economies, emphasizing the need to balance local and global challenges. Their research is relevant for understanding the security implications of transitioning to renewable heating systems. Ensuring energy security involves diversifying energy sources and increasing the resilience of heating infrastructures

Kurbatova et al. (2023b) discuss improvements to feed-in tariff policies to promote renewable energy in Ukrainian households. Effective economic policies can incentivize the adoption of renewable heating systems by making them more financially attractive. This study provides policy recommendations that can support the economic viability of sustainable heating solutions. Sala et al. (2023) investigate investment and innovation activities in the renewable energy sector in southeastern Ukraine. Their findings highlight the importance of targeted investments in renewable energy technologies, including heating systems. Facilitating investment in innovative heating solutions is essential for developing cost-optimal and environmentally friendly strategies.

Bashynska et al. (2022) assess the investment and innovation image of Ukrainian regions in terms of sustainable transformations. Their study underscores the need for regional strategies that align with national sustainability goals. Regional initiatives can drive the adoption of eco-friendly heating systems, contributing to broader environmental and economic benefits.

Overall, the conducted analysis indicates that the vast majority of researchers employ a “top-down” approach to determine residential heating strategies based primarily on the goals of national decarbonization policies (for example, Esmat et al. 2023; Meng et al. 2023; Yu et al. 2023; Wang et al. 2023). By constructing various greening scenarios for the sector, researchers develop sets of organizational, economic, and financial instruments for application in the household sector to shape optimal economic and ecological heating strategies for homes. However, insufficient attention is paid to the “bottom-up” approach, which involves adjusting sectoral policies based on the study of current microeconomic heating strategies adopted by households in real economic conditions (Trachenko et al. 2021). Furthermore, predominantly micro-level studies consider only specific types or a limited range of energy carriers/technologies for household heating needs (for example, Luboń et al. 2020; Marino et al. 2021). Standard tools include calculators for evaluating the comparative cost of homes' heating, ranging from simple to more complex ones, and considering house area, desired indoor temperature, insulation, and local climatic conditions (Efficiency Nova 2024; Efficiency Maine 2024; Nordpeis 2024). However, these calculators are micro-level instruments that are not directly connected to the regional and macro-level energy policy and, therefore, do not allow managing the household greening processes.

Due to discrepancies and limitations in approaches, the understanding of households' actual expenditures on different heating systems and their reaction to potential changes in energy policy may significantly differ. Consequently, this affects the effectiveness of sectoral policy. Additionally, applying a "top-down" approach makes it challenging to account for all factors influencing a household's decision to adopt a specific heating strategy, including the availability of different energy carriers, their interchangeability, energy prices, and their fluctuations, frequency of power supply, level of heating equipment servicing, required automation of the heating process, and more.

Therefore, based on the findings from the literature review, this paper presents fresh insights into determining cost-optimal heating strategies for households and modeling regional energy policies to enhance their environmental sustainability utilizing the "bottom-up" approach. The key contributions of this study are as follows:

1. Methodological advancement: The developed research methodology stands out for its consideration of various climatic zones where households are situated, different types of energy carriers and their combinations used for heating, accounting for both operational and capital costs of home heating systems, application of multi-zone electricity tariffs, and the potential for heating automation. Furthermore, this approach facilitates the comparison of the effects of different policy and regulatory factors on households' choices of heating technologies while other studies lack these features.

2. Application to real-world data and case study: By applying our methodology to real-world data on the example of a typical Ukrainian household, we obtain valuable insights into the cost-optimal selection of heating technologies, energy carriers, and their combinations. Furthermore, we explore how these choices can be made more environmentally friendly under the influence of sectoral policies.

3. Policy implications: The research methodology offers practical utility for policymakers, enabling them to influence individual heat decarbonization and understand the repercussions of various policies on heat decarbonization efforts. Additionally, the results shed light on the effectiveness of existing policies by demonstrating how they may impede or contribute to adopting more environmentally friendly household heating strategies.

2. Methods

2.1. Development of the methodological approach

The methodological approach aiming for the selection of cost-optimal strategies for residential heating systems is developed for application in households that have private houses with autonomous heating systems across different climatic zones. Using the methods of technical and economic calculations, comparison, and economic optimization, the approach extends the previous studies (in particular, Luboń et al. 2020; Marino et al. 2021) and online calculators (for example, Efficiency Nova 2024; Efficiency Maine 2024; Nordpeis 2024), which formed its basis. The methodology considers the possibility of using six of the most common types of energy carriers (coal, natural gas, firewood, wood pellets, wood briquettes, and electricity) both separately and in combinations. In addition, electricity for thermal energy generation can be involved through two technologies: an electric boiler and a heat pump. Within the selected types of energy carriers, we assume that the residential heating system allows the use of gas boilers (natural gas as the energy carrier), solid fuel boilers (energy carriers: coal, firewood, wood pellets, and wood briquettes), and electric boilers (electricity as the energy carrier), as well as a heat pump (electricity as the energy carrier) without system's alteration or modernization. The approach includes seven stages, as depicted in Figure 1.

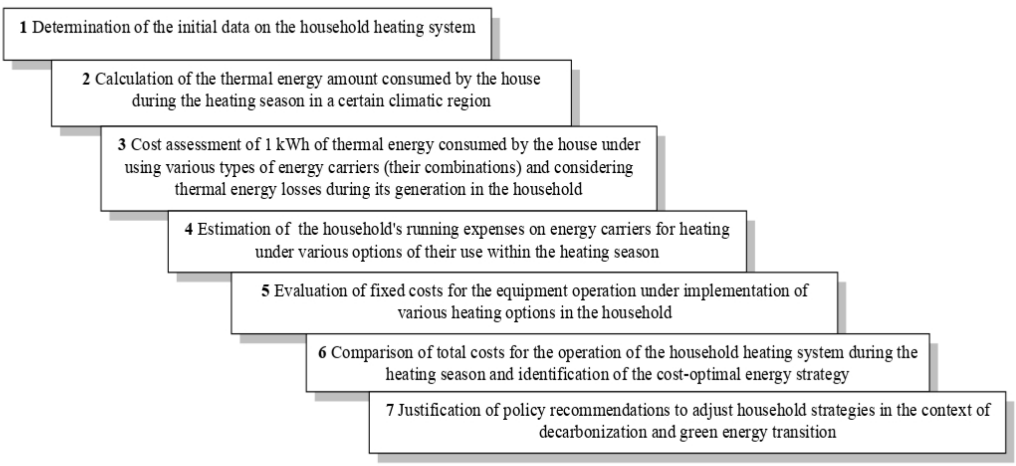

Fig. 1. Stages of the methodological approach

Rys. 1. Etapy podejścia metodologicznego

In the first stage, initial data on the heat consumption capacity of the household building are determined using analytical and design data, as well as the results of energy audits of the building.

