Energy 263 (2023) 125774

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Algorithm for the comprehensive thermal retrofit of housing stock aided by renewable energy supply: A sustainable case for Krakow

Krzysztof Barnaś [a,*], Tomasz Jeleński [a], Marzena Nowak-Ocłoń [b], Kinga Racoń-Leja [a], Elżbieta Radziszewska-Zielina [c], Bartłomiej Szewczyk [c], Grzegorz Śladowski [c], Cezary Toś [d], Petar Sabev Varbanov [e]

[a] *Cracow University of Technology, Faculty of Architecture, Department of Urbanism and City Structure Architecture, ul. Podchorążych 1, 30-084, Krakow, Poland*
[b] *Cracow University of Technology, Faculty of Environmental Engineering and Energy, Department of Energy, Al. Jana Pawła II 37, 31-864, Krakow, Poland*
[c] *Cracow University of Technology, Faculty of Civil Engineering, Division of Management in Civil Engineering, ul. Warszawska 24, 31-155, Krakow, Poland*
[d] *Cracow University of Technology, Faculty of Environmental Engineering and Energy, Department of Geoengineering and Water Management, ul. Warszawska 24, 31-155, Krakow, Poland*
[e] *Sustainable Process Integration Laboratory – SPIL, NETME Centre, Faculty of Mechanical Engineering, Brno University of Technology – VUT Brno, Technická 2896/2, 616 69 Brno, Czech Republic*

A R T I C L E I N F O

Keywords:
Thermal retrofitting
Housing stock
Renewable energy sources

A B S T R A C T

This paper proposes an approach to the comprehensive adaptation of prefabricated panel-block buildings, many of which were built before 1989, to climate change and the requirements of people with special needs while alleviating Modernist planning deficiencies. The proposal targets panel-block technologies of Eastern Bloc countries, and its application is demonstrated based on the Polish W-70/Wk-70 system but can be applied to any other prefabricated housing. The large-scale use of such systems in Central and Eastern Europe after the Second World War, coupled with their service life being far longer than initially expected, means that they form sizeable parts of these regions' housing stocks, which are often energy-inefficient and are hard to replace with new development. We propose a novel, structured approach to identifying buildings from this group using Geographic Information Systems (GIS), urban and social analysis, and Multi-Criteria Decision-Making support methods (MCDM) for comprehensive thermal retrofitting, combined with remodelling to address crucial deficiencies in accessibility and public space renewal. Our approach can aid in extending the utility of panel-block buildings in preparation for their eventual replacement. The model presented includes an energy audit of buildings, proposing measures to reduce their energy consumption. It is proposed to retrofit the mechanical ventilation and change the heating system to a significant share of renewable energy supply by applying the current method. This would allow the users to save up to 80% of their current energy consumption and related Greenhouse Gas emissions.

1. Introduction

Climate change is a globally recognised problem that threatens the sustainable development of societies. While some fringe voices argue that it may not necessarily be too late to prevent it from becoming excessively severe, the current state of implementation of policies aimed to do so leans towards decidedly pessimistic outlooks, as discussed in a 2022 report by the Intergovernmental Panel on Climate Change [1]. One of the tactics of implementing sustainable development is the thermal retrofitting and adaptive reuse of existing buildings, as studies have shown that energy inefficiency in this sector is one of the leading causes of high energy consumption, which was stated in a report by the United Nations Environment Programme [2]. One of the fields with great potential in this regard is housing, specifically panel-block housing – due to its standardised nature.

The European Union (EU) has been taking a wide range of measures to improve the environment by reducing pollutants and improving energy efficiency for many years. One of the latest programs in this respect is "Renovation Wave" which features an action plan with additional, comprehensive tools to facilitate the rate at which existing building

* Corresponding author. Cracow University of Technology/Politechnika Krakowska, Ul. Warszawska 24, 31-155, Kraków, Poland.
E-mail address: krzysztof.barnas@pk.edu.pl (K. Barnaś).

https://doi.org/10.1016/j.energy.2022.125774
Received 6 July 2022; Received in revised form 10 October 2022; Accepted 14 October 2022
Available online 28 October 2022

stock is renovated [3].

Potential benefits from thermally retrofitting panel-block housing as a part of multi-building initiatives.

Panel-block housing from the 1960s and 70s is a well-known fixture of the cityscape of former Eastern Bloc countries. Based on data for Poland, which can be considered a representative case for such countries, such buildings form a sizeable portion of their housing stock. A report published in 2013 by the General Statistics Office of Poland, as discussed by Mańkowski and Szczechowiak [4], shows that buildings constructed during the years 1945–1970 were the most numerous out of all the investigated building groups – at around 1.3639 × 10^6 – and featured energy demand rates within 250–300 kW h/(m^2 × y) and final energy values within 220–260 kW h/(m^2 × y). A comparison with buildings from other time periods in the twentieth century has been presented in Table 1.

As these buildings have a high degree of standardisation, developing an approach that could potentially be applied to a large section of this housing stock is both feasible and beneficial, as it could contribute to the spread of easily applicable thermal retrofit and spatial renewal guidelines. The significance of the proposed method is in the holistic package of tools and measures for the large-scale decrease of energy consumption from the housing stock, based on the proposed combination of a step-by-step approach to identifying panel blocks, comprehensive thermal retrofit, and accessibility enhancement and spatial renewal.

Similar initiatives have been undertaken in the United Kingdom. They include the Community Green Deal and the joint action by Carbon Co-op and URBED, which demonstrated that multi-building initiatives that cover the largest building complexes could lower the cost due to, among others, bulk purchases and large-scale contracts, as indicated by Lehmann [5].

1.1. Literature review

Thermal retrofit of the housing stock, especially mass or social housing, is a problem experienced worldwide and represents a worthwhile research direction, as reasoned by Flamant et al. [6]. They have presented their own approach to retrofitting social housing that accounts for environmental considerations. They analysed three retrofit scenarios under four contrasting climatic conditions that are designed to improve the building envelope, with and without extending the solar space.

This was corroborated by Mikulić et al. [7], who presented the effects of mass retrofitting on the economy and argued that it contributes positively to combating climate change. In a study on the effects of public building retrofits in Korea, Lee et al. [8] recommended community-level retrofits as effective cooperative actions, which is why stakeholder consultations are advised in planning and executing such projects. An interdisciplinary approach to adapting cities to climate change was proposed by Masson et al. [9], which tackled energy in the form of a Town Energy Balance model.

Residential buildings are usually retrofitted on an individual basis since there are many retrofit scenarios in terms of energy demand and consumption. Energy modernisation concepts are based on thermally insulating the building's envelope, including the slab on grade and roof, the replacement of windows, and the modernisation of the ventilation and heating systems. Deep thermal modernisation of public buildings was found to allow for significant final energy savings of about 46–65%, as reported by Sadowska [10].

An analysis of optimal retrofit solutions that accounted for Life-Cycle Cost Analysis (LCCA) was undertaken by Wang and Holmberg [11]. Consideration of a ventilation replacement process with heat recovery and the use of a low-temperature supply (LTH) was, in turn, analysed by Wang et al. [12]. They presented their concept with the example of a building located in Sweden. They showed a considerable saving of final energy of about 55%. Similar studies were conducted on buildings in Poland by Sadowska et al. [13]. They showed energy savings (at a level of about 50%) achieved after thermo-modernisation in comparison with previous assumptions.

By reducing the heat load values of a building, studies by other researchers showed the adaptability of various low-temperature heating systems in existing buildings. An analysis was carried out by Tunzi et al. [14] with the intent to explore the adaptation of existing hydronic systems in buildings to use low-temperature district heating. It investigated cost savings due to lowering a system's temperature to the required logarithmic mean temperature difference (LMTD) for a low-temperature heating system. The results of two sample scenarios showed that more efficient radiator operation could result in cost reductions at levels of 14% and 16%. These are analyses based on situations when no intervention in the building envelope or heating systems had been performed.

In another paper, Benakopoulos et al. [15] analysed the reduction of the grid supply temperature while maintaining sufficient user thermal comfort. A thermal-hydraulic model of a building's radiator system was created to calculate the minimum supply temperature required at maximum pump output. The presented case showed minimized supply and return temperatures of 44 °C and 30 °C. However, the required heat at these temperatures is only possible with sufficient hydraulic balance and by using all available radiators. Lowering the grid supply temperature results in the possibility of using a 4th generation grid, as described by Lund et al. [16], or also 5th generation District Heating (DH), as described by Buffa et al. [17]. These works have shown that in old buildings, it is possible to reduce the temperature in the heating system and obtain satisfactory user thermal comfort. This enables the use of a different heat supply based on renewable energy sources, which produce a lower temperature. One such solution is the use of heat pump systems.

The use of air-source heat pumps for building heating was discussed by Calame et al. [18]. It was shown that in the case of single-family houses, despite the relatively high investment costs compared to gas heating, and the operating costs are lower. Medium-sized multi-family buildings financially represent the most unfavourable case for heat pump integration, and in the case of large buildings, these are complex projects requiring experts in the field and require additional investigation. In their work, Lämmle et al. [19] analysed the performance of air-source and ground-source heat pump systems with temperature reduction methods in a space heating circuit. After analysing several single-family buildings, it was demonstrated that selective replacement of only 7% of all radiators was sufficient to reduce the heating temperature from 75 °C/60 °C–55 °C/45 °C resulting in a 40–42% reduction in electricity consumption. However, the potential of such a study is specific because a lot depends on the condition of the building, its thermal upgrading and the power of the installed radiators in the rooms.

A study by Mauri, Vallati and Ocłoń [20] investigated low impact energy saving strategies for a thermal retrofit of a modern building in Rome, which showed that the proposed solutions could provide energy savings of up to 44%. When paired with lowering set-point temperatures by 2 °C, which required changing user behaviours, the savings could be increased up to 63%. The study also noted the socio-economic cost of

Table 1
Housing stock age structure in Poland for buildings constructed prior to 2002, along with their energy demand characteristics [36].

Building construction date	Number of buildings (× 10^3)	Number of residential units (× 10^6)	Primary Energy (PE) [kWh/(m^2 × y)]	Final Energy (FE) [kWh/(m^2 × y)]
Prior to 1918	404.7	1.18	>350	>300
1928–1944	803.9	1.45	300–350	260–300
1945–1970	1363.9	3.11	250–300	220–260
1971–1978	659.8	2.07	210–250	190–220
1979–1988	754.0	2.15	160–210	140–190
1989–2002	670.9	1.52	140–180	125–160

Greenhouse Gas emissions and the importance of lowering them, highlighting the need for potential efforts to be as widespread as possible.

Heinz and Rieberer [21] proposed a system based on air-to-water heat pumps supported by a photovoltaic system, a heat storage tank (water tank), and an intelligent rule-based control system that enables the directed operation of the heat pump using electricity from a local photovoltaic installation. After analysing the two cases in TRANSYS software, a reduction of grid electricity consumption by 29% and in the net cost of electricity by 35% was found. The study analysed one country and a single-family house.

Fraga et al. [22] analysed and compared the potential and limitations of different heat sources used by heat pumps (air, geothermal wells, lake, river, groundwater and solar heat). The study was conducted for different types of buildings (new, retrofitted and non-retrofitted) and showed that the higher the heat source temperature, the higher the Seasonal Performance Factor (SPF) value. The highest values are achieved by solar thermal heat and ambient air as heat sources. Additionally, photovoltaic panels were added to the heat pump system in each of the three cases. The simulation results showed that the final energy consumption would be below 15 kW h/(m^2·y) (for low-demand buildings) and below 45 kW h/($m^2 \times$ y) (for high-demand buildings). The study was conducted on the city of Geneva and its conditions.

In another paper [23], Kowalski et al. presented source heating using an electric compressor Air–Water Heat Pump (AWHP) to recover waste heat from exhaust air. By analysing the system in TRNSYS software and comparing different locations of this system, a significant potential was shown from an energy and environmental point of view. The most energy-efficient system is the one with the lowest heating system temperatures. The system can be augmented with photovoltaics which could reduce the value of non-renewable primary energy for heating.

An analysis of a similar heating system based on Solar-Assisted Ground Source Heat Pumps (SAGSHP) with heat recovery and energy storage is presented by Hosseinnia and Sorin [24]. In their work, they proposed a novel dynamic targeting method that takes into account the dynamic loads of the building and the variability of renewable and waste energy sources over time. The presented method allows for determining the maximum heat recovery with the minimum number of PV panels and energy storage. The method was applied to a test multifamily house without considering the economic analysis of such a solution. Another heating system that is feasible for both new and already retrofitted buildings is presented by Ocłoń et al. [25]. The system is based on hybrid photovoltaic (PVT) panels with cooling, evacuated solar collector and water-to-water heat pump, and underground tanks serving as energy storage. Optimisation of the performance of this system has been performed using Genetic Algorithm (GA), Particle Swarm Optimisation (PSO) and Jay's algorithm methods and comparing the results from these optimizations. However, actual measurements from the operation of such a system have not been considered.

