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Energy and Ecological Concept of a Zero-Emission Building Using Renewable Energy Sources—Case Study in Poland

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Abstract: Zero-emission buildings, which do not emit CO_2 or other greenhouse gases throughout their entire life cycle, play a crucial role in sustainable development and the fight against climate change. Achieving carbon neutrality in construction requires considering emissions associated with material production, construction, operation, as well as demolition and disposal. These buildings utilize energy-efficient technologies, renewable energy sources, and low-carbon materials, minimizing their environmental impact. The building sector accounts for a significant percentage of global greenhouse gas emissions, making it a key area for climate action. In Poland, where aging and energy-inefficient buildings prevail, the need for a transition towards zero-emission buildings is particularly urgent. This paper assesses the feasibility and hurdles of retrofitting existing buildings to achieve zero emissions by utilizing renewable energy systems like solar photovoltaic and heat pump technologies. The publication discusses the technical, economic, and legal aspects of this transformation, with particular emphasis on the Polish context and available support programs. The purpose of this publication is to disseminate practical knowledge and foster innovation among architects, investors, and decision-makers engaged in the development of a sustainable built environment. A key example is Net Zero Energy Buildings (NZEBs), which generate as much energy as they consume over a year through technologies such as photovoltaic panels, solar collectors, and heat pumps. NZEBs combine effective insulation, energy-efficient systems, and smart energy management to minimize consumption, and may even produce excess energy that feeds back into the grid. Despite challenges in construction and maintenance, the increasing adoption of zero-emission and NZEBs worldwide reflects their long-term ecological, economic, and health benefits. The focus of this publication is to analyze the potential for transforming standard buildings, as defined by current regulations, into zero-emission buildings powered entirely by renewable energy sources. This case study analyzes the energy potential of a residential building located in Krakow, Poland. The building's energy efficiency potential was assessed through computer simulations using Audytor OZC software (version 7.0 Pro, Sankom), taking into account local climate conditions and building standards. The study analyzed the impact of various strategies, such as upgrading thermal insulation, using energy-efficient windows, and installing photovoltaic panels, on energy consumption and CO_2 emissions.

Keywords: zero-emission buildings; net-zero energy buildings; renewable energy sources; energy efficiency; heat pump; photovoltaics

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1. Introduction

The urgency of combating climate change has placed the building sector in the spotlight. The building sector's contribution to climate change is immense, responsible for around 40% of energy use and 36% of CO_2 emissions in Europe. Its decarbonization is not merely preferable, but essential for mitigating the climate crisis. This is particularly critical in Poland, where a significant portion of the building stock is outdated and energy-inefficient. The European Union's ambitious goal of climate neutrality by 2050 is driving a profound transformation in the construction market. Companies and institutions are embracing decarbonization strategies, spurring innovation in building materials, design processes, and energy sources. This change is necessary because all stages of a building's life cycle, from manufacturing materials to dismantling, have environmental consequences. Traditional construction methods, heavily reliant on fossil fuels, release harmful substances into the air, water, and soil. Zero-emission buildings offer a powerful solution. By harnessing renewable energy sources like photovoltaics and heat pumps, these buildings minimize their environmental footprint. They prioritize natural and biodegradable materials, implement water-saving systems, and employ advanced insulation and ventilation techniques. This publication delves into the potential of zero-emission buildings to revolutionize the Polish construction industry. We explore the technical, economic, and legal aspects of transforming existing buildings and constructing new ones that contribute to a sustainable future. Our aim is to provide valuable insights and inspire architects, investors, and policy-makers to embrace this crucial step towards a greener built environment. The construction market is undergoing a transformation process geared towards the implementation of the European Union's strategy of becoming climate neutral by 2050. More and more measures are being taken with a view to developing a green and sustainable construction sector. Various companies and institutions related to the construction industry and the real estate market are adopting decarbonization strategies and implementing initiatives towards climate neutrality. Widespread transformation-oriented actions have become necessary, especially the modification of the approach to the manufacture of building materials, the designing and construction processes, as well as the use of individual sources of energy. After all, the construction of any building involves enormous interference with nature. Every phase of construction, from the sourcing and delivery of materials to readying the building site, contributes to the release of detrimental substances into the environment. Hence, a great deal of importance has been attached to replacing the fossil fuel-dependent methods used so far with environmentally friendly and zero-emission methods. Zero-emission houses and buildings are erected using modern technologies based on natural and biodegradable materials, systems for saving drinking water and storing rainwater, as well as adequate heat insulation and ventilation techniques. In this context, the concept of zero-emission buildings takes on particular importance as a key element in reducing energy consumption and greenhouse gas emissions and becomes not only a priority but also an integral part of the future of the construction industry.

The European Green Deal and Renovation Wave Strategy place a strong emphasis on sustainable construction and renovation practices to address the pressing need for energy and resource efficiency. The European Commission indicates that achieving zero-carbon status in new buildings requires the use of renewable energy sources. This shift towards ecological construction practices has profound implications for the economy, climate, and public health. Constructing zero-emission buildings presents a significant challenge for EU citizens, but the benefits of owning and inhabiting such buildings are numerous. These benefits extend beyond individual homeowners to encompass sectoral, national, and international advantages, as highlighted by the International Energy Agency (IEA). The scale of these benefits is influenced by factors such as a country's economic structure and government policies [1,2].