Based on this, the types of available energy carriers for heating, their technical feasibility, pricing characteristics, etc., are identified.

In the second stage, the volumes of thermal energy consumed by the house during the heating season in the f-th climatic region (Q_{cons_f} [kWh]) are calculated using a simplified formula:

$$Q_{cons\_f} = Q_{base} \cdot k_{klimat\_f} \cdot k_{heat\_f} \cdot D_{heat\ season\_f} \cdot 24 \quad (1)$$

or according to the specified formula:

$$Q_{cons\_f} = \sum_{j=1}^{N} Q_{consjf} = \sum_{j=1}^{N} Q_{base} \cdot k_{klimat\_f} \cdot k_{heat\_jf} \cdot D_{jf} \cdot 24 \quad (2)$$

where:

- Q_{base} – thermal load of the house with pre-determined characteristics in the base climatic region [kW];
- k_{klimat_f} – climatic coefficient reflecting the change in the house thermal load relative to its base value in the *f*-th climatic region;

$$k_{klimat\_f} = \frac{t_f^{\circ}}{t_{base}^{\circ}} \quad (3)$$

where:

- t_f° – minimum ambient air temperature during the coldest five-day period within the heating season in the *f*-th climatic region [°C],
- t_{base}° – minimum ambient air temperature during the coldest five-day period within the heating season in the base climatic region [°C],
- k_{heat_f} – coefficient considering the average value of ambient air temperature during the heating season; it is determined by the ratio of the house thermal load under the average ambient air temperature in the *f*-th climatic region during the heating season ($Q_{t_{av\_f}^{\circ}}$ [kW]) to the house thermal load under the minimum ambient air temperature during the coldest five-day period within the heating season in the base climatic region ($Q_{t_{base}^{\circ}}$ [kW]):

$$k_{heat\_f} = Q_{t_{av\_f}^{\circ}} / Q_{t_{base}^{\circ}} = \left(t_{1av\_f} - t_{2av\_f}\right) / \left(t_{1base} - t_{2base}\right) \quad (4)$$

where:

- $(t_{1av\_f} - t_{2av\_f})$, $(t_{1base} - t_{2base})$ – difference in temperatures of direct (index 1) and return (index 2) heating agents in the building heating system under the average value of ambient air temperature in the *f*-th climatic region during the heating season and under the minimum ambient air temperature during the coldest five-day period in the base climatic region during the heating season [°C],

$D_{heat\ season\_f}$ – duration of the heating season in the f-th climatic region [days],

24 – length of day [hours],

Q_{cons_jf} – amount of thermal energy consumed by the house during the j-th period of the heating season [kWh], $j = \overline{1, N}$,

N – the number of periods within the heating season depending on the defined ranges of ambient air temperatures,

k_{heat_jf} – coefficient considering the average value of ambient air temperature during the j-th period of the heating season; it is determined by the ratio of the house thermal load under the average ambient air temperature in the f-th climatic region during the j-th period of the heating season ($Q_{t^\circ_{av\_jf}}$ [kW]) to the house thermal load under the minimum ambient air temperature during the coldest five-day period within the heating season in the base climatic region ($Q_{t^\circ_{base}}$ [kW]):

$$k_{heat\_jf} = Q_{(t^\circ_{(av_j f)})} / Q_{t^\circ_{base}} = \left(t_{1av\_jf} - t_{2av\_jf}\right) / \left(t_{1base} - t_{2base}\right) \tag{5}$$

where:

$(t_{1av\_jf} - t_{2av\_jf})$ – difference in temperatures of direct (index 1) and return (index 2) heating agents in the building heating system under the average value of ambient air temperature in the f-th climatic region during the j-th period of the heating season [°C],

D_{jf} – the duration of the j-th period allocated within the heating season depending on the pre-defined ranges of ambient air temperatures during the heating season in the f-th climatic region [days].

Overall, formula (1) is applied for averaged calculations of the household's thermal energy consumption over the entire heating season, while formula (2) allows for refined calculations of such consumption, taking into account fluctuations of ambient air temperature during the heating season.

In the case of using a heat pump, the volume of electricity consumed by the heat pump for heating the house during the heating season in the f-th climatic region (Q_{consHP_f} [kWh]) is determined by the formula:

$$Q_{consHP\_f} = \sum_{j=1}^{N} \frac{Q_{cons\_jf}}{COP_j} \tag{6}$$

where:

COP_j – coefficient of performance of the heat pump (Grundfos 2024) during the j-th period of the heating season.

In the third stage, the cost of 1 kWh of thermal energy consumed by the household for the i-th type of energy carrier ($Cost_{1kWh\_i}$ [EUR/kWh]) is determined, considering the thermal energy loss during its generation in the household:

$$Cost_{1kWh\_i} = Cost_{1i} / (q_{1i} \cdot \eta) \tag{7}$$

where:

- $Cost_{1i}$ – unit cost of energy carrier [m^3, t, etc.],
- q_{1i} – calorific value of a unit of energy carrier [kW/m^3, kW/t, etc.],
- η – coefficient of thermal energy loss during its generation in the household (considering the efficiency coefficient of a thermal generator).

In the case of electricity use, $Cost_{1i}/q_{1i}$ is assumed equal to the electricity tariff.

In the fourth stage, based on the calculations of the volume of thermal energy consumed by the household during the heating season in the *f*-th climatic region and the cost of 1 kWh of thermal energy consumed, the household running expenses on energy carriers for heating are calculated for various options of their application within the heating season (*Heating cost$_f$* [EUR]):

$$Heatingcost_f = \sum_{i=1}^{n} \sum_{j=1}^{N} Q_{cons\_jf} \cdot Cost_{1kWh\_i} \cdot \frac{2 \cdot a + k_t \cdot b}{3} \tag{8}$$

where:

- k_t – coefficient of the night tariff (usually applied from 11 p.m. to 7 a.m.). For electricity, we assume that $k_t = 0.5$ for a two-rate tariff and $k_t = 1$ for a single-rate tariff; for other types of energy carriers $k_t = 1$,
- *a, b* – parameters indicating the usage of the *i*-th energy carrier correspondingly during the daytime and overnight periods. If $a = 1$, then the energy carrier is used from 7.00 a.m. to 11.00 p.m. (2/3 of the day), if $a = 0$, then the energy carrier is not used during the daytime. If b=1, then the energy carrier is used from 11.00 p.m. to 7.00 a.m. (1/3 of the day); if b=0, then the energy carrier is not used overnight.