In addition, there are multiple studies on the thermal retrofitting of historical buildings, including heritage sites. As buildings from the 1960s and 70s are now potentially entering their sixth or seventh decade of use, some scholars have started to voice proposals to have them be considered a form of heritage. However, most currently published studies focus on actual heritage buildings, including tenement buildings, as presented by Orlik-Kożdoń et al. [26] and masonry buildings in general, as demonstrated by Piasecki et al. [27]. Dedicated thermal retrofitting solution assessment algorithms were also proposed for wooden heritage buildings by Fedorczak-Cisak et al. [28]. Jeleński et al. [29] proposed algorithms as a universal tool to assist with the systemic analysis of historical buildings to facilitate the decision-making processes involving various stakeholders in climate-friendly renovation and retrofitting interventions.

Erba and Barbieri [31] explored the concept of retrofitting buildings into thermal batteries, reasoning this may be beneficial during power outages, presenting their investigation using the case of a public housing complex in Milan, Italy. From an urban planning and regeneration standpoint, panel-block housing estates were investigated by Tofiluk et al. [30], who presented a diagnosis of the causes behind the need for comprehensive action to make them more comfortable to live and inhabitant-friendly. Accessibility issues have also been assessed in Poland by the Office of the Ombudsman [32] and by accessibility researchers, notably Chan et al. [34], who explored the problem in China's public housing dating from the 1970s to the 1990s, which followed similar design patterns to Polish housing estates in the period under consideration.

Another element that can aid in combating climate change is Nature-Based Solutions (NBS), whose overview was presented by Xing et al. [33], while practical applications and policy tools were outlined by Naumann et al. [35]. Such solutions can include measures intended to aid in preventing floods and droughts, such as rain gardens, which were discussed by Majidi et al. [36]. With modern domestic hot and cold water systems proposed by Zielina [37], energy and water consumption can be significantly reduced like it, as reported by Lee and Yim [38].

Zwierzchowska et al. [39] presented the potential of NBS with a specific focus on multi-family residential areas in Europe, noting that Socialist Modernist housing estates, i.e., the building complexes investigated in this study, appeared promising due to having high amounts of biologically active surfaces, thus showing potential for green infrastructure. This is especially crucial as ongoing densification and contradictory land-use policies can lead to green space loss, as argued by Badiu et al. [40]. A similar study was performed by Schmid and Säumel [41], who investigated how residential greenery was perceived in multi-story housing estates in Berlin, Germany. Their study resulted in a range of greening and amenity solutions that were positively and negatively perceived by respondents and can serve as an indicator as to which regeneration solutions should be adopted first.

The comprehensive implementation of nature-based solutions can also aid in alleviating the urban heat island (UHI) effect, which changes with land cover and is positively correlated with the development and negatively with biologically active areas, as found by Tepanosyan et al. [42], who investigated how the effect presented itself in Yerevan, Armenia, a city where post-Soviet panel-block buildings are plentiful. In addition, Yang et al. [43] investigated the thermal effects of vegetation on urban surface temperature, which is a highly contributing factor to the UHI, and have found that surface vegetation fraction (SVF) begins having a cooling effect on surface temperature in cities when above 0.2, reaching maximum efficiency between 0.5 and 0.6. This lends credence to the argument that urban greening can lessen the loads placed on indoor cooling systems and should be paired with thermal retrofitting solutions.

The provided literature review shows that multi-building thermal retrofitting is a topic that merits investigation and the development of new tools and approaches, as well as a broad body of research. Important issues were investigated – such as thermal performance, Life Cycle emission and cost issues, the influence of the target temperature settings on the final energy demand, and finding suitable renewable energy sources and supply – but they were predominantly investigated in isolation. There is a knowledge gap in the application of PVT panels at a large scale for such buildings. Also, a comprehensive procedure accounting jointly for the thermal, economic and social aspects of sustainability improvement is difficult to find. It is therefore justified to explore the means of identifying the largest possible groups of buildings for which a standardised set of solutions can be formulated and effectively applied, one that would also encompass community- and environment-focused urban regeneration solutions that would help to make the best out of the existing housing stock.

1.2. Objectives and novelty of the study

This study has the following objectives:

- Formulate a multi-stage algorithm for identifying large groups of panel-block buildings for which standardised, and comprehensive thermal retrofitting schemes could be developed and paired with environmental and accessibility enhancements;
- Validate the algorithm on a case city by identifying a representative building within an actual panel-block housing complex and preparing a set of thermal retrofitting solutions coupled with environmental and accessibility enhancement measures;
- The measures proposed are intended to prolong the service life of buildings, increase their energy efficiency, contribute to water retention and bring them closer to current accessibility standards;
- Perform a financial analysis of how the implementation of these measures could be funded from savings on energy.

The novelty of the study consists in:

- Formulating an original, comprehensive, multi-stage building identification algorithm that employs GIS data, the TOPSIS method, urban analysis of building typologies, social analysis, existing condition reports and energy audits to preselect entire building groups for energy- and environment-focused interventions;
- Pairing the proposed identification algorithm with a set of proposed RES-based thermal retrofitting, NBS-based environmental enhancement, accessibility improvement and barrier-free design solutions that can be implemented in target building complexes,
- Forming a highly exhaustive package of solutions that can significantly aid in modernising panel-block housing estates and making them more climate-friendly and liveable.

To the authors' knowledge, no similar, fully exhaustive approach has been proposed in the literature so far.

1.3. Study overview and justification

This study presents an approach to identifying panel-block buildings that are suitable for standardised thermal retrofitting and remodelling to increase their energy efficiency, enhance accessibility to people with special needs, adapt the building's general area to climate change and facilitate community renewal via additional greening and the overall enhancement of the surrounding areas. The proposed approach is presented using the case of Krakow, Poland, which is the country's second-largest city in terms of population and has a sizeable stock of Eastern-Bloc-era panel-block buildings from the 1960s and 70s. The study was concluded in the second half of 2021, and the data used was from this period.

The deep thermal retrofitting of housing stock in cities is a topical challenge faced by European countries. Housing estates erected after the Second World War do not meet contemporary use comfort standards, including energy, spatial and social standards, and previously implemented thermal retrofitting measures were often superficial and insufficient. The need for widely applicable thermal retrofit solutions has been noted in the literature, for instance by Mauri et al. [20].

The objective of this paper is to present an original algorithm for the selection of buildings and solutions based on Renewable Energy Sources (RES) that accounts for the challenges of the mass thermal retrofitting of the housing stock developed by an international team of researchers. The algorithm's use and performance are illustrated in a case study – derived from a project that the authors performed. It involved developing an interdisciplinary model of the approach to lowering Greenhouse Gas (GHG) emissions of the City of Krakow, accounting for the challenges of mass, deep thermal retrofitting of buildings, the use of renewable energy, the development of blue-green infrastructure and deep regeneration of local communities (the concept of "green neighbourhoods," a pilot project for the city of Krakow), which was commissioned by the Municipality of Krakow's Department of Municipal Management.

The algorithm is based on five steps:

(i) An urban and architectural analysis intended to identify building types for thermal retrofitting and neighbourhood regeneration;
(ii) A social analysis intended to identify key stakeholders and probe for the availability of key building documentation and, ultimately, the selection of the building to formulate detailed solutions for;
(iii) A technical analysis of the building and its general area, coupled with formulating accessibility and pro-environmental solutions;
(iv) An energy audit and analysis of the building coupled with formulating thermal retrofitting solutions;
(v) An economic project feasibility analysis based on Simple Pay Back Time (SPBT) and Net Present Value (NPV).

These steps, when based on suitable selection criteria, of which a set has been proposed in this paper, can lead to identifying potential for the large-scale thermal retrofitting and urban regeneration of existing housing stock that was built using standardised, prefabricated housing technologies. While this approach was developed with panel-block housing from Central and Eastern Europe in mind, with minor modifications, it could be successfully applied to housing development from a similar period regardless of its location, making it universal.

2. Method

2.1. Algorithm overview

A general overview of our comprehensive housing thermal retrofit and urban regeneration algorithm has been presented in Fig. 1.

Step 1. Identification of buildings for retrofitting: urban and architectural analysis

The first stage of the study was the identification of a representative building to which the proposed solutions could be tailored. The building was to be a demonstration case intended to popularise the approach among potential stakeholders. This stage was further divided into substages, intended to assess the overall number of buildings the proposal could be applied to with some modifications, its potential application, as well as the number of buildings on which the solutions developed could be used directly, i.e., those which resembled the model building the most. The later identification stages consisted of on-site inspections and visual assessments, which were followed by a multi-criteria analysis performed using the TOPSIS method (Technique for Order Preference by Similarity to an Ideal Solution).

The identification stage was divided into the following three substages:

- Initial city-wide identification of buildings based on characteristics typically shared by panel-block buildings;
- Visual identification and inspection of buildings that displayed the greatest degree of similarity and standardisation, which could potentially allow the applicability of a standardised approach and that met a set of predefined criteria;
- selection of a number of top candidate building complexes using a decision-making support method.

2.1.1. Initial city-wide identification of suitable buildings

The objective of the initial identification stage was to determine the number of buildings that could potentially be panel block buildings. The criteria used in this identification stage were as follows:

- Primary use: multi-family housing;
- Five floors;
- Built during 1945–1995;

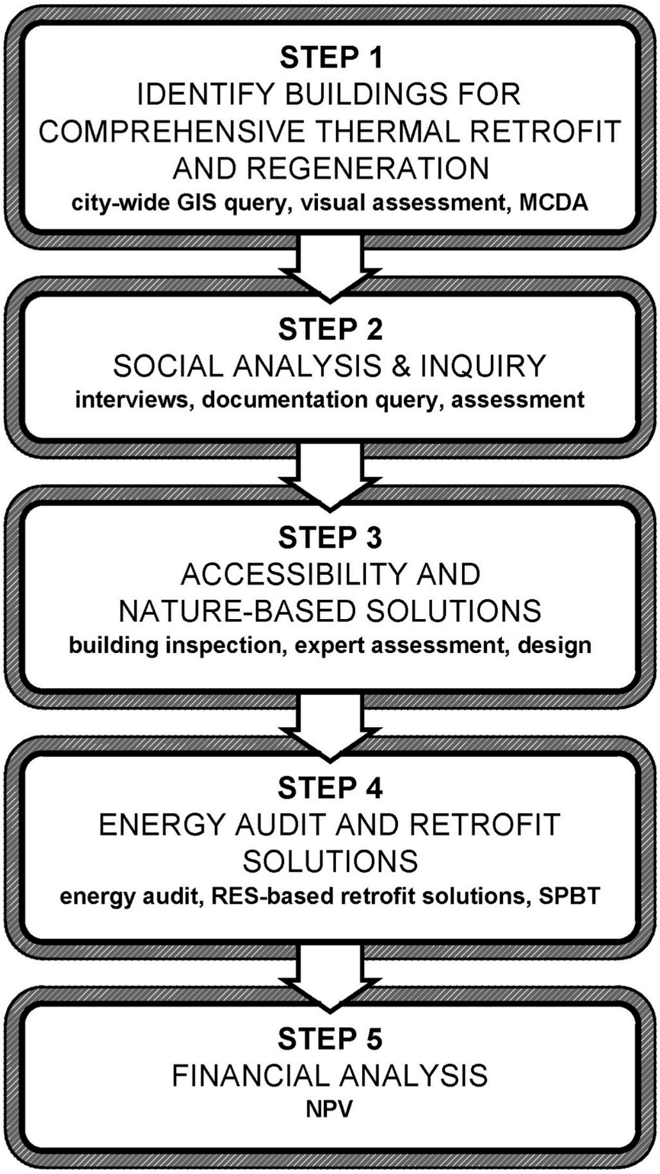

Fig. 1. Synthetic presentation of the algorithm for selecting buildings and RES-based solutions intended to take on the challenges of comprehensive thermal retrofitting of housing stock, along with a proposal of analysis methods.

These criteria were adopted for a number of reasons. First, multi-family housing was chosen due to its high technological, structural and architectural similarity in the case of panel-block systems, expected to yield the highest number of standardised building types. Second, the number of stories was chosen because five was the preferred number of stories in most panel-block housing constructions. The date range used was dictated by the record-keeping convention for building construction dates in the real estate property register (Land and Building Register, data provided by the City of Krakow, this data is public but is made available on request), which listed them as either a single year or a date range, especially in the case of large multi-building projects, resulting in discrepancies.

2.1.2. Visual assessment – identification of panel-block buildings and grouping into complexes

In the next stage, the buildings identified were grouped into complexes by address and visually assessed using satellite imagery, orthophoto maps and site inspections for the following characteristics:

- Detachedness;
- Technological uniformity within a complex;

These two characteristics were selected because they are typical of panel-block buildings. In Central and Eastern Europe, such buildings were typically constructed as detached and planned in large complexes that were not divided into city blocks, which allowed greater freedom in their placement. This facilitated the use of technological uniformity – the buildings were almost identical copies of each other. This uniformity is easily detectable based on architectural features such as roof and attic wall shape, window layout, entrance section layout and story height. The buildings also form complexes with clearly visible, homogenous urban layouts that can be easily distinguished both from non-panel-block development and from other panel-block complexes constructed as a part of other projects (colloquially and administratively called housing estates) on maps and during a site inspection. These complexes were not necessarily fully homogenous, as they often featured buildings constructed using two or three different panel-block systems.

Complexes are considered to be technologically uniform when at least ten buildings within their respective housing estate are identified to have been built using the same panel-block technology. This threshold was put in place to ensure that the final solutions developed would be directly applicable to the highest possible number of buildings.

2.1.3. Multicriteria analysis – building complex preselection

The identified complexes are then once again inspected and rated using the following criteria:

- Number of buildings in a complex;
- Maximum number of technologically uniform buildings of a given type in a complex;
- The ratio between buildings with balconies in relation to the number of all buildings in the complex;

Additional criteria may be added depending on project goals or decision-maker preferences. The criteria presented were used due to two main considerations. The first goal is to ensure that the solutions developed for the representative building are readily applicable to the largest possible number of buildings. This gives rise to the first two criteria.

The second motivation stems from the project's urban renewal goals, as balconies are considered a desirable feature of buildings, especially for seniors and people with special needs who have limited mobility, as they allow such people a limited experience of going outside without leaving their dwelling. The proposal was particularly enforced during the COVID-19 pandemic, and, given the typical age structure of panel-block building inhabitants, which displays an overrepresentation of seniors, as found by Gronostajska [44], it can greatly improve their well-being.

Afterwards, the complexes are subjected to a multicriteria analysis using the TOPSIS method (Technique for Order Preference by Similarity to an Ideal Solution) as presented by Kobryń [45] in a study on spatial management, as well as the determination of the scope for renovation by Bucoń and Sobotka [46]. It is widely applied in many areas, which was observed in the state-of-the-art review by Behzadian et al. [47] and also analysed by Zyoud and Fuchs-Hanusch [48] in their bibliometric survey emphasizing the indicators used.

TOPSIS supports the selection of the most beneficial decision alternative from the standpoint of a set of criteria. In this method, the synthetic rating of decision alternatives is based on determining the distance of each alternative from the ideal alternative – defined based on the best available values for each criterion – and the anti-ideal alternative, which is defined based on the worst available values for each criterion. Criteria can act as stimuli or dampers, which define which value should be accounted for. For the ideal alternative, the maximum value is taken for stimuli, and the minimum value is taken for dampers.

The anti-ideal alternative, it is the opposite. The best alternative is the one whose value vector is both the closest to the ideal alternative's vector and the farthest from the vector of the anti-ideal alternative in a multidimensional Euclidean space. As the TOPSIS method was not modified in this study, a step-by-step overview of its use has not been included.

It is possible to use other multicriteria decision analysis methods (MCDA) during this stage, as it has been proven that they are of significant benefit in decision-making concerning remodelling projects, which was presented by Radziszewska-Zielina and Śladowski [49], and selecting forms of use in adaptive reuse projects from a set number of possible alternatives, also presented by Radziszewska and Śladowski [50], as well as in energy and environmental modelling, as discussed by Zhou et al. [51] and, in a separate study, by Hossein Dehshiri, who applied it to traditional buildings [52].

Step 2. Social analysis – final building complex selection

The objective of this stage is to select the complex with the building for which detailed solutions are to be formulated. This is done using social analysis and inquiry that includes the following:

- Identification of key stakeholders, their needs and expectations,
- Organising meetings and in-depth interviews with representatives of identified communities,
- Determining whether property managers possess detailed documentation that can aid in formulating detailed solutions, i.e., plans and utilities data for specific buildings.

In-person interviews are used to obtain as much detailed information on stakeholder structure – such as whether there is a single large institutional property manager or multiple smaller homeowners' associations in a given complex. It is crucial to identify how these parties operate and whether they can be effective partners, as well as whether they express interest in participating in or supporting thermal retrofit and urban regeneration projects. Stakeholder consultation is a key element, as it aids in identifying the pool of buildings that can be included in a retrofit project due to ownership or management determinants, as technological uniformity alone is not enough to enable such projects to go forward, as noted by Lee et al. [8].

Step 3. Building and site – community- and environment-focused enancements

In this stage, the building and its site are inspected, and detailed accessibility and environment-focused measures are formulated. The building is to be inspected by a certified specialist, following a methodology suitable for inspecting buildings slated for remodelling [3]. A building inspection and energy audits were recommended as essential tools of panel-block building complex revitalisation by Ostańska [53] and should also involve accessibility enhancement and barrier-free design measures, as panel-block buildings display significant deficiencies in this area, as noted by an assessment report of the Polish Ombudsman [48] and by the research of Chan et al. [11] on design for people with disabilities.

Accessibility solutions should implement an inclusive and barrier-free design, as defined by Holmes-Siedle [54] in their manual for building designers and managers and separately in the World Bank accessibility guidelines discussed by Rickert [55]. Environmental enhancements should be based on nature-based solutions, such as green roofs, whose use in this capacity was recommended by Calheiros and Stefanakis [56], and rain gardens, proposed as means of preventing flood risk by Majidi et al. [36]. The practical and technical considerations of the application of rain gardens were discussed by Kasprzyk et al. [57], who proposed using them to enhance local biodiversity and assist in water retention while noting that sometimes they should be paired with additional surface runoff purification devices. Rain gardens were also recommended for use as a part of comprehensive NBS toolsets by Naumann et al. [35].

Flood prevention is a major goal of nature-based solutions, as shown in the concept of Sponge City, intended to provide as much water retention as possible, and for which Wan et al. [58] developed a multi-objective optimisation model. The overall benefits of NBS have been presented in Fig. 2 below.

Step 4. Energy audit and thermal retrofit solutions

This stage consists of performing an energy audit of the selected building and is meant to identify.

The audit evaluates the effectiveness of the following improvements:

- insulation of building partitions, i.e., external walls, floor slabs, roofs, ceilings over unheated basements, the slab on grade;
- modernisation or replacement of the heating system in the building or with modernisation or replacement of the heat source.
- modernisation or replacement of a hot water supply system;
- modernisation of ventilation system;
- introduction of equipment using energy from RES, e.g., solar collectors, photovoltaic cells, heat pumps, energy heating and electric storage;
- introduction of an energy monitoring and management system.

Step 5. Economic analysis

The economic analysis was used to estimate the expenditure that could be covered by savings from the building's retrofitting, as well as the amount that would have to be covered from other sources. The analysis was performed with the use of Net Present Value (NPV), as proposed by Akalu [59], using data available in Q4 of 2021.

The analysis was performed for a range of varied retrofit scopes. Six alternative retrofit scopes were analysed and included two heating and domestic hot water preparation systems that utilised RES. Furthermore, each of the alternatives included accessibility solutions, either in their basic or extended form, namely with or without elevators.

A 30 y building service life was analysed. It was assumed that 90% of the savings from the retrofit would be used to fund the project. A discount rate of 3% was used. Inflation was accounted for by including a corrected discount rate (without an inflation element). The analysis did not cover nature-based solutions.

3. Case study

The algorithm presented in this study was developed and validated based in the city of Krakow, Poland. Krakow is Poland's second-largest city, with a population of just above 800 thousand, according to Statistics Poland [60], and is located in the southern part of the country. Like many Central and Eastern European cities, a considerable portion of its housing stock dates back to the 1960s and 70s and takes on the form of panel-block housing.

3.1. Urban and architectural analysis

Based on the criteria presented in section 2.2.1. the initial identification used publicly available Geographic Information System (GIS) data supplied by the Office of the City of Krakow. Building geometry in this system was imported from the BDOT10k country-wide database. The content of the BDOT10k database generally corresponds to a traditional topographic map drawn to a scale of 1:10,000 with an accuracy of about 3 m. Building attributes such as an address, building use, construction date and the number of storeys were taken from the Land and Building Register (Ewidencja Gruntów i Budynków, EGiB). The analysis also utilised spatial data from the Utilities Network Database (Geodezyjna Ewidencja Sieci Uzbrojenia Terenu, GESUT), which contains information about utility grids and related infrastructure, with an accuracy of up to 10 cm. The use of GESUT data enabled the identification of buildings with access to district heating. The spatial scope of the analysis was confined to Krakow's districts, using information

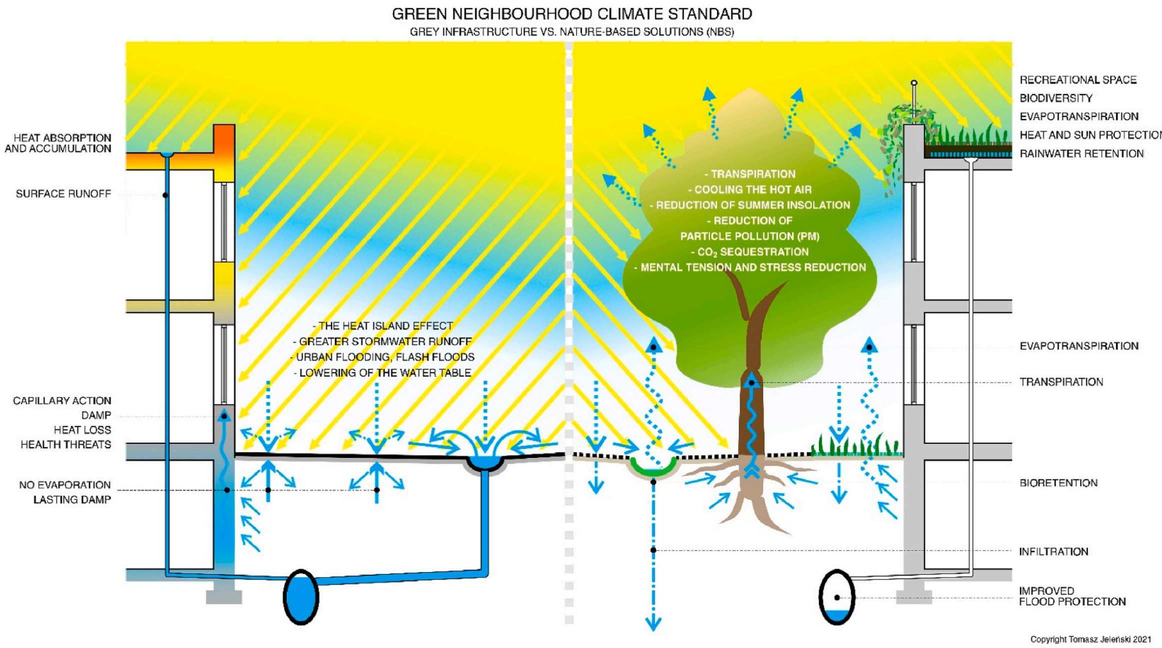

Fig. 2. Benefits of nature-based solutions (NBS), original image.

sourced from the National Register of Boundaries (Państwowy Rejestr Granic, PRG) and the National Register of Geographic Names (Państwowy Rejestr Nazw Geograficznych, PRNG).

The data was procured in July 2021. A total of 1,619 buildings were found to meet these criteria. As not all of them were panel-block buildings, as such information was not included in the GIS data available, the buildings had to be visually assessed.

Using high-resolution orthophoto maps with a pixel size of 10 cm supplied by the Municipality and by performing site inspections, a total of 11 building complexes were identified to meet the visual identification criteria specified in section 2.2.2. The number of technologically uniform buildings in these complexes ranged between 11 and 58. The complexes named after their addresses were: Azory, Mazowiecka–Kmieca–Litewska, Podwawelskie Housing Estate, Płaszów, Na Kozłówce Housing Estate, Tysiąclecia Housing Estate, Złotego Wieku Housing Estate, Albertyńskie Housing Estate, Piastów Housing Estate, Dąbie, Ugorek, and Grzegórzki-Wschód–Grzegórzki-Północ–Sądowa.

3.1.1. Multicriteria analysis results

As the pilot project the algorithm was developed for required the selection of a demonstration building that could be used for promotion, the criterion of visibility was added to the criteria specified in section 2.2.3. Visibility was understood as a complex having buildings located along busy thoroughfares that were exposed to public view. This was an important element of the project, as the implementation of the solutions presented in the pilot building would later be used to promote that approach to other stakeholders. For that reason, favourable exposition conditions were deemed a significant element of the decision process. This criterion was also adopted in response to the recommendations by Lee et al. [8] as it ties into raising public awareness of retrofit projects. The ratings for each criterion have been presented in Table 2.

The weights for each criterion were determined by the authors, who acted as decision-makers in the pilot project. The set of criteria selected is not final and can be altered. In the case presented, visibility was assigned a significant weight as the purpose of the analysis was to select a model building that would later be used for presentation and potential encouragement of other stakeholders to engage in the project. As such, this criterion may not be applicable in later uses of the approach. The weights assigned for each criterion by the authors have been presented in Table 3.

Table 2
Alternative ratings in each criterion.

Alternative	Alternative ratings for each criterion			
	Number of buildings in complex [pc]	Maximum number of technologically uniform buildings of a given type in the complex [pc]	Ratio between the number of buildings with balconies relative to the total number of buildings in the complex [-]	Average building visibility [−]
Azory	39	25	0.872	0.872
Mazowiecka–Kmieca–Litewska	19	11	0.211	1.211
Podwawelskie	28	11	0.000	1.000
Płaszów	13	10	0.000	0.667
Na Kozłówce Housing Estate	41	27	0.487	1.179
Tysiąclecia Housing Estate	23	12	0.000	1.000
Złotego Wieku Housing Estate	40	28	0.000	0.975
Albertyńskie Housing Estate	15	12	0.000	1.471
Piastów Housing Estate	33	28	0.000	0.618
Dąbie	15	15	0.286	1.107
Ugorek	17	17	0.333	0.579
Grzegórzki-Wschód–Grzegórzki-Północ–Sądowa	18	18	0.000	1.389

The values of the ranking coefficient for each alternative have been presented in Table 7, with the alternatives sorted in descending order by the coefficient's value. Table 4 shows the final ranking of alternatives.