In the case of a heat pump, the household running expenses on electricity for heating the house during the heating season in the *f*-th climatic region (*Heating cost$_{HP_f}$* [EUR]) are determined by the formula:

$$Heatingcost_{HP\_f} = \sum_{i=1}^{n} \sum_{j=1}^{N} \frac{Q_{cons\_jf}}{COP_j} \cdot Cost_{1kWh\_i} \cdot \frac{2 \cdot a + k_t \cdot b}{3} \tag{9}$$

Thus, formulas (8)–(9) allow taking into account the variation in the cost of 1 kWh of thermal energy consumed by the house for different types of energy carriers across time zones of the day, the duration of using energy carriers in their combinations, as well as the utilization of energy carriers for heating the house within specific periods of the heating season.

The fifth stage involves determining the fixed operating costs of equipment when implementing different heating options in the household. These costs include annual depreciation expenses and additional fixed costs for powering the equipment. The consideration of expenditures is carried out only for those items that differ for different types of energy carriers. Depreciation expenses are calculated using the straight-line method of depreciation. The calculation of fixed operating costs of equipment when using the *i*-th type of energy carrier or their combination (*Maintenance cost* [EUR]) is carried out by the formula:

$$Maintenance\ cost = \left(\sum_{i=1}^{n} \frac{C_{purchase\_i} + C_{instal+transp\_i}}{T} \right) + \frac{C_{con\_cap}}{T} + Feed\ cost \tag{10}$$

where:

$C_{purchase\_i}$ – purchase cost of equipment for using the *i*-th type of energy carrier for heating in the household [EUR],

$C_{instal+transp\_i}$ – transportation and installation costs of equipment for using the *i*-th type of energy carrier for heating in the household [EUR],

C_{con_cap} – one-time fee for additionally connected electrical power (if necessary) to use the *i*-th type of energy carrier or their combination for heating the household [EUR];

$$C_{con\_cap} = C_{1kW\_coni} \cdot (Cap_{reqi} - Cap_{acti}) \tag{11}$$

where:

C_{1kW_coni} – cost of 1 kW of connected electrical power to use the *i*-th type of energy carrier [EUR/kW],

Cap_{reqi}, Cap_{acti} – respectively, required and actual connected electrical power of the household for using the *i*-th type of energy carrier [kW]. When involving a combination of energy carriers, the calculation of the connected power is carried out according to the type of energy carrier that requires the largest connected electrical power,

T – estimated service life of the equipment [years],

Feed cost – additional fixed costs for powering the equipment [EUR];

$$Feed\ cost = \sum_{i=1}^{n} \sum_{j=1}^{N} Q_{day\_i} \cdot D_{use\_ij} \cdot C_{1kWhi} \cdot \frac{2 \cdot a + k_t \cdot b}{3} \tag{12}$$

where:

Q_{day_i} – daily electricity consumption for equipment needs using the *i*-th type of energy carrier [kWh];

D_{use_ij} – number of days of equipment operation using the *i*-th energy carrier within the *j*-th period of the heating season [days].

The sixth stage involves comparing the total costs ($Total\ cost_{lf}$ [EUR]), which is the sum of the household running expenses on energy carriers for heating ($Heating\ cost_{fl}$ [EUR]) and the fixed operating costs of equipment ($Maintenance\ cost_{l}$ [EUR]), when using the *i*-th type of energy carrier or their combination within the heating season in the *f*-th climatic region. Based on these indicators, the cost-optimal heating strategy of the household is determined using the following objective function:

$$Total\ cost_{lf} = Heating\ cost_{fl} + Maintenance\ cost_{l} \rightarrow min \tag{13}$$

In the seventh stage, based on the analysis of the formed strategies and the selection of the optimal one among them, recommendations are justified for adjusting sectoral policies, taking into account the priorities of state and regional power development, decarbonization goals, and ensuring the green energy transition of households.

Overall, this approach allows for identifying which types of energy carriers are most economically viable for application in households of a particular climatic region under current technical and economic conditions and, based on this, adjusting pricing, taxation, investment, and other policies in the power and residential sectors to transform household strategies into more environmentally friendly ones.

2.2. Data for approach approbation

The validation of the developed methodological approach for forming cost-optimal strategies for using residential heating systems was conducted on an example of a typical Ukrainian household, whose members reside in a private house with autonomous heating. The house, with an area of 120 m^2, is located in the northeast of Ukraine, belonging to the climatic region with the lowest ambient air temperatures during the coldest five-day period within the country. Due to the lowest ambient air temperatures in winter, this climatic region is considered the base in the study, thus $k_{klimat\_f} = 1$. Based on empirical experience from energy audits of residential buildings in this region, the average heat consumption of the house is assumed to be 70 W/m^2, corresponding to a heat load of 8.4 kW.

Table 1 demonstrates the initial data for calculating the thermal energy amount consumed by the house during the heating season in the selected climatic region. The calculation of the thermal energy consumption is performed using the specified formula (2), which takes into account specific periods of ambient air temperature ranges during the heating season. Information regarding these periods and their initial indicators is provided in Table 2.

Table 3 contains the initial data for calculating the cost of 1 kWh of thermal energy consumed by the house for the studied types of energy carriers. The calculations are provided in euros based on the official exchange rate of the National Bank of Ukraine as of May 1, 2024: 1 EUR = = 42,3641 UAH (The National Bank of Ukraine 2024).