The three complexes that scored the highest were Azory, the Na

Table 3
Weights assigned to each criterion.

Alternative	Criteria weights			
	Number of buildings in the complex	Maximum number of technologically uniform buildings of a given type in the complex	Ratio between the number of buildings with balconies relative to the total number of buildings in the complex	Average building visibility
Author 1	2	5	4	5
Author 2	3	5	2	5
Author 3	3	5	3	5
Author 4	2	5	3	5
Author 5	3	5	3	4
Average	2.6	5.0	3.0	4.8
Standardised average	**0.169**	**0.325**	**0.195**	**0.312**

Table 4
Final ranking of alternatives.

Alternative	Ranking coefficient *R*	Position in the ranking
Azory	0.768	1
Na Kozłówce Housing Estate	0.659	2
Złotego Wieku Housing Estate	0.401	3
Piastów Housing Estate	0.359	4
Dąbie	0.351	5
Ugorek	0.327	6
Grzegórzki-Wschód–Grzegórzki-Północ–Sądowa	0.327	7
Mazowiecka–Kmieca–Litewska	0.309	8
Albertyńskie Housing Estate	0.304	9
Podwawelskie Housing Estate	0.202	10
Tysiąclecia Housing Estate	0.189	11
Płaszów	0.037	12

Kozłówce and Złotego Wieku housing estates, and were qualified for the next stage.

3.2. Social analysis results

Major property management stakeholders such as housing co-operatives and homeowners associations were identified in the three top candidate housing estates selected during the previous stage. Contact was initiated, and in-depth interviews were performed with the stakeholders, gauging their attitude towards thermal retrofitting and community- and environment-focused enhancements, as well as probing for the presence of project-specific building accessibility characteristics. Simplified ratings for each of the criteria used have been presented in Table 5, while a more detailed overview of the scores listed is provided in the subsections below.

3.2.1. Azory

The Azory complex was found to be unsuitable for further work on the pilot project due to significant stakeholder decentralisation and overall indecisiveness, and a general unwillingness to engage in the project.

Table 5
Interview results are displayed as ratings of stakeholder attitudes towards the project and other retrofit-specific criteria.

Criteria	Azory	Na Kozłówce Housing Estate	Złotego Wieku Housing Estate
Interest in the project	0	4	6
Thermal retrofit self-evaluation	No data	3	6
Energy demand diversification	No data	1	3
Interest in RES	No data	3	3
Stormwater management	No data	3	3
Scalability/uniformity	No data	4	6
Construction documentation	No data	2	3
Balconies	No data	3	3
Elevators	No data	2	3
Decisiveness	0	2	3
Participation	No data	0	6
Service buildings	No data	1	3
Shared spaces	No data	3	3
Other	No data	1	3
In Total	0	32	54
Rank	**3**	**2**	**1**

3.2.2. Na Kozłówce housing estate

Na Kozłówce Housing Estate was assessed as a suitable potential candidate for engagement in the pilot project, yet the major property management body that managed most of the complex's real estate assets had no interest in participating in the thermal retrofitting section of the project as it deemed the buildings under its management to be sufficiently modernised in this respect and was sceptical of the existence of a potential for enhancements. This major stakeholder reported that between 2003 and 2015 its real estate assets saw the addition of thermal insulation, the replacement of all windows and central heating and domestic hot water utilities, including heaters. The party also expressed some interest in renewable energy sources but none in water management solutions.

The complex was also deemed unfit for the project due to the absence of numerous key elements, such as the original building design documentation or its copies, and the specific systems in which the buildings were constructed being largely unknown to the property management body. The body also reported that it communicated little with homeowners and tenants and saw no potential in wider public consultations.

3.2.3. Złotego Wieku Housing Estate

Złotego Wieku Housing Estate proved to be the most suitable for the project as all of its property was administered by a single entity, the local housing cooperative, which expressed great interest in all aspects of the pilot project and had all the required documentation at its disposal, with full knowledge of all the types of prefabricated construction systems used to erect the assets under its management as well as their energy characteristics and utilities. The buildings the cooperative had under its management had been subjected to thermal retrofitting twenty years prior, and as such, the project could result in meaningful benefits, both in terms of energy and climate change adaptation.

The complex was also located favourably in terms of visibility and access to sunlight. A major district thoroughfare ran adjacent to the complex's southern border, and there was a bus terminal near its southwestern tip. These were both separated from the complex's buildings by landscaped greenery that did not obscure the façade and did not block access to sunlight for use by potential photovoltaic cells. A figure-ground plan of Złotego Wieku Housing Estate will be presented in Fig. 3.

The social analysis was concluded, and Złotego Wieku Housing Estate was selected as the complex from which the model building would be chosen.

3.2.4. The building selected for investigation

The building selected for investigation and the preparation of detailed solutions was located at 70 Złotego Wieku Housing Estate. The building's selection was based on the following criteria:

- The building's visibility within the complex is understood as being visible from public and semi-public spaces both within and outside the complex, with a preference for visibility from areas with a potentially high pedestrian traffic flow;
- The building's repetitiveness within the complex is understood as the highest possible number of typologically and technologically similar buildings within it;
- Documentation completeness is understood as the possibility of obtaining the fullest possible set of documentation and starting data that would allow for starting its investigation and the formulation of detailed solutions as soon as possible.

Fig. 3. Figure-ground plan of Złotego Wieku Housing Estate (top half of the image) and Tysiąclecia Housing Estate (bottom half of the image) imposed on a black-and-white satellite image, source: [61].

In the case of the building at 70 Złotego Wieku Housing Estate, all the criteria were met, as it was highly visible: near to a major circulation path, a public green area, and a bus terminal. It also belonged to the predominant building typology within the housing estate, and there was a complete set of documentation available for it, including its original technical drawings and utility data. The building's location on a survey map has been presented in Fig. 4.

Technical analysis results and regeneration solutions proposed

For the purposes of the technical analysis, the building selected during the previous stage was inspected by a structural engineer, an architect specializing in accessibility, and an architect specializing in nature-based solutions.

3.2.5. Building overview

The building was located at 70 Złotego Wieku Housing Estate, at plot no. 120/1, cadastral region NH-5, register unit Nowa Huta. It was built in 1978 using the W-70/Wk-70 prefabricated reinforced-concrete panel construction system. It was a multi-family residential building with five stories, an elevated ground floor and a full basement. It was covered by a flat roof with an incline of 6°. There were 50 residential units in the building, grouped around five circulation cores, with each core having a separate entrance, resulting in two units per story per core. The building was oriented with its longer side at an angle of 16° relative to the east-west direction. The building's east, south and west facades featured loggias on each floor. A photo of the building taken from the level of a nearby football pitch located to its south has been presented in Fig. 5.

3.2.6. Inspection results in key areas

The building's roof was deemed suitable for remodelling into an extensive green roof and for the installation of photovoltaic panels. In terms of accessibility solutions, the building lacked an elevator and featured several architectural barriers such as high curbs, stairs leading up to the entrance zone and an elevated ground floor with no amenities for the wheelchair-bound or persons with mobility impairments. No parking spaces for the disabled and no spaces for bicycles were found. In these areas, the building was found not to conform to the Ordinance of the Minister of Infrastructure on the technical conditions to be met by buildings and their placement [41], making it non-compliant with Polish building codes. The building was in an overall good technical condition, showing no signs of structural failure.

The building's surroundings were deemed satisfactory in terms of greening potential and public amenities. A small open-air gym, a well-landscaped playground and a neglected grassy football pitch were present in its vicinity, along with a large strip of public lawn equipped with benches.

3.2.7. Proposed accessibility solutions

Two alternative sets of accessibility solutions were proposed. The elements they shared included:

- Remodelling of curbs in the building's vicinity to obtain a barrier-free transition between road and pavement surfaces;
- Alter the layout of parking spaces by dedicating at least two to the disabled and one space dedicated to rescuing services;
- Remodelling of the entrance zone to allow persons with mobility impairments to easily enter the building via an external ramp and a larger landing in front of the main door;
- Allowing persons with impaired mobility to access residential units on the elevated ground floor by installing stair platforms;
- Adding foldable, non-flammable seats to landings to allow seniors or persons with impaired mobility to rest on their way to higher floors;
- Improving access to daylight in the staircases by installing larger windows;
- Equipping external stairs with ramps and additional balustrades;

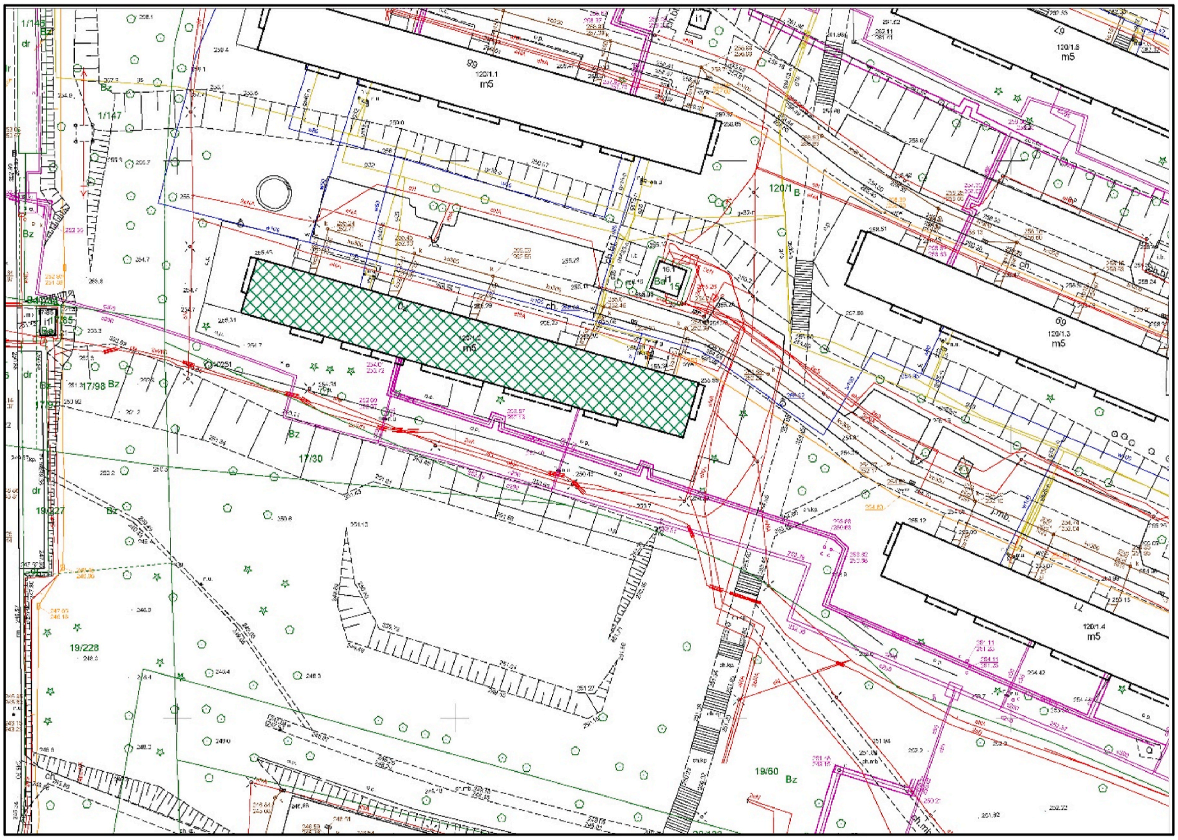

Fig. 4. The building at 70 Złotego Wieku Housing Estate is marked in green hatching on a survey map supplied by the Office of the City of Krakow. Several sets of stairs are visible to the right of the building, denoting a busy footpath that connects the housing estate's circulation layout with a bus terminal directly to the south.

Fig. 5. Photos of the building selected for the formulation of detailed solutions and the building's surroundings, 2021 original work; clockwise: view from the northeast; view from the east; view from the west, northern facade; view from the southeast, southern facade.

- Installing benches near the entrance zones;
- Installing improved streetlamps and facade lighting;
- Replacing intercoms with versions with larger markings and Braille script;
- Introducing colour solutions for visually impaired persons.

The second alternative, dubbed an extensive alternative, features all of the solutions presented above and adds the remodelling of circulation cores via the addition of elevators and the resultant extension of the entrance zone, as the pre-existing stairwells were found to be too small to accommodate elevator shafts.

Proposed nature-based and pro-environmental solutions.

Three alternative sets of nature-based and pro-environmental solutions were proposed. The first was based on installing a green roof with a vegetative layer 15 cm thick that can contribute to water retention and reduce stormwater volume, reducing the risk of inundation. The green roof could also be combined with photovoltaic panels, which would provide additional shade.

The second set included the green roof with the addition of rain gardens in the form of open niches or bioretention trenches which could be sited at the foot of the escarpment to the building's south. This could absorb the entirety of stormwater and meltwater from the roof and would alleviate some of the load placed on storm drains. These solutions would require a remodelling of the building's roof drainage installation, as collector pipes in the basement would have to be redirected to the new trenches.

The third set of solutions included stormwater tanks and rain gardens. Due to how the building's stormwater drainage installation had been designed and the shape of the terrain, it was deemed unfeasible to utilise surface reservoirs for stormwater retention. Instead, it was proposed to use underground tanks that could store excess stormwater and, upon filling up, could be drained into bioretention ditches. The capacity of such tanks was estimated at ca. 32 m^3 for the roughly 800 m^2 of roof area. However, due to the costliness of this solution and the earthwork required to build the tanks, it is advised to only apply this solution when a green roof is not chosen.

Separate nature-based elements that can be used alongside all the sets presented include green walls and bicycle parking canopies that could be used as treillages, especially along a cycling path planned by the municipality. Biodiversity could be retained and supported by introducing animal feeders, such as insect hotels, hedgehog houses or birdhouses, as well as purposefully untrimmed lawns with flower patches.

3.2.8. Proposed community regeneration solutions

As the football pitch located south of the building was found to be the only lacking public amenity in the area, it was decided to focus community regeneration solutions on this location, modelled after the Polish Orlik football pitch construction campaign. As the Złotego Wieku Housing Estate featured a primary school and the pitch itself was located near a busy local footpath, this solution was expected to find no shortage of users.

3.2.9. Energy analysis results and thermal retrofit solutions proposed

Optimisation calculations were performed for a range of enhancements. Enhancements concerning lowering heat loss via heat transfer through building partitions and heating ventilated air:

- Adding thermal insulation to the roof;
- Adding thermal insulation to the ceiling above the cellar;
- Replacing windows along with adding window vents;
- Replacing windows in the circulation core;
- Installing mechanical ventilation.

Enhancements concerning lowering heat demand for domestic hot water preparation included installing a heat pump and an individual domestic hot water preparation installation, while enhancements concerning heat source replacement included a heat pump and photovoltaics installation. In the case analysed, applying additional thermal insulation to external walls was not proposed, as they were found to already meet building code requirements [62].

During the first stage, an analysis of alternative thermal retrofitting enhancements that did not include replacing the pre-existing gravity ventilation was performed. The enhancement alternatives have been presented in Table 6.

After the implementation of these proposals, the demand for thermal capacity and useable energy were calculated using Audytor OZC 7.0 Pro software. The results of the calculations are presented in Table 7 below.

The results showed that after implementing all the enhancements listed, the building's demand for thermal energy would decrease only by around 23%.

The high values of the heating system's components (high heat pump power, high building thermal energy demand, very high photovoltaic panel power) do not allow for using the solution in the entire building. This is why it was proposed to lower thermal energy consumption to cover ventilation losses by modernising the ventilation system from gravity-based to mechanical. The thermal retrofit alternatives that were further analysed have been presented in Table 8.

In the case of the modernisation of central heating and hot water systems, two concepts based on power supply from renewable energy sources (RES) have been proposed.

After performing thermal energy savings calculations for the alternatives, a cost analysis of each thermal retrofitting project alternative was performed using Simply Pay Back Time (SPBT). A comparison of optimal enhancements and projects, in ascending order based on SPBT values, have been presented below in Table 9.

$$SPBT = \frac{I}{E}\ [-] \tag{1}$$

where.

I – investment cost [PLN].

E – price savings [PLN].

By introducing mechanical ventilation, the useable energy demand declined by over 50%. The greatest potential for energy savings was identified in this thermal retrofitting alternative. The useful and final energy is presented in Fig. 6.

3.2.10. ventilation system modernisation

It was proposed to install individual supply-exhaust ventilation with heat recovery. This ventilation type allows users to lower energy consumption and provides them with better comfort and living conditions (it protects interiors from dust, noise and pollutants).

Ventilation units with an output of up to 150 m^3/h are recommended for residential units with a maximum floor area of 90 m^2.

The best place to install a ventilation control unit is a bathroom, as it is typically located in the centre of a residential unit, allowing for ease of installing supply ducts leading to each room and an exhaust duct into the kitchen (or a second duct into a bathroom). A bathroom can also feature an exhaust gravity ventilation duct, popularly called a vent, which can be used to dispose of used air. Fresh air intakes are best placed above balconies (unless a unit is located on the ground floor), as it would be easier to access them during installation and cleaning. Supply and exhaust ducts can be hidden using a gypsum board, for instance, by using a suspended ceiling or an imitation of a structural beam in the

Table 6
Thermal retrofitting enhancement alternatives.

Item no.	Thermal retrofitting enhancement	1	2	3	4	5
0	Original state (as encountered)	X	X	X	X	X
1	Domestic hot water preparation and central heating modernisation, heat pump and photovoltaic panel installation	X	X	X	X	X
2	Applying thermal insulation to the basement ceiling	X	X	X	X	
3	Replacement of windows in residential units (including window vents)	X	X	X		
4	Applying thermal insulation to the roof	X	X			
5	Replacement of windows in the circulation core	X				

Table 7
Thermal capacity and useable energy calculation results.

Alternative	Thermal capacity [MW]	Heat demand Q_H, [GJ/y]	Heat demand Q_H, [kWh/y]
1	0.1476	1,196	332
2	0.1482	1,204	334
3	0.1521	1,238	343
4	0.1701	1,390	386
5	0.1759	1,461	405
0 – original state	**0.1759**	**1,540**	**428**

Table 8
Thermal retrofitting project alternative definition.

Item no.	Thermal retrofitting enhancements	Alternative number					
		1	2	3	4	5a 5 b	6
0	Original state	X	X	X	X	X	X
1	Mechanical ventilation installation	X	X	X	X	X	X
2a	Domestic hot water preparation and central heating modernisation, heat pump and photovoltaic panel installation without energy storage	X	X	X	X	X	
2 b	Domestic hot water preparation and central heating modernisation, heat pump and photovoltaic panel installation include energy storage						
3	Applying thermal insulation to the basement ceiling	X	X	X	X		
4	Replacement of windows in residential units	X	X	X			
5	Applying thermal insulation to the roof	X	X				
6	Replacement of windows in the circulation core	X					

Table 9
Listing of optimal improvements and projects in ascending order of value SPBT.

Item no.	Type and scope of thermal retrofit improvement	Planned cost of works, PLN	SPB, y
1	Modernisation of gravitational ventilation	750,000	15
2a	Domestic hot water preparation and central heating modernisation, heat pump and photovoltaic panel installation – SYSTEM 1	1,624,744	17
2 b	Domestic hot water preparation and central heating modernisation, heat pump and photovoltaic panel installation, energy storage – SYSTEM 2	1,824,744	18
3	Applying thermal insulation to the basement ceiling	57,225	26
4	Replacement of windows in residential units	1,047,506	92
5	Applying thermal insulation to the roof	247,985	113
6	Replacement of windows in the circulation core	2,280	138

cornice area. Prior to building gypsum board covers, it is, of course, necessary to apply acoustic insulation to all ducts using mineral wool.

Gypsum board structures are also used to install supply and exhaust anemostats, which are vent endings with regulating throughput, via which air is supplied to a room and removed from another. The use of an exhaust duct to eject used air from a ventilation control unit is sometimes impossible in buildings where collective exhaust ventilation is installed (with rooftop ventilators). In such cases, both the intake and exhaust vents need to be installed in a residential unit's wall, which means that no exhaust ducts can be used.

3.2.11. *proposed heating system*

In the case of modernisation of central heating and hot water installations, two systems based on power supply from renewable energy sources (RES) have been proposed. A preliminary cost estimate is presented in the table below.

SYSTEM 1

The first proposed option for retrofitting the building heating network is based on a ground heat pump. Heating systems equipped with heat pumps are electric heating systems. In order to increase the ecological effect - lowering the demand for non-renewable primary energy for the building - it is beneficial to use the systems of obtaining electricity from RES. The most popular solution, in this case, is the photovoltaic installation. The power of the photovoltaic panels should be designed so that the amount of electricity produced from them covers the consumption of that energy by the heat pump.

The cooperation of the heat pump with the PV installation provides even complete coverage of the demand for thermal energy of the building from RES.

A comparison of thermal retrofit variant costs using System 1 has been presented in Table 10.

The schematic of SYSTEM 1, which produce energy for heating and domestic hot water, is presented in Fig. 7.

The selection of this system after thermal retrofitting for the analysed ZW70 building is presented below.

The system uses:

- A ground-source heat pump, which is powered by PV cells (PC power of about 150 kW)
- The power of PV panels needed to power the system is 52 kW at an average annual heating demand of the building $\Phi = 156$ MW h and the assumed COP coefficient = 3,
- The bottom source of the heat pump is the ground; the size of boreholes would be ca. 2.5 km (25 boreholes, 100 m each), assuming that for 1 m of boreholes, the heat power is 60 W,
- In order to prepare domestic hot water, a thermal buffer would be necessary.

SYSTEM 2

The second system, based on a heat pump heat source – the RESHeat system, is an innovative, zero-emission and autonomous energy system based only on Renewable Energy Sources (RES) installations. It is a more expensive system but with better energy efficiency, including thermal energy storage in underground tanks. Innovations in the system include integrated, cooled solar panels and solar collectors equipped with solar tracking systems, as well as advanced underground energy storage systems. The latter aim to achieve a high heat pump coefficient of performance over the long term, ensuring efficient underground energy storage while reducing the amount of energy consumed by the heat pump compressor. Additionally, the solution will allow the storage of heat from various sources, including low-temperature waste heat sources.

The main opportunities of the proposed solution are:

- Use of solar energy as the main source of renewable energy (RES),
- Generation of heat and electricity using PVT modules (thermal photovoltaics) of a new design,
- Use of PVT modules and vacuum tube solar collectors equipped with solar tracking systems to increase solar energy harvesting,
- Seasonal energy storage in underground heat storage facilities,
- Ground regeneration by means of low-temperature heat from the cooling of the PVT modules,
- Heating (possibly cooling) the building by means of a heat pump.

As the underground energy storage has been taken into account, the average annual efficiency of the heat pump has been increased (to approx. COP = 3.5). As a result, the output of the PV panels has been

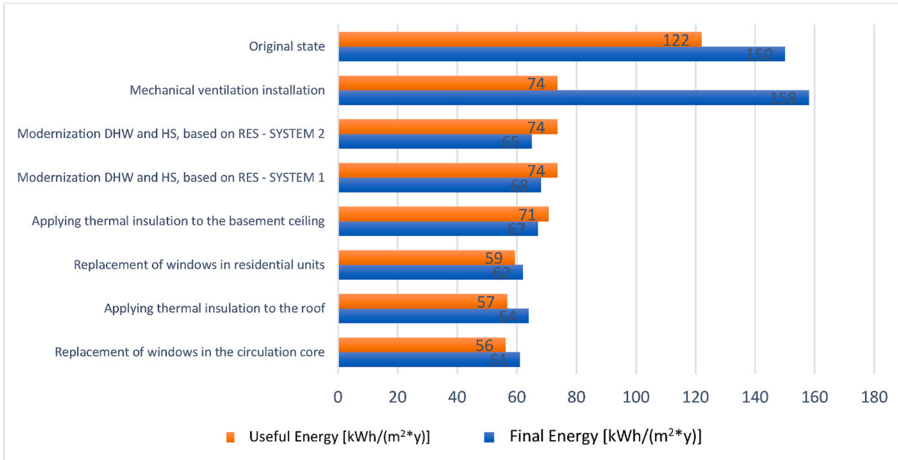

Fig. 6. The value of useful and final energy after thermal retrofitting.

Table 10
Comparison of costs of particular variants of thermal retrofit including costs of thermal retrofit audit – SYSTEM 1.

Item no.	Comparison of costs of each thermal retrofit variant, including costs of thermal retrofit audit - SYSTEM 1	Total cost [PLN]
1	1+2a+3 + 4+5 + 6	3,733,240
2	1+2a+3 + 4+5	3,730,960
3	1+2a+3 + 4	3,482,975
4	1+2a+3	2,435,469
5	1+2a	2,378,244
6	1	753,500

reduced compared to system 1.

The schematic of SYSTEM 2, which produce energy for heating and domestic hot water, is presented in Fig. 8. A price savings comparison between systems 1 and 2 has been shown in Fig. 9, while a comparison of thermal retrofit variant costs using System 2 has presented in Table 11.

The selection of heating equipment which the proposed RES-based heating system was as follows – System 2.

- Ground heat pump power – ca. 150 kW;
- Photovoltaic panel power required by the system was 45 kW with an average annual demand for thermal energy of $\Phi = 156$ MW h with COP = 3.5.
- The lower source for the heat pump is the soil, with a combined borehole length of ca. 2.5 km (25 boreholes, each 100 m long), with an assumption that every 1 m of borehole equals a thermal capacity of 60 W; the recommended distance between boreholes is 10 m (the acceptable minimum is 5 m). In order to drill the boreholes, geological analyses are necessary to verify the actual heat output from 1 linear metre of borehole and also whether groundwater is present,
- Energy storage in the form of a 100 m^3 tank;
- 12 rotating solar collectors.

After implementing the thermal retrofitting solutions, the building investigated would have:

- A RES share of 100%, up from 0% prior to retrofitting;
- A per unit share of CO2 emissions of 0, down from 0,044 tCO2/m2·y;
- A primary energy indicator of PE = 0, down from 144 kW h/m2·y.