Table 4 presents the initial data for calculating the fixed operating costs of equipment when utilizing a specific type of energy carrier. Transportation and installation costs are assumed at 20% of the equipment purchase price, with an equipment lifecycle of 10 years. Electricity supply connection fees are only considered for the electric boiler and heat pump. For the rest of the

Table 1. Initial data for calculating the thermal energy amount consumed by the household during the heating season in the studied climatic region (northeastern Ukraine, Sumy City)

Tabela 1. Dane wyjściowe do obliczenia ilości energii cieplnej zużywanej przez gospodarstwo domowe w sezonie grzewczym w badanym regionie klimatycznym (północno-wschodnia Ukraina, miasto Sumy)

Indicator	Indicator designation	Value of the indicator	Source
Minimum ambient air temperature during the coldest five-day period in the base climatic region (northeastern Ukraine, Sumy City)	$t^{\circ}_{f}, t^{\circ}_{base}$	–25°C	(DSTU-N B V.1.1-27:2010)
Duration of the heating season	$D_{heat\ season\_f}$	187 days	
Temperature of the direct heating agent in the building heating system under the minimum ambient air temperature during the coldest five-day period in the base climatic region	t_{1base}	110°C	(Sumyteploenergo 2021)
Temperature of the return heating agent in the building heating system under the minimum ambient air temperature during the coldest five-day period in the base climatic region	t_{2base}	70°C	
Thermal load of the house of a certain area in the base climatic region (northeastern Ukraine, Sumy City)	Q_{base}	8.4 kW	authors' calculations

Table 2. Initial indicators for periods identified within the heating season in the studied climatic region (northeastern Ukraine, Sumy City) depending on defined ranges of ambient air temperature

Tabela 2. Wskaźniki początkowe dla okresów wyznaczonych w sezonie grzewczym w badanym regionie klimatycznym (północno-wschodnia Ukraina, miasto Sumy) w zależności od zdefiniowanych zakresów temperatury powietrza otoczenia

Indicator	Period 1	Period 2	Period 3	Source
Ambient air temperature range [°C]	above –3°C	from –3 to –10°C	below –10°C	averaged values based on seven-year meteorological observations in the region
Average value of ambient air temperature [°C]	+1.9	–7	–13	
Duration of the period [days] (D_{jf})	125	44	18	
Temperature of the direct heating agent in the building heating system under the average value of ambient air temperature [°C] (t_{1av_jf})	59.2	77	88	(Sumyteploenergo 2021)
Temperature of the return heating agent in the building heating system under the average value of ambient air temperature [°C] (t_{2av_jf})	44.1	53	59	
Coefficient of performance of a heat pump (air-water) (COP_j)	3.5	2.5	1.0	(Heat pumps)

equipment, it is assumed that a pre-installed connected electrical power of 5 kW is sufficient for the equipment operation. Additional fixed costs for powering the equipment are considered only for gas and pellet boilers, as they have an automated fuel supply system. Supply of firewood and

Table 3. Initial data for determining the cost of 1 kWh of thermal energy consumed by the house for the studied types of energy carriers

Tabela 3. Dane wstępne do określenia kosztu 1 kWh energii cieplnej zużywanej przez dom dla badanych rodzajów nośników energii

Type of energy carrier	Unit cost of energy carrier (Drova-Kiev 2023; Babenko 2024; Baza-drov 2024; Minfin 2024a; Minfin 2024b)	Calorific value of a unit of energy carrier (Comparative characteristics 2016; The calorific value 2017)	Efficiency coefficient of a thermal generator (Energosberezhenie.com 2024)
Hard coal	397 EUR/t	7.5 kWh/kg	0.82
Firewood	38 EUR/m^3	3.9 kWh/kg	0.82
Wood briquettes	217 EUR/t	4.4 kWh/kg	0.85
Wood pellets	221 EUR/t	4.7 kWh/kg	0.85
Natural gas	0.24 EUR/m^3	9.3 kWh/m^3	0.93
Electricity	0.06 EUR/kWh	1 kWh/kWh	0.96

briquettes to the furnaces of the boilers is provided in manual mode. The costs of powering the electric boiler and heat pump are included in the heating cost and are not separately allocated. Daily electricity consumption for equipment needs is determined based on the average indicators of a specific type of equipment, relying on empirical experience from energy audits.

3. Results and discussion

To validate the methodological approach and provide the policy recommendations on its base, the calculations according to the developed stages were conducted taking into account the initial data presented in section 2.2.

Based on the data from Tables 1 and 2, the thermal energy amount consumed by the house during the heating season was processed using the formulas (2)–(6). The calculated value is 17,454 kWh, of which the amount consumed by the heat pump using electricity (in the case of its application) is 7,474 kWh.

Next, the costs of 1 kWh of thermal energy consumed by the house while using different heating technologies and carriers were determined by formula (7). The results are presented in Table 5. In addition, Table 5 shows the summary calculations of the components of the total expenses for operating the household heating system (according to the formulas (8)–(13)) when using a single energy carrier (without their combinations) throughout the entire heating season and at a single-rate tariff for electricity.

TABLE 4. Initial data for calculating the fixed operating costs of equipment for the studied types of energy carriers

TABELA 4. Dane wyjściowe do obliczenia stałych kosztów eksploatacji urządzeń dla badanych rodzajów nośników energii

<table>
<tr><th rowspan="3">Indicator</th><th colspan="7">Type of equipment</th></tr>
<tr><th rowspan="2">gas boiler (Teploradist 2024a)</th><th rowspan="2">electric boiler (Teploradist 2024b)</th><th colspan="4">solid fuel boiler</th><th rowspan="2">heat pump (Klimat-SpetsService 2024)</th></tr>
<tr><th>hard coal (Teploradist 2024c)</th><th>firewood (Teploradist 2024c)</th><th>wood pellets (OVK Complect 2024)</th><th>wood briquettes (Teplomontag 2024)</th></tr>
<tr><td>Power [kW]</td><td>12</td><td>12</td><td colspan="2">24</td><td>12</td><td>12</td><td>12</td></tr>
<tr><td>Purchase cost [EUR]</td><td>897</td><td>718</td><td colspan="2">888</td><td>2,772</td><td>578</td><td>6,036</td></tr>
<tr><td>Transportation and installation costs [EUR]</td><td>179</td><td>144</td><td colspan="2">178</td><td>555</td><td>116</td><td>1,207</td></tr>
<tr><td>Estimated service life [years]</td><td colspan="7">10</td></tr>
<tr><td>Cost of 1 kW of connected electrical power (Sumyoblenergo) [EUR]</td><td colspan="7">42 (NERCU 2024)</td></tr>
<tr><td>Pre-installed connected electrical power of the household [kW]</td><td colspan="7">5 (Ukrainian energy 2022)</td></tr>
<tr><td>One-time fee for connected electrical power [EUR]</td><td>–</td><td>295</td><td colspan="2">–</td><td>–</td><td>–</td><td>295</td></tr>
<tr><td>Annual depreciation expenses and the fee for connected electrical power [EUR]</td><td>108</td><td>116</td><td colspan="2">107</td><td>333</td><td>69</td><td>754</td></tr>
<tr><td>Daily electricity consumption for equipment needs, [kWh]</td><td>1.3</td><td>–</td><td colspan="2">–</td><td>1.92</td><td>–</td><td>–</td></tr>
<tr><td>Additional fixed costs for powering the equipment* [EUR]</td><td>16</td><td>–</td><td colspan="2">–</td><td>22</td><td>–</td><td>–</td></tr>
</table>

* Provided that the energy carrier is used during the entire heating season (187 days) and the single-rate electricity tariff is applied.

Table 5. Components of total expenses for operating the household heating system for the studied types of energy carriers

Tabela 5. Składniki całkowitych wydatków na eksploatację domowego systemu grzewczego la badanych rodzajów nośników energii

Indicator	Type of equipment						
	gas boiler	electric boiler	solid fuel boiler				heat pump
Energy carrier	natural gas	electricity	hard coal	firewood	wood pellets	wood briquettes	electricity
Energy carrier code	NG1	EL1	C	W	P1	B	HP1
The cost of 1 kWh of thermal energy consumed by the house, $Cost_{1kWh\_i}$ [EUR/kWh]	0.03	0.07	0.06	0.02	0.06	0.06	0.03*
Household running expenses on energy carriers for heating, $Heating\ cost_{fl}$ [EUR]	474	1,133	1,125	299	969	1,013	466
Fixed operating costs of equipment, $Maintenance\ cost_{l}$ [EUR]	123	116	107	107	355	69	754
Household total costs for the heating system operation during the heating season, $Total\ cost_{lf}$ [EUR]	598	1,249	1,232	405	1,324	1,083	1,220

* The average cost of thermal energy generated by the heat pump during the heating season assuming that the cost of electricity consumed by the heat pump from the grid is 0.06 EUR/kWh.

As seen from Table 5, the most optimal in terms of minimizing the total household costs is the use of firewood for heating throughout the entire heating season, considering the affordability of this resource. The second most economical option (with costs 47% higher) is natural gas, again due to the preferential prices for this energy carrier set for the population in Ukraine. The most costly heating option, which exceeds the costs of using firewood by 3.3 times, is the use of wood pellets due to their high purchase price and the cost of equipment (wood pellet boilers). Compared to wood pellets, the expenses are lower for using electricity (–6% for electric boilers and –8% for heat pumps) and coal (–7%). For these energy carriers, the main factors contributing to the increased level of expenditures are the high prices of coal and electricity (for electric boilers) as well as the cost of equipment (for a heat pump).

Ukrainian households can take advantage of a two-rate electricity tariff. It involves the regular daytime tariff and the night tariff, which is 50% lower and applies from 11.00 p.m. to 7.00 a.m. Thus, household expenses can be essentially reduced due to the night tariff when consuming significant amounts of electricity for heating purposes. Therefore, we will further assess the impact of the two-rate electricity tariff on declining the total household costs for cases where the use of a certain type of energy carrier requires the use of electricity.

Alongside the cost characteristics, an important aspect of choosing an energy carrier is the possibility of automating the heating process in the household, particularly during nighttime and daytime working hours. The use of gas and electric boilers, as well as heat pumps fully automates the heating system. In the case of wood pellets, the heating process is partially automated due to the automatic fuel feed from the pellet loading tank, which needs to be periodically replenished. Thus, these types of equipment can be used at night and during the working day in the absence of household members in the house. Considering these conveniences, even with increased total costs, the household may prefer options for automated or partially automated heating throughout the entire day or its part (day or night), combining several energy carriers.

In the conditions of northeastern Ukraine, with the lowest ambient air temperature during the coldest five-day period at –25°C, the efficiency of using a heat pump in severe frosts significantly decreases and may be equal to the efficiency of using an electric boiler. To save on heating costs during period 3 (Table 2) with ambient air temperatures below –10°C, it is advisable to use other energy carriers, such as gas or firewood. On the other hand, using combinations of energy carriers that require different equipment will increase the fixed equipment costs. Therefore, such options require detailed economic justification, including considering the prospects for automating the heating process.

Table 6 presents additional heating options for the household using different energy carriers and their combinations, taking into account the two-rate electricity tariff, possibilities for automating the heating process, and ambient air temperatures. Additionally, when selecting combinations of energy carriers, estimates of the household total costs for the heating system operation during the heating season, as provided in Table 5, were considered. Thus, combination options, where partial replacement of the energy carrier resulted in higher total costs without significant other benefits, were excluded. For example, coal was not considered in any combination, nor was the combination of natural gas and wood pellets or natural gas and electricity (electric boiler) under a single-rate tariff for electricity.

For the options given in Table 6, the household total costs for the heating system operation during the heating season were processed. The calculation results are presented in Figure 2.

The analysis of the data in Figure 2 indicates that among single energy carriers and their combinations, the lowest household heating costs are achieved when using firewood due to its low market price. The second place (+42% compared to the minimum costs) belongs to the combination of “firewood (daytime) + natural gas (night)” with a barely noticeable difference in costs when applying single-rate and two-rate tariffs for electricity used to power the gas boiler. The third position is held by natural gas (both under single-rate and two-rate electricity tariffs) and the combination of “firewood (daytime) + electricity (night) (electric boiler)” under a two-rate electricity tariff, adding 47–50% to the minimum costs. The most expensive heating options are the use of wood pellets (3.3 times higher than firewood due to high wood pellet prices and the cost of wood pellet boilers) and electricity under a single-rate tariff (2.8–3.1 times higher than firewood) when using both electric boilers (due to high electricity costs) and heat pumps (due to

TABLE 6. Additional heating options for the household using different energy carriers and their combinations

TABELA 6. Dodatkowe możliwości ogrzewania gospodarstwa domowego przy wykorzystaniu różnych nośników energii i ich kombinacji