The savings achieved by selecting these two concepts (System 1 and System 2) are shown below in The left-hand Y-axis of the graph shows the annual monetary saving after applying various thermal retrofit measures, and the right-hand Y-axis shows the energy savings in percentage terms. The COP efficiency of the heat pump was increased by using heat storage in a tank (System 2). This increased the cost of the installation but resulted in a reduction of heat energy consumption and reduced charges for hot water and central heating.

In the case of modernising central heating and domestic hot water generation installations, a proposal based on renewable energy sources (RES) was formulated.

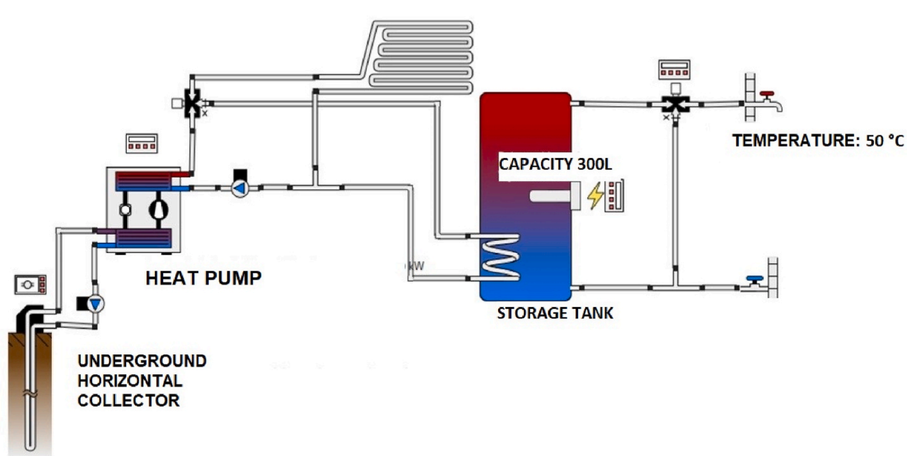

Fig. 7. An exemplary installation scheme of System 1, original image.

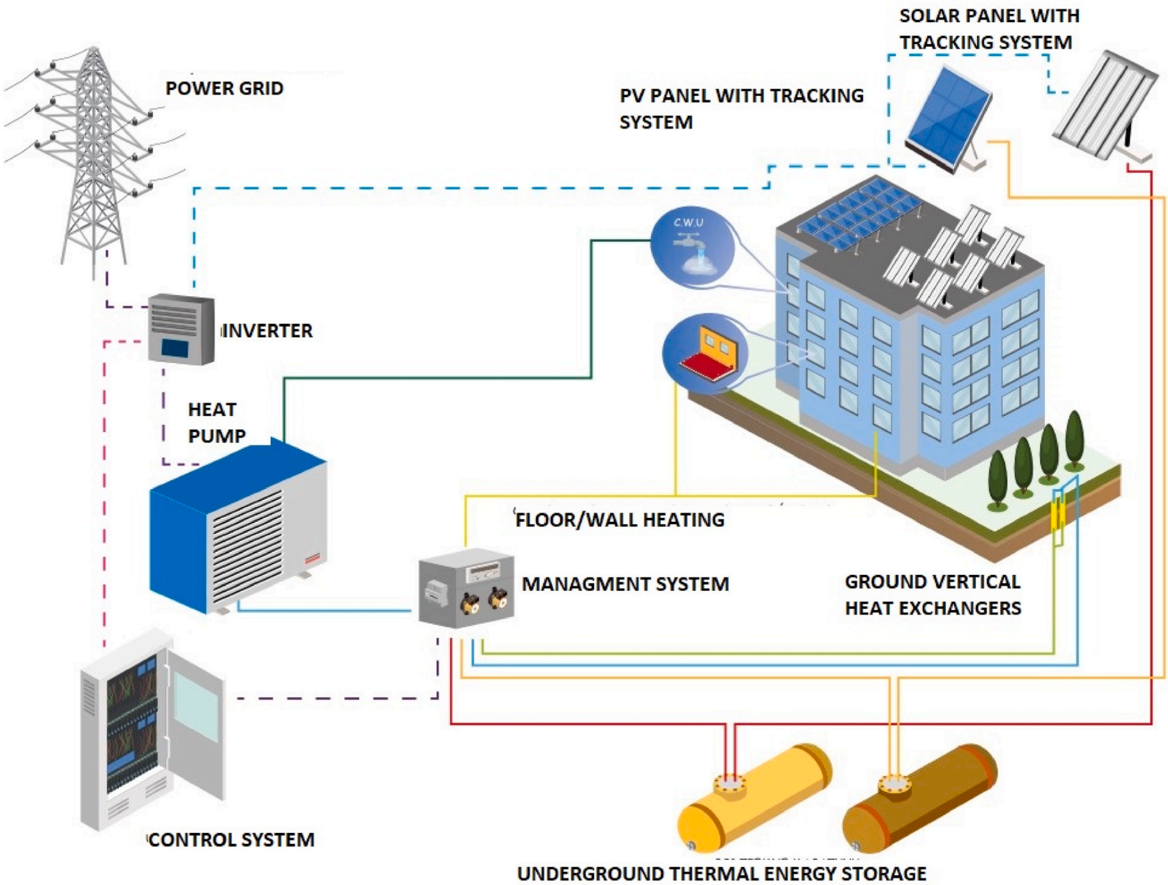

Fig. 8. An example installation scheme of System 2, original image.

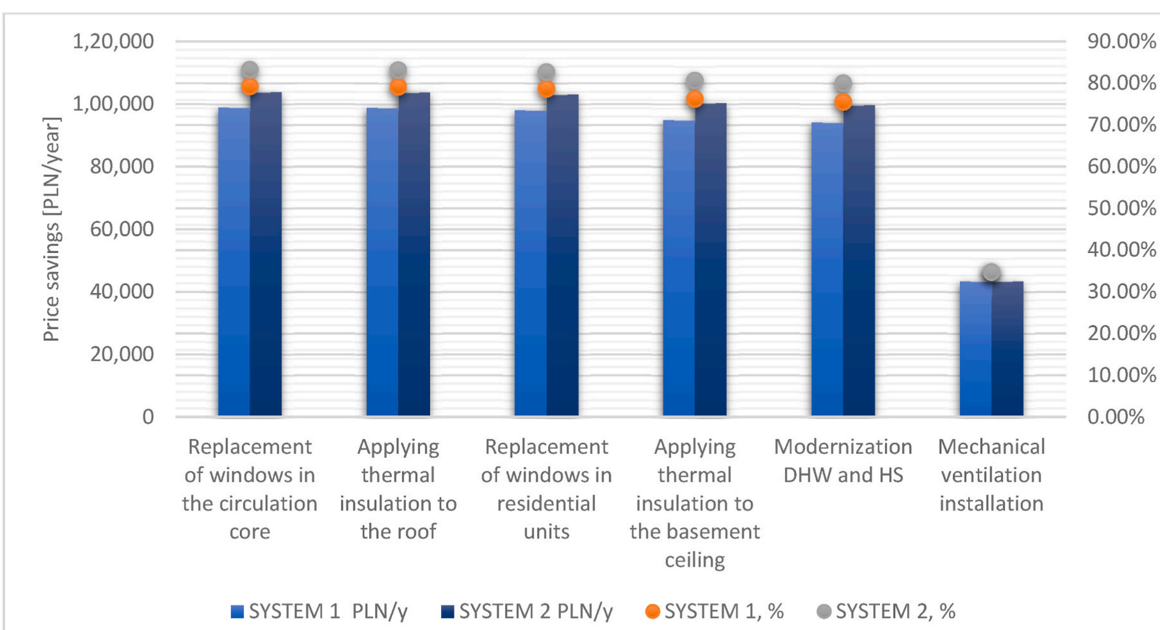

Fig. 9. Price savings after the thermal retrofitting enhancements, original image.

The proposed system is based solely on installations that utilise renewable energy sources (RES). It is an expensive system but offers better energy performance and also features thermal energy storage in the form of underground tanks. The system's novelty includes integrated, cooled solar panels and collectors equipped with a follow-up system that tracks the sun's position, as well as advanced underground energy storage systems. The objective of these storage systems is to attain a high heat pump performance level over the long term, which

Table 11
Comparison of costs of particular variants of thermal retrofit, including costs of thermal retrofit audit – SYSTEM 2.

Item no.	Comparison of costs of particular variants of thermal retrofit, including the cost of thermal retrofit audit - SYSTEM 2	Total cost [PLN]
1	1+2a+3 + 4+5 + 6	3,933,240
2	1+2a+3 + 4+5	3,930,960
3	1+2a+3 + 4	3,682,975
4	1+2a+3	2,635,469
5	1+2a	2,578,244
6	1	753,500

ensures effective underground energy storage while also lowering the amount of energy used by the heat pump's compressor. Additionally, this solution allows for storing heat from other sources, including low-temperature waste heat.

3.3. Economic analysis results

The results of the economic analysis have been presented in Table 12. It was found that despite assuming a relatively long analysis period, it was not possible to recoup the entire project cost from the savings provided by the retrofit. This means that the project must be funded from other sources. This applied to all the 22 alternative retrofit variants. The financing gap, depending on the retrofit variant, ranged between 823 k PLN for variant 6 without elevators – which are the most expensive accessibility solution and are not expressly required by Polish construction code in every circulation core and can be considered optional to a degree – to 4,122 thousand PLN for variant 2 with energy storage and elevators in every circulation core. Variant 6 only featured the installation of mechanical ventilation.

The results of the economic analysis for each alternative have been presented in Table 12 with an indication of whether a given alternative featured a RES-based system with energy storage and elevators, as these were the two most expensive elements. A complete listing of the alternatives and their results can be made available by the authors upon request.

Table 12
Economic analysis results.

Retrofit alternative number	RES system with energy storage	Elevators	Project cost [PLN]	Portion of the cost covered by savings [PLN]	Financing gap [PLN]
1	✓	✓	5,875,214	1,753,217	4,121,997
1	✓	x	4,708,840	1,753,217	2,955,623
1	X	✓	5,675,214	1,677,875	3,997,339
1	X	x	4,508,840	1,677,875	2,830,965
2	✓	x	5,872,934	1,750,468	4,122,466
2	✓	x	4,706,560	1,750,468	2,956,092
2	X	✓	5,672,934	1,674,676	3,998,257
2	X	x	4,506,560	1,674,676	2,831,884
3	✓	✓	5,624,949	1,737,511	3,887,438
3	✓	x	4,458,575	1,737,511	2,721,064
3	X	✓	5,424,949	1,659,596	3,765,353
3	X	x	4,258,575	1,659,596	2,598,979
4	✓	✓	4,577,443	1,681,756	2,895,687
4	✓	x	3,411,069	1,681,756	1,729,313
4	X	✓	4,377,443	1,594,704	2,782,738
4	X	x	3,211,069	1,594,704	1,616,365
5	✓	✓	4,520,218	1,667,228	2,852,990
5	✓	x	3,353,844	1,667,228	1,686,616
5	X	✓	4,320,218	1,577,796	2,742,422
5	X	x	3,153,844	1,577,796	1,576,048
6	X	✓	2,695,474	705,783	1,989,690
6	X	x	1,529,100	705,783	823,317

3.3.1. Summary

A site plan of the project site, including the most robust thermal retrofit, accessibility and NBS proposals combined into one, has been shown in Fig. 10.

4. Discussion

The proposed approach was validated using Krakow as a case city. The building identification algorithm was used to find and select a building for the formulation of detailed, RES-based thermal retrofit solutions coupled with environmental and accessibility intervention measures that can be easily reapplied to other buildings in the same complex and, with little modification, to other buildings constructed using the same or similar panel-block systems, with the number of such buildings potentially being in the tens of thousands in Poland alone. The validation can be considered successful, and the proposed solutions are applicable to real-world mass thermal retrofit and urban renewal scenarios.

In the case of modernising multifamily residential buildings, the chief challenge is to reduce non-renewable primary energy. To this end, it is necessary to replace heat sources for central heating and domestic hot water installations and implement RES and energy storage. The heating system proposed in this study is an energy trigeneration system, which uses RES to produce electrical power, heat and cooling for use in residential, commercial and public buildings. However, costs are important aspects of such retrofits, as it is a well-established fact that any RES-based installations and energy storage solutions are expensive.

The period when this study was conducted should be kept in mind when interpreting its findings, as two historical events may be seen as affecting them. The financial analysis allows a glimpse into the degree of funding that must be procured to implement the presented solutions. However, its results must be approached with caution due to the global economic and supply-chain instability caused by the Russian Federation–Ukraine War, as the financial data used in the study was from the fourth quarter of 2021 – prior to the conflict, when the geopolitical tensions surrounding its inception had not yet made a major impact. Likewise, the results of the social analysis were affected by the COVID-19 pandemic and some of the criteria, such as the desirability of balconies – while still worthy of accounting for – may not be given as much weight after the pandemic's conclusion.

In light of the above, this study can be seen as significant in that, by facilitating mass, RES-based thermal retrofitting of a large segment of the housing stock, the approach proposed could also contribute to lessening the reliance on grid-sourced energy and enhancing energy security. This is important due to the instability of the energy market that has been observed as a result of recent geopolitical developments.