Type of energy carrier (their combination)	Code of the option	Time period of using energy carrier	Purpose of using energy carriers (their combination)
1	2	3	4
Electricity (electric boiler) (under the two-rate electricity tariff)	El2	7.00–23.00 (electricity, daytime tariff)	Reduction of total costs when applying the night tariff for electricity
		23.00–7.00 (electricity, night tariff)	
Electricity (heat pump) (under the two-rate electricity tariff)	HP2	7.00–23.00 (electricity, daytime tariff)	Reduction of total costs when applying the night tariff for electricity
		23.00–7.00 (electricity, night tariff)	
Wood pellets (under the two -rate electricity tariff)	P2	7.00–23.00 (electricity for powering the equipment, daytime tariff)	Reduction of additional fixed costs for powering the equipment when applying the night tariff for electricity
		23.00–7.00 (electricity for powering the equipment, night tariff)	
Natural gas (under the two-ra-te electricity tariff)	NG2	7.00–23.00 (electricity for powering the equipment, daytime tariff)	Reduction of additional fixed costs for powering the equipment when applying the night tariff for electricity
		23.00–7.00 (electricity for powering the equipment, night tariff)	
Firewood + natural gas (under the single-rate electricity tariff)	(W+NG)1	7.00–23.00 (firewood)	Automation of the heating process at night
		23.00–7.00 (natural gas)	
		24 hours a day (electricity for powering the equipment, single-rate (daytime) tariff)	
Firewood + natural gas (under the two-rate electricity tariff)	(W+NG)2	7.00–23.00 (firewood)	✦ Automation of the heating process at night ✦ Reduction of additional fixed costs for powering the equipment when applying the night tariff for electricity
		23.00–7.00 (natural gas)	
		7.00–23.00 (electricity for powering the equipment, daytime tariff)	
		23.00–7.00 (electricity for powering the equipment, night tariff)	
Firewood + wood pellets (under the single-rate electricity tariff)	(W+P)1	7.00–23.00 (firewood)	Automation of the heating process at night
		23.00–7.00 (wood pellets)	
		24 hours a day (electricity for powering the equipment, single-rate (daytime) tariff)	

1	2	3	4
Firewood + wood pellets (under the two-rate electricity tariff)	(W+P)2	7.00–23.00 (firewood) 23.00–7.00 (wood pellets) 7.00–23.00 (electricity for powering the equipment, daytime tariff) 23.00–7.00 (electricity for powering the equipment, night tariff)	✦ Automation of the heating process at night ✦ Reduction of additional fixed costs for powering the equipment when applying the night tariff for electricity
Firewood + electricity (electric boiler) (under the single-rate electricity tariff)	(W+El)1	7.00–23.00 (firewood) 23.00–7.00 (electricity, single-rate (daytime) tariff)	Automation of the heating process at night
Firewood + electricity (electric boiler) (under the two-rate electricity tariff)	(W+El)2	7.00–23.00 (firewood) 23.00–7.00 (electricity, night tariff)	✦ Automation of the heating process at night ✦ Reduction of electricity costs when applying the night tariff for electricity
Natural gas + electricity (electric boiler) (under the two-rate electricity tariff)	(NG+El)2	7.00–23.00 (natural gas) 23.00–7.00 (electricity, night tariff) 7.00–23.00 (electricity for powering the equipment, daytime tariff)	✦ Reduction of electricity costs when applying the night tariff for electricity
Wood pellets + natural gas (under the two-rate electricity tariff)	(P+NG)2	7.00–23.00 (wood pellets) 23.00–7.00 (natural gas) 7.00–23.00 (electricity for powering the equipment, daytime tariff) 23.00–7.00 (electricity for powering the equipment, night tariff)	✦ Automation of the heating process at night ✦ Reduction of additional fixed costs for powering the equipment when applying the night tariff for electricity
Electricity (heat pump) + natural gas (under the single-rate electricity tariff)	(HP+NG)1	24 hours a day, periods 1 and 2 (electricity, single-rate (daytime) tariff) 24 hours a day, period 3 (natural gas) 24 hours a day, period 3 (electricity for powering the equipment, single-rate (daytime) tariff)	Reduction of total heating costs when replacing electricity with natural gas on the coldest days (period 3) due to a decrease in the efficiency of the heat pump

1	2	3	4
Electricity (heat pump) + natural gas (under the two-rate electricity tariff)	(HP+NG)2	7.00–23.00, periods 1 and 2 (electricity, daytime tariff)	✦ Reduction of total heating costs when replacing electricity with natural gas on the coldest days (period 3) due to a decrease in the efficiency of the heat pump ✦ Reduction of electricity costs when applying the night tariff for electricity
		23.00–7.00, periods 1 and 2 (electricity, night tariff)	
		24 hours a day, period 3 (natural gas)	
		7.00–23.00, period 3 (electricity for powering the equipment, daytime tariff)	
		23.00–7.00, period 3 (electricity for powering the equipment, night tariff)	
Electricity (heat pump) + natural gas + firewood (under the single-rate electricity tariff)	(HP+NG+W)1	24 hours a day, periods 1 and 2 (electricity, single-rate (daytime) tariff)	✦ Reduction of total heating costs when replacing electricity with natural gas and firewood on the coldest days (period 3) due to a decrease in the efficiency of the heat pump ✦ Automation of the heating process at night in period 3 ✦ Reduction of total heating costs in period 3 when replacing natural gas with firewood for daytime heating
		7.00–23.00, period 3 (firewood)	
		23.00–7.00, period 3 (natural gas)	
		23.00–7.00, period 3 (electricity for powering the equipment, single-rate (daytime) tariff)	
Electricity (heat pump) + natural gas + firewood (under the two-rate electricity tariff)	(HP+NG+W)2	7.00–23.00, periods 1 and 2 (electricity, daytime tariff)	✦ Reduction of total heating costs when replacing electricity with natural gas and firewood on the coldest days (period 3) due to a decrease in the efficiency of the heat pump ✦ Automation of the heating process at night in period 3 ✦ Reduction of total heating costs in period 3 when replacing natural gas with firewood for daytime heating ✦ Reduction of electricity costs when applying the night tariff for electricity
		23.00–7.00, periods 1 and 2 (electricity, night tariff)	
		7.00–23.00, period 3 (firewood)	
		23.00–7.00, period 3 (natural gas)	
		23.00–7.00, period 3 (electricity for powering the equipment, night tariff)	