We see two main methodological limitations in our approach that can be seen as affecting the scale on which it may be applied. The first limitation is reliance on GIS data in the initial building search. Some municipalities, especially smaller ones, may not possess such data, or it may come in a form that is difficult to process. This may limit the applicability of the methodology to bigger cities that operate GIS data repositories. This limitation is also tied to the composition of GIS data available, as some municipalities or, indeed, entire countries may have different standards on what data is stored and how it can be accessed.

The second limitation is the potential ineffectiveness at the interface between the social analysis and design documentation procurement stages, which requires cooperation from stakeholders – housing co-operatives, homeowners' associations and other such institutions in charge of managing specific buildings or complexes. Due to the organisational structure of these actors and the varying documentation archiving standards they may follow, procuring documentation may prove difficult in some cases and would require more comprehensive existing condition reports and surveying.

The approach proposed is not exclusively tailored to Polish conditions and should be successfully used in other countries that feature

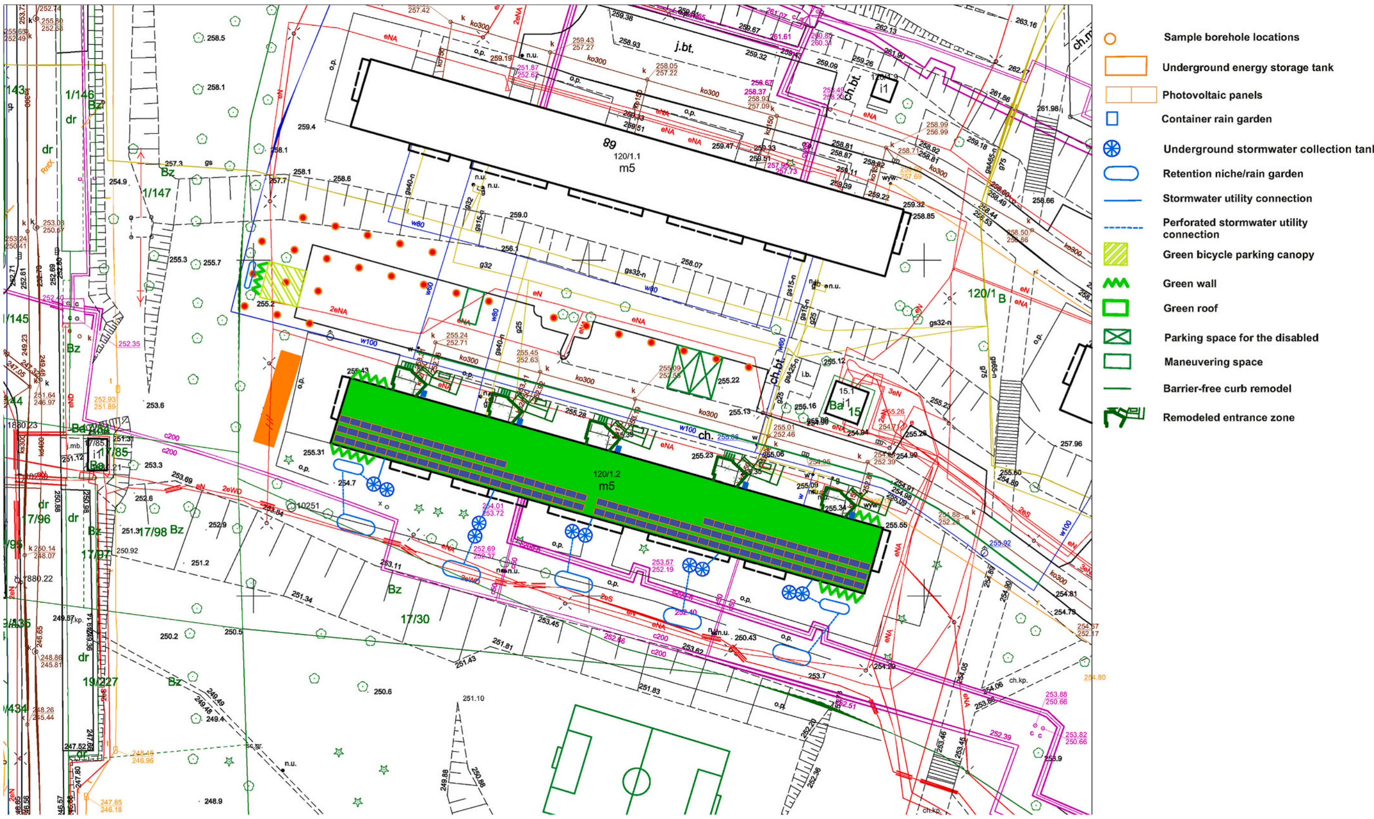

Fig. 10. Proposed solutions are presented on a survey map of the building and its site, original image

similar large complexes of panel-block housing in need of thermal retrofitting and accessibility enhancement and that operate publicly accessible GIS data repositories that can be used to identify a building's construction date and its number of storeys. The methodology can accommodate a wide range of post-Second-World-War panel-block technologies and is formulated specifically to be flexible in this regard, featuring the assessment of buildings in the form of existing condition reports, energy audits and, where available, design documentation reviews.

5. Conclusions

The comprehensive retrofit and regeneration solutions proposed can be an attractive solution to combating climate change and prolonging the service life of Central and Eastern European housing stock dating to the 1960s and 1970s, contributing to implementing sustainability policies and combating climate change over the long term.

This study's achievements have been listed below:

- The formulation of a multidisciplinary model of mass building thermal retrofitting is developed and presented on a case study of Krakow;
- The model allows to perform of large-scale thermal retrofitting of panel-block buildings, which form substantial shares of Central and Eastern European housing stocks;
- Two Renewable-Energy-Based Heating systems were studied as a solution for prefabricated housing, including social housing. The results show that it is possible to eliminate energy demand from external sources in the buildings investigated. Once the recommended changes are taken into account, energy consumption savings would decrease by more than 80%. In the first proposed heating system without storage energy, the cost is lower than the second system, but the savings from SYSTEM 2 (RESHeat) are about 5%.
- Novel thermal retrofit approaches are combined with accessibility and nature-based solutions, offering a robust and holistic package that can prove useful in combating climate change.

The solutions proposed are aligned with major global climate change prevention and alleviation strategies, focusing on RES-based thermal retrofitting, cooling urban space using greenery, and flood prevention via surface runoff retention enhancement. They can also improve the comfort of living of building users by improving accessibility and making spaces friendlier to pedestrians and cyclists, lessening the need for vehicle use. The financial analysis presented can aid in informing stakeholders on the costs of each section of the proposal and, depending on the area they may wish to emphasise in their projects, allow them to make informed decisions. i.e., whether they want to focus on investing in the thermal retrofit and minimize accessibility and greening or apply all elements to their full extent.

Future research should focus on attempts at adapting the solutions proposed to other climates and housing typologies, as standardised prefabricated housing was implemented in many places across the world, not just Central and Eastern Europe, which shows the substantial potential of engaging in this research and the benefits that it can bring. In addition, energy planning for buildings has to be developed, following the example of Mohammad Rozali et al. [63]. After the methodology is matured, it can be propagated to countries like China, where many buildings from the initial socialist period still remain, and new buildings are built at a high pace. The planning has to account for the water-energy-emission nexus [64]. Process Integration tools [65] can be considered for identifying advantageous energy and emission reduction options.

Credit author contributions

Krzysztof Barnaś: Writing—original draft, Data Curation, Resources, Investigation, Writing—review and editing, Tomasz Jeleński: Data Curation, Investigation, Writing—review and editing, Marzena Nowak-Ocłoń: Data Curation, Formal Analysis Writing—original draft, Writing—review and editing, Kinga Racoń-Leja: Conceptualisation, Methodology, Data Curation, Elżbieta Radziszewska-Zielina: Conceptualisation, Project Administration, Data Curation, Bartłomiej Szewczyk: Formal Analysis, Data Curation, Validation, Grzegorz Śladowski: Formal Analysis, Data Curation, Validation, Cezary Toś: Formal Analysis, Investigation, Data Curation, Petar Sabev Varbanov: Validation, Supervision, Writing—review and editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Krzysztof Barnas reports financial support was provided by Municipality of Krakow. Elzbieta Radziszewska-Zielina reports was provided by Municipality of Krakow. Kinga Racoń-Leja reports was provided by Municipality of Krakow. Tomasz Jelenski reports financial support was provided by Municipality of Krakow. Grzegorz Sladowski reports financial support was provided by Municipality of Krakow. Bartlomiej Szewczyk reports financial support was provided by Municipality of Krakow. Cezary Tos reports financial support was provided by Municipality of Krakow. Marzena Nowak-Ocło reports financial support was provided by Municipality of Krakow, Petar Sabev Varbanov acknowledges the financial support was provided by the European Commission under the RESHeat project on the basis of Grant Agreement No. 956255.

Data availability

Data will be made available on request.

Acknowledgements

We would like to sincerely thank Andrzej Łazęcki, Director of the Department of Municipal Management of the City of Krakow, for his support and for providing access to crucial data and documentation. We would also like to express our gratitude to the Municipality of Krakow and the Climate-KIC team for their fruitful cooperation. This research was supported by the Municipality of Krakow and carried out within the framework of the Centre for Scientific Research Development of the Cracow University of Technology by researchers from the Process Engineering in Sustainable Construction interdisciplinary research group (contract no. W/1/2838/GK/22/2021, internal no. R-14/244/2021/D, project manager: Professor Elżbieta Radziszewska-Zielina). The RESHeat system presented in this article is being developed as a part of the RESHeat project funded by the European Commission's Horizon 2020 programme under grant agreement no. 956255 (project scientific and technical coordinator: Professor Paweł Ocłoń).

References

[1] IPCC. Climate change 2022: climate change 2022: Mitigation of climate change. Contribution of working group III to the sixth assessment report of the intergovernmental panel on climate change. Cambridge, UK and New York, US: Cambridge University Press; 2020. https://www.ipcc.ch/report/ar6/wg3/. [Accessed 5 October 2022]. accessed.
[2] United Nations Environment Programme. Global status report for buildings and construction:towards a zero-emission, efficient and resilient buildings and construction sector. Nairobi, https://globalabc.org/sites/default/files/inline-files/2020%20Buildings%20GSR_FULL%20REPORT.pdf; 2020. accessed 5 October 2022.
[3] Europa.eu. A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives. 2022. https://ec.europa.eu/energy/sites/ener/files/eu_renovation_wave_strategy.pdf. accessed 5 October 2022.
[4] Mańkowski E, Szczechowiak S. Integrated system to reduce operational energy intensity of buildings. Poland: Politechnika Poznańska; 2013. 2013.
[5] Grimshaw H, Aktinson J. A Community Approach to Retrofit and Potential Implications for the Fuel Poverty Agenda. Manchester: URBED Ltd and Carbon Co-op. Manchester: URBED Ltd and Carbon Co-op; 2015. http://urbed.coop/sites/default/files/20150923_Chesshire%20Lehmann%20final%20report_0.pdf. [Accessed 5 October 2022].
[6] Flamant G, Bustamante W, Schmitt C, Bunster V, Osorio C. Thermal and environmental evaluation of mid-rise social housing retrofit under different climate conditions. J Build Eng 2022;46:103724. https://doi.org/10.1016/j.jobe.2021.103724.
[7] Mikulić D, Slijepčević S, Buturac G. Energy renovation of multi apartment buildings: contributions to economy and climate changes. Energy Build 2020;224:110247. https://doi.org/10.1016/j.enbuild.2020.110247.
[8] Lee J, McCuskey Shepley M, Choi J. Exploring the effects of a building retrofit to improve energy performance and sustainability: a case study of Korean public buildings. J Build Eng 2019;25:100822. https://doi.org/10.1016/j.jobe.2019.100822.
[9] Masson V, Marchadier C, Adolphe L, Aguejdad R, Avner P, Bonhomme M, et al. Adapting cities to climate change: a systemic modelling approach. Urban Clim 2014;10:407–29. https://doi.org/10.1016/j.uclim.2014.03.004.
[10] Sadowska B. Effects of deep thermal modernization and use of renewable energy in public buildings in North-Eastern Poland. Latvia University of Agriculture; 2018. https://doi.org/10.22616/ERDev2018.17.N447.
[11] Wang Q, Holmberg S. A methodology to assess energy-demand savings and cost effectiveness of retrofitting in existing Swedish residential buildings. Sustain Cities Soc 2015;14:254–66. https://doi.org/10.1016/j.scs.2014.10.002.
[12] Wang Q, Ploskić A, Song X, Holmberg S. Ventilation heat recovery jointed low-temperature heating in retrofitting—an investigation of energy conservation, environmental impacts and indoor air quality in Swedish multifamily houses. Energy Build 2016;121:250–64. https://doi.org/10.1016/j.enbuild.2016.02.050.
[13] Sadowska B, Piotrowska-Woroniak J, Woroniak G, Sarosiek W. Energy and economic efficiency of the thermomodernization of an educational building and reduction of pollutant emissions—a case study. Energies 2022;15:2886. https://doi.org/10.3390/en15082886.
[14] Tunzi M, Østergaard DS, Svendsen S, Boukhanouf R, Cooper E. Method to investigate and plan the application of low temperature district heating to existing hydraulic radiator systems in existing buildings. Energy (Oxf) 2016;113:413–21. https://doi.org/10.1016/j.energy.2016.07.033.
[15] Benakopoulos T, Tunzi M, Salenbien R, Svendsen S. Strategy for low-temperature operation of radiator systems using data from existing digital heat cost allocators. Energy (Oxf) 2021;231:120928. https://doi.org/10.1016/j.energy.2021.120928.
[16] Lund H, Duic N, Østergaard PA, Mathiesen BV. Future district heating systems and technologies: on the role of smart energy systems and 4th generation district heating. Energy (Oxf) 2018;165:614–9. https://doi.org/10.1016/j.energy.2018.09.115.
[17] Buffa S, Cozzini M, D'Antoni M, Baratieri M, Fedrizzi R. 5th generation district heating and cooling systems: a review of existing cases in Europe. Renew Sustain Energy Rev 2019;104:504–22. https://doi.org/10.1016/j.rser.2018.12.059.
[18] Calame N, Freyre A, Rognon F, Callegari S, Rüetschi M. Air to water heat pumps for heating system retrofit in urban areas: understanding the multi-faceted challenge. J Phys Conf Ser 2019;1343:012079. https://doi.org/10.1088/1742-6596/1343/1/012079.
[19] Lämmle M, , Bongs C, Wapler J, Günther D, Hess S, Kropp M, et al. Performance of air and ground source heat pumps retrofitted to radiator heating systems and measures to reduce space heating temperatures in existing buildings. Energy 2022;242:122952. https://doi.org/10.1016/j.energy.2021.122952. Oxf.
[20] Mauri L, Vallati A, Ocłoń P. Low impact energy saving strategies for individual heating systems in a modern residential building: a case study in Rome. J Clean Prod 2019;214:791–802. https://doi.org/10.1016/j.jclepro.2018.12.320.
[[2][1] Heinz A, Rieberer R. Energetic and economic analysis of a PV-assisted air-to-water heat pump system for renovated residential buildings with high-temperature heat emission system. Appl Energy 2021;293:116953. https://doi.org/10.1016/j.apenergy.2021.116953.
[22] Fraga C, Hollmuller P, Schneider S, Lachal B. Heat pump systems for multifamily buildings: potential and constraints of several heat sources for diverse building demands. Appl Energy 2018;225:1033–53. https://doi.org/10.1016/j.apenergy.2018.05.004.
[23] Kowalski P, Szałański P, Cepiński W. Waste heat recovery by air-to-water heat pump from exhausted ventilating air for heating of multi-family residential buildings. Energies 2021;14:7985. https://doi.org/10.3390/en14237985.
[24] Hosseinnia SM, Sorin M. Energy targeting approach for optimum solar assisted ground source heat pump integration in buildings. Energy (Oxf) 2022;248:123528. https://doi.org/10.1016/j.energy.2022.123528.
[25] Ocłoń P, Ławryńczuk M, Czamara M. A new solar assisted heat pump system with underground energy storage: modelling and optimisation. Energies 2021;14:5137. https://doi.org/10.3390/en14165137.
[26] Orlik-Kożdoń B, Radziszewska-Zielina E, Fedorczak-Cisak M, Steidl T, Białkiewicz A, Żychowska M, et al. Historic building thermal diagnostics algorithm presented for the example of a townhouse in Lviv. Energies 2020;13:5374. https://doi.org/10.3390/en13205374.
[27] Piasecki M, Radziszewska-Zielina E, Czerski P, Fedorczak-Cisak M, Zielina M, Krzyściak P, et al. Implementation of the indoor environmental quality (IEQ) model for the assessment of a retrofitted historical masonry building. Energies 2020;13:6051. https://doi.org/10.3390/en13226051.
[28] Fedorczak-Cisak M, Radziszewska-Zielina E, Orlik-Kożdoń B, Steidl T, Tatara T. Analysis of the thermal retrofitting potential of the external walls of Podhale's historical timber buildings in the aspect of the non-deterioration of their technical condition. Energies 2020;13:4610. https://doi.org/10.3390/en13184610.
[29] Jelenski T, editor. Renovation and retrofitting of old buildings in times of climate crisis. Warsaw: Sendzimir Foundation and Croatia Green Building Council; 2022.

https://sendzimir.org.pl/en/projects/climate-mitigation-in-heritage-buildings/renovation-and-retrofitting-of-old-buildings-in-times-of-climate-crisis/. [Accessed 10 October 2022].

[30] Tofiluk A, Knyziak P, Krentowski J. Revitalization of twentieth-century prefabricated housing estates as interdisciplinary issue. IOP Conf Ser Mater Sci Eng 2019;471:112096. https://doi.org/10.1088/1757-899x/471/11/112096.

[31] Erba S, Barbieri A. Retrofitting buildings into thermal batteries for demand-side flexibility and thermal safety during power outages in winter. Energies 2022;15: 4405. https://doi.org/10.3390/en15124405.

[32] RPO reiterates plea for full access to public facilities and multi-family homes for people with disabilities. Gov.pl; 2022. https://bip.brpo.gov.pl/pl/content/rpo-ponownie-upomina-sie-o-pelny-dostep-osob-z-niepelnosprawnosciami-do-obiektow-uzytecznosci-publicznej%20i%20domow. [Accessed 5 October 2022]. accessed.

[33] Xing Y, Jones P, Donnison I. Characterisation of nature-based solutions for the built environment. Sustainability 2017;9:149. https://doi.org/10.3390/su9010149.

[34] Chan EHW, Lee GKL, Chan ATS. Universal design for people with disabilities: a study of access provisions in public housing estates. Property Manag 2009;27: 138–46. https://doi.org/10.1108/02637470910946435.

[35] Naumann S, Davis M, Iwaszuk E, Freundt M, Mederake L. Addressing climate change in cities: policy instruments to promote urban nature-based solutions. Poland: Ecologic Institute, the Sendzimir Foundation; 2020. Berlin-Kraków.

[36] Majidi Vojinovic, Alves Weesakul, Sanchez Boogaard, et al. Planning Nature-Based Solutions for urban flood reduction and thermal comfort enhancement. Sustainability 2019;11:6361. https://doi.org/10.3390/su11226361.

[37] Zielina M, Bielski A, Młyńska A. Leaching of chromium and lead from the cement mortar lining into the flowing drinking water shortly after pipeline rehabilitation. J Clean Prod 2022;362:132512. https://doi.org/10.1016/j.jclepro.2022.132512.

[38] Lee JY, Yim T. Energy and flow demand analysis of domestic hot water in an apartment complex using a smart meter. Energy 2021;229:120678. https://doi.org/10.1016/j.energy.2021.120678.

[39] Zwierzchowska I, Haase D, Dushkova D. Discovering the environmental potential of multi-family residential areas for nature-based solutions. A Central European cities perspective. Landsc Urban Plann 2021;206:103975. https://doi.org/10.1016/j.landurbplan.2020.103975.

[40] Badiu DL, Onose DA, Niță MR, Lafortezza R. From "red" to green? A look into the evolution of green spaces in a post-socialist city. Landsc Urban Plann 2019;187: 156–64. https://doi.org/10.1016/j.landurbplan.2018.07.015.

[41] Schmid H-L, Säumel I. Outlook and insights: perception of residential greenery in multistorey housing estates in Berlin, Germany. Urban For Urban Greening 2021; 63:127231. https://doi.org/10.1016/j.ufug.2021.127231.

[42] Tepanosyan G, Muradyan V, Hovsepyan A, Pinigin G, Medvedev A, Asmaryan S. Studying spatial-temporal changes and relationship of land cover and surface Urban Heat Island derived through remote sensing in Yerevan, Armenia. Build Environ 2021;187:107390. https://doi.org/10.1016/j.buildenv.2020.107390.

[43] Yang J, Shi Q, Menenti M, Xie Y, Wu Z, Xu Y, et al. Characterizing the thermal effects of vegetation on urban surface temperature. Urban Clim 2022;44:101204. https://doi.org/10.1016/j.uclim.2022.101204.

[44] Gronostajska BE, Politechnika Wrocławska Wydział Architektury Katedra Projektowania Architektoniczo-Konstrukcyjnego. Seniors in the Popowice housing estate in Wrocław – selected issues. Space & FORM 2020;2020:23–44. https://doi.org/10.21005/pif.2020.44.b-02.

[45] Kobryń A. Multi-criteria decision support in land management. Warszawa, Poland: Difin publishing press; 2014.

[46] Bucoń R, Sobotka A. Determining the scope of renovation of a residential building. Budownictwo i Architektura 2013;12(1):15–22.

[47] Behzadian M, Khanmohammadi Otaghsara S, Yazdani M, Ignatius J. A state-of the-art survey of TOPSIS applications. Expert Syst Appl 2012;39:13051–69. https://doi.org/10.1016/j.eswa.2012.05.056.

[48] Zyoud SH, Fuchs-Hanusch D. A bibliometric-based survey on AHP and TOPSIS techniques. Expert Syst Appl 2017;78:158–81. https://doi.org/10.1016/j.eswa.2017.02.016.

[49] Radziszewska-Zielina E, Śladowski G. Proposal of the use of a fuzzy stochastic network for the preliminary evaluation of the feasibility of the process of the adaptation of a historical building to a particular form of use. IOP Conf Ser Mater Sci Eng 2017;245:072029. https://doi.org/10.1088/1757-899x/245/7/072029.

[50] Radziszewska-Zielina E, Śladowski G. Supporting the selection of a variant of the adaptation of a historical building with the use of fuzzy modelling and structural analysis. J Cult Herit 2017;26:53–63. https://doi.org/10.1016/j.culher.2017.02.008.

[51] Zhou P, Ang B, Poh K. Decision analysis in energy and environmental modeling: an update. Energy 2006;31:2604–22. https://doi.org/10.1016/j.energy.2005.10.023.

[52] Hosseini Dehshiri SS. A new application of multi criteria decision making in energy technology in traditional buildings: a case study of Isfahan. Energy 2022;240: 122814. https://doi.org/10.1016/j.energy.2021.122814.

[53] Ostańska A. Technical condition and energy analysis as basic aspects for the revitalisation of housing estates with large-plate buildings. Przegląd Budowlany 2009;9:40–7.

[54] Tiller J, Gowings S. Book review: barrier-free design, A manual for building designers and managers. Br J Occup Ther 1998;61:134. https://doi.org/10.1177/030802269806100315. 134.

[55] Rickert T. BRT accessibility guidelines. Washington, USA: The World Bank; 2007.

[56] Calheiros CSC, Stefanakis AI. Green roofs towards circular and resilient cities. Circ Econ Sustain 2021;1:395–411. https://doi.org/10.1007/s43615-021-00033-0.

[57] Kasprzyk M, Szpakowski W, Poznańska E, Boogaard FC, Bobkowska K, Gajewska M. Technical solutions and benefits of introducing rain gardens - gdańsk case study. Sci Total Environ 2022;835:155487. https://doi.org/10.1016/j.scitotenv.2022.155487.

[58] Wan S, Xu L, Qi Q, Yang H, Zhou Y. Building a multi-objective optimization model for Sponge City projects. Urban Clim 2022;43:101171. https://doi.org/10.1016/j.uclim.2022.101171.

[59] Akalu MM. Re-examining project appraisal and control: developing a focus on wealth creation. Int J Proj Manag 2001;19:375–83. https://doi.org/10.1016/s0263-7863(00)00019-3.

[60] Statistics Poland. Information on the results of the results of the national population and housing census. 2021. https://stat.gov.pl/spisy-powszechne/nsp-2021/nsp-2021-wyniki-ostateczne/informacja-o-wynikach-narodowego-spisu-powszechnego-ludnosci-i-mieszkan-2021-na-poziomie-wojewodztw-powiatow-i-gmin. accessed 5 October 2022.

[61] SARP. Modernist housing estates of the 20th century, 5.12 Mistrzejowice. http://www.sarp.krakow.pl/sd/om/012/index.html. [Accessed 5 October 2022]. accessed.

[62] Poland WK. Amendment of the Regulation on technical conditions to be met by buildings and their location. OpenLEX n.d. https://sip.lex.pl/akty-prawne/dzu-dziennik-ustaw/zmiana-rozporzadzenia-w-sprawie-warunkow-technicznych-jakim-powinny-19201384. accessed 5 October 2022

[63] Wang X-C, Klemeš JJ, Wang Y, Dong X, Wei H, Xu Z, et al. Water-Energy-Carbon Emissions nexus analysis of China: an environmental input-output model-based approach. Appl Energy 2020;261:114431. https://doi.org/10.1016/j.apenergy.2019.114431.

[64] Manan ZA, Mohd Nawi WNR, Wan Alwi SR, Klemeš JJ. Advances in Process Integration research for CO_2 emission reduction – a review. J Clean Prod 2017;167: 1–13. https://doi.org/10.1016/j.jclepro.2017.08.138.

[65] Mohammad Rozali NE, Wan Alwi SR, Abdul Manan Z, Klemeš JJ, Hassan MY. Optimal sizing of hybrid power systems using power pinch analysis. J Clean Prod 2014;71:158–67. https://doi.org/10.1016/j.jclepro.2013.12.028.