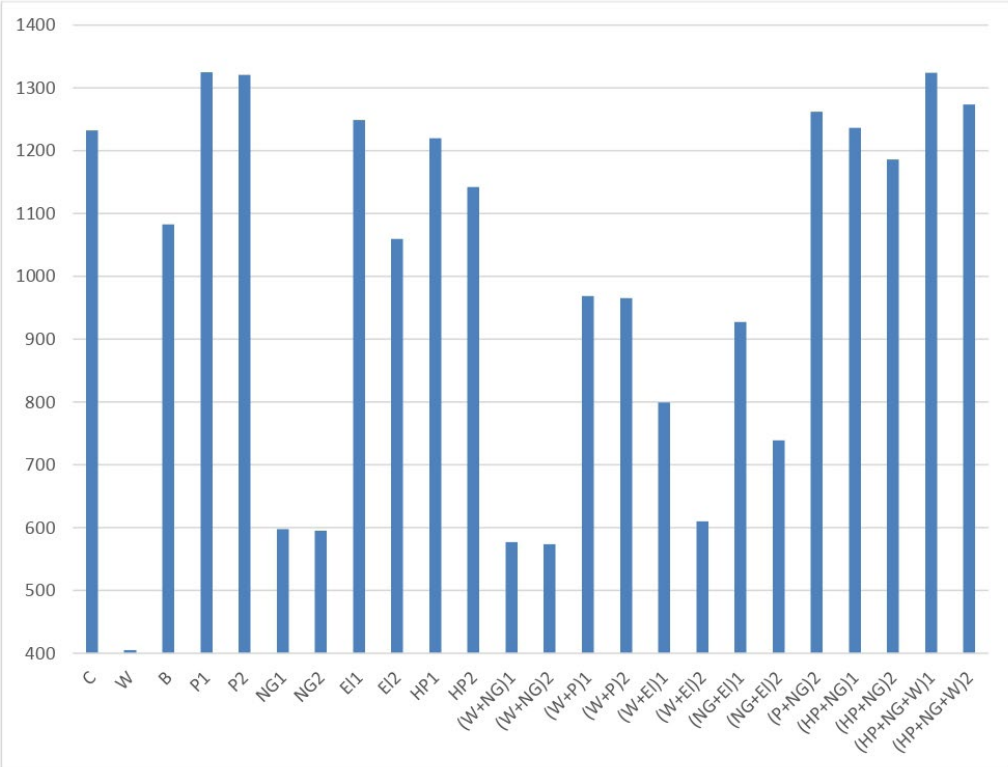

Fig. 2. Household total costs for the heating system operation under different options of energy carriers and their combinations used during the heating season [EUR] (explanations for the heating options codes are provided in Tables 5 and 6)

Rys. 2. Całkowite koszty eksploatacji systemu grzewczego dla gospodarstw domowych przy różnych wariantach nośników energii i ich kombinacjach wykorzystywanych w sezonie grzewczym [EUR] (objaśnienia kodów wariantów ogrzewania podano w tabelach 5 i 6)

the high cost of equipment). It is worth noting that options involving electricity for a heat pump, both single and in combination with natural gas and firewood (for heating in cold weather), demonstrate values of total costs close to the maximum.

Thus, under current market conditions, the cost-optimal strategies for households in the northeastern region of Ukraine involve favoring firewood heating, with natural gas or the combination of "firewood (daytime) + natural gas (night)" being preferred for automation of the heating process when needed. In case of constraints on gas supply, an alternative inexpensive option is the combination of "firewood (daytime) + electricity (night)" with the use of an electric boiler. To sum up, the current state policy concerning the energy supply of the private residential sector stimulates the maximum use of firewood and natural gas by the population for heating purposes. Since firewood is a renewable resource, its use by households does not result in additional CO_2 emissions. However, firewood availability can be limited for various reasons, such as the scarcity of firewood in many regions of Ukraine, difficulties in harvesting the firewood due to military actions and forest mining, concerns over the sustainability of biomass burning, etc. To overcome many of the obstacles mentioned, dedicated energy crops could be grown and used as a substitute for firewood (Trypolska 2023). Moreover, the inability to automate a heating process at affordable investment costs while involving firewood often leads to the household preference for natural gas, whose domestic reserves in Ukraine are limited. This cost imbalance slows down the processes of decarbonizing the residential sector. In this context, according to the results of Zimmermannova et al. (2023), it is advisable to consider initiatives to encourage households of pensioners to prefer firewood heating, as they may have lower needs in the heating process automation.

The high cost of environmentally friendly heat pumps is the main cause for the reluctance of Ukrainian households to implement them. Among other reasons is the low efficiency of heat pumps when ambient air temperatures drop below -10°C, which requires the use of other energy carriers and/or significant restructuring of the heating system with additional investment. A positive aspect is the high costs associated with involving coal, which discourages its use and reduces environmental pollution. At the same time, the usage of renewable energy resources such as wood pellets and briquettes is restrained due to their high market price and the cost of pellet boilers. Until 2022, the Ukrainian government implemented a program of partial state compensation for private households installing non-electric and non-gas boilers and heat pumps, thereby encouraging the transition to the use of renewables for heating purposes. However, under martial law and essential levels of housing and energy infrastructure destruction, the implementation of this program has been suspended.

The continuation of the current state policy will keep a high dependence of the residential sector on natural gas for heating needs and expand the use of firewood due to the decrease in Ukrainians' incomes. However, in the conditions of the ongoing war, centralized gas networks are frequent targets for shelling, which increases the security risks of gas supply for households (Koval et al. 2019). Therefore, an accelerated transition to renewable energy sources that provide full autonomy of household heating systems and contribute to the decarbonization of the residential sector is advisable. This, in turn, will require significant changes in economic policy in the sector (Shmygol et al. 2021).

Specifically, for the northeastern region of Ukraine, the use of wood pellets and briquettes for heating private houses instead of natural gas is promising, as it allows for automation of the heating process and there is a necessary raw material base for the production of solid biofuel. This practice can be extended to western regions of Ukraine, where there is also an adequate raw material base. However, due to relatively high prices for wood pellets on the European market, this product is primarily exported, and domestic producers are not interested in selling wood pellets and briquettes at lower prices to Ukrainian households with limited financial capabilities. Additionally, to ensure the comfortable use of pellets and briquettes in households, it is advisable to develop a market infrastructure for servicing relevant boiler equipment and logistics for biofuel supply. Specialized enterprises should take on the functions of technical support for boiler equipment, it's servicing, and supplying consumers with biofuel while forming warehouse stocks on the supplier's territory. Considering the high cost of pellet boilers, which are manufactured in Ukraine using imported components, it is advisable to provide state economic support to local boiler equipment manufacturers, as well as to introduce partial reimbursement of the cost of pellet boilers for households using them, similar to the pre-war "warm credit" program (SAEE 2024), combined with compensations at both state and local levels. To eliminate price barriers, an important policy component is the application of a subsidy system for low-income households-consumers of wood pellets and briquettes for heating purposes. In particular, the necessity of financial support for low-income households is emphasized by De Mel et al. (2023).

In the central and southern regions of Ukraine with milder climates, it is advisable to promote heating technologies using heat pumps, which will be facilitated by establishing comprehensive service maintenance of such equipment based on local enterprises. Considering the current high cost of heat pump systems, it is relevant to renew and expand state investment support for such projects in the form of partial compensation for the cost of heat pumps. Since electric power is required for the operation of heat pumps, it is necessary to develop a system of distributed electricity generation with the creation of regional grids of small power plants, including those utilizing green energy sources (Kurbatova et al. 2023b; Kurbatova et al. 2024).

In the eastern regions of Ukraine, due to the lack of sufficient raw material base for the production of wood pellets and briquettes and low ambient air temperatures in winter, it will be most feasible to use heat pumps in combination with electric boilers for operation during the coldest periods. To meet the growing demand for electricity for heating purposes, it is necessary to simultaneously develop industrial wind power generation and home systems for thermal energy storage. Therefore, partial state compensations for the purchase and installation of thermal energy storage systems and heat pumps in households should be provided. This conclusion is consistent with Yu et al. (2023).

An important measure to promote heat pump systems in Ukraine is to keep a two-rate electricity tariff for households, significantly reducing their current heating costs and encouraging the transition to green energy technologies. On the other hand, it is necessary to review the gas prices for the population, which are currently subsidized by the state. Increasing them to economically justified levels will exclude gas from the list of the cheapest energy carriers for heating private houses. However, considering the energy poverty of a large share of Ukrainian households, exacerbated by the ongoing war, the growth in gas prices should be compensated by a system of state economic support for the use of green energy technologies for heating. Given that some types of energy-efficient heating equipment or their components (such as heat pumps) are not manufactured or have no domestic analogs in Ukraine, it is advisable to introduce customs privileges to stimulate the import of such products.

Conclusions

The developed methodological approach for determining cost-optimal strategies for using home heating systems and its testing on a typical household in the northeastern region of Ukraine has allowed justifying the selection of the most economical energy carriers for application in the residential sector for heating purposes and evaluating the environmental friendliness of such strategies. Understanding the strategic economic behavior of households enables the assessment of the effectiveness of existing state policies and their adjustment to manage the further development of power supply in the residential sector in the context of achieving decarbonization goals and increasing household energy efficiency, thereby stimulating the green energy transition. The proposed methodological approach is universal and can be applied in any country to identify the current preferences of homes in using certain types of energy carriers for heating purposes. Moreover, it can be successfully applied to forecast changes in household heating strategies in case of changes in state economic policies (such as increasing prices for energy resources, introducing state compensations for certain types of heating equipment, etc.).

Alongside its undeniable advantages, the developed approach has its limitations. Firstly, it assumes that households can use various types of energy carriers without reconstructing the heating system of the house, which in practice may result in significant costs to meet this requirement. Secondly, it is presumed that in the case of using solid biofuels, households have sufficient areas for storing these energy resources while maintaining the necessary microclimate conditions in warehouse premises. The absence of such areas may result in additional costs for delivering energy resources. Thirdly, the costs of servicing different types of heating equipment were assumed to be equal, but in practice, they may vary significantly. Fourthly, the research considers an "air-to-water" heat pump, the efficiency of which significantly decreases in frosty weather. Instead, the inclusion of a "water-to-water" heat pump in the study increases its energy efficiency and stability of operation during the coldest periods of the heating season and in many cases, may eliminate the need for using an electric boiler. However, the "water-to-water" heat pump requires either a constant heat source (such as flowing river water) or a larger land area for arranging a heat collector. Fifthly, the number of energy carriers for heating in the calculations was limited to six types, although this scope can be expanded depending on the practices used in a specific country.

Taking into account the limitations of the study, the prospects for further research include refining and expanding the composition of household expenses for the operation of the heating system, involving the time factor in assessing current and capital costs, expanding the range of energy carriers and heating technologies, considering the necessary degree of automation of the heating system operation, prospects for using thermal accumulators in households, etc.

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Iryna Sotnyk, Mykola Sotnyk, Tetiana Kurbatova, Olha Prokopenko, Oleksandr Telizhenko

Kształtowanie optymalnych kosztowo i przyjaznych środowisku strategii systemów grzewczych gospodarstw domowych: przypadek Ukrainy

Streszczenie

Procesy ogrzewania prywatnych budynków mieszkalnych wymagają znacznych zasobów paliw i energii oraz przyczyniają się do globalnego ocieplenia, co wymaga przejścia na energooszczędne i przyjazne dla środowiska ogrzewanie. Niniejsza analiza ma na celu opracowanie metodologicznego podejścia do wyboru optymalnych kosztowo strategii dla domowych systemów grzewczych poprzez ocenę wpływu na środowisko i opłacalności dostępnych opcji paliw kopalnych i energii odnawialnej wykorzystywanych w sektorze mieszkaniowym w sezonie grzewczym, przy jednoczesnym zapewnieniu ekologiczności i efektywności energetycznej domów. Badanie rozszerza istniejącą metodologię, biorąc pod uwagę strefy klimatyczne i ich wahania temperatury powietrza w sezonie grzewczym, efektywność energetyczną gospodarstw domowych, różne nośniki energii wykorzystywane do ogrzewania, koszty bieżące i kapitałowe ogrzewania gospodarstw domowych, wielostrefowe taryfy energii elektrycznej oraz perspektywy automatyzacji ogrzewania, pomagając decydentom w kształtowaniu wyborów dotyczących ogrzewania mieszkań. Podejście to, przetestowane na typowym ukraińskim gospodarstwie domowym, przyczynia się do poprawy polityki sektorowej poprzez tworzenie energooszczędnych i dekarbonizacyjnych strategii dla zasobów mieszkaniowych, z potencjalnym zastosowaniem w innych krajach. Wyniki pokazują, że najbardziej optymalnymi pod względem kosztów opcjami ogrzewania w Ukrainie są drewno opałowe i wykorzystanie gazu ziemnego w ramach obecnej polityki energetycznej. W oparciu o wyniki badania zaproponowano zalecenia w kontekście regionalnym Ukrainy i celów neutralności węglowej. Zapewniają one przejście na odnawialne źródła energii (pelety drzewne i pompy ciepła) poprzez rozwój infrastruktury rynkowej do serwisowania urządzeń kotłowych i logistyki dostaw biopaliw, wsparcie ekonomiczne państwa dla lokalnych producentów urządzeń kotłowych oraz częściowy zwrot inwestycji w kotły na pelety i pompy ciepła dla gospodarstw domowych, dostosowanie taryf energii elektrycznej itp.

Słowa kluczowe: gospodarstwo domowe, ogrzewanie, strategia optymalna kosztowo, dekarbonizacja, efektywność energetyczna, energia odnawialna, Ukraina