This article investigates practical strategies for reducing energy consumption and enhancing energy efficiency in buildings to mitigate climate change. We explore tangible methods for achieving these goals through sustainable construction techniques. This study utilizes energy calculations that comply with relevant European and Polish standards. These standards include European directives on nearly zero-energy and zero-emission buildings, as well as Polish regulations concerning design heating load and various energy performance indicators (final, useful, and non-renewable primary energy).

2. Review of Literature, State Policy and External Funds

As a major contributor to environmental issues, the construction sector presents a vital opportunity for implementing sustainable development strategies [3]. The construction industry and building resources are very energy intensive and cause significant greenhouse gas emissions. The production, installation, transportation, and disposal of building materials consume enormous amounts of energy [4,5]. This sector has a large, multidimensional impact on the environment, both in terms of energy consumption (it is the main energy user in the world) and greenhouse gas emissions, as well as in terms of extracted materials and waste generation [6].

The building sector is responsible for a significant proportion of global energy consumption, accounting for roughly 40%, and contributes to approximately 36% of energy-related greenhouse gas emissions. Residential buildings, in particular, have substantial energy demands, requiring considerable amounts of energy for both thermal comfort (such as water heating, space heating, and cooling) and the operation of electrical appliances and lighting [7]. According to the European Commission's communications, with a staggering 75% of existing buildings in the EU classified as energy inefficient and renovation efforts lagging behind at a mere 0.4% to 1.2% per year, the need for accelerated action is clear [3]. Global CO_2 emissions related to energy from buildings are 26% [8]. A further obstacle is that the Polish building stock is largely outdated, resulting in high energy consumption and continued reliance on fossil fuels. As many as 92.84% of all residential buildings come from before 2011, which necessitates modernization [7]. Therefore, the European Commission has recognized the construction sector and the construction industry as one of the key areas of action in response to climate and environmental challenges [9], and the construction of zero-energy, zero-emission buildings (where zero-emission means no local carbon dioxide emissions resulting from the use of fossil fuels [10]) is one of the decarbonization strategy and the major challenge for all Member States [7].

Net-zero energy buildings are becoming increasingly popular because they optimize the energy performance of buildings, whether they are newly built, modernized, or renovated [8]. New regulations from the European Commission introduce stricter standards for newly constructed facilities. From 2028, they will have to meet emission-free criteria and be equipped with solar panels and heat pumps. In the case of public buildings, this requirement will apply even earlier, from 2026. However, residential buildings undergoing thorough renovation should be zero-emission from 2032. Another significant change related to EU requirements is the introduction of energy certificates for buildings which classify facilities in the range from class A (emission-free building) to class G (low energy efficiency) [11].

The European Green Deal (2019) and the subsequent Renovation Wave Strategy (2020) underscore the imperative for energy- and resource-efficient construction and refurbishment practices. Furthermore, these initiatives champion the integration of circular economy principles into all new and renovated building projects [9]. Therefore, there is currently an increased interest in buildings with net zero or almost zero energy consumption around the world (also in non-EU countries), and the main goal of designers of residential and public buildings is to improve their energy efficiency, as well as the use of energy from renewable sources [7]. Zero-emission buildings are characterized by extremely high energy efficiency. They are designed and equipped in such a way that energy consumption is minimal, and all energy requirements are met exclusively by renewable energy sources [10] produced on the site or nearby [11]. Net-zero energy buildings strive for energy self-sufficiency by generating enough renewable energy to compensate for their energy consumption over a given period, typically an annual cycle [10]. EU member states may have dissimilar definitions and categories of zero-emission buildings due to different climatic conditions, building types, or ways of calculating energy consumption [4,6]. However, the European

Commission obliges Member States to develop national plans to increase the number of zero-energy buildings, taking into account national, regional, or local conditions and possible measures [5].

The first stage of introducing zero-emission standards is "buildings with almost zero energy consumption". In practice, this means that they will have extremely low energy consumption, which will be covered exclusively by renewable sources. This is an important step towards zero-emission buildings that represents a shift in thinking about the way buildings are designed, constructed, renovated, and operated. To reduce energy consumption, thermal insulation (of walls, windows, etc.), tightness, and high-efficiency equipment, as well as more efficient use of renewable energy should be introduced at the design stage. Buildings with almost zero energy consumption use the following solutions indicated by the European Commission [11]:

- roof insulation—which helps retain heat inside the building;
- air filtration and ventilation systems—which ensure a clean and healthy indoor environment;
- effective and economical lighting and heating systems—which minimize energy consumption;
- photovoltaic panels—which obtain solar energy and convert it for the needs of the building;
- high-performance windows—which effectively insulate the interior against heat loss;
- energy-saving electronics and household appliances—which consume less energy;
- intelligent thermostat—which regulates the temperature in an optimized way.

Zero-emission buildings are designed to utilize energy derived from sustainable sources, harnessed through naturally recurring processes. These sources offer a viable substitute for conventional, finite energy resources like fossil fuels [12]. Sustainable energy technologies are recognized for their clean energy production, efficient resource utilization, and minimal environmental footprint, including waste generation [13]. They embody the principles of environmental stewardship and contribute to counteracting the adverse effects of greenhouse gas emissions, ultimately aiding in the mitigation of climate change [14]. Including renewable energy sources in energy receivers in residential buildings reduces the consumption of non-renewable energy sources, which results in reduced CO_2 emissions [15]. To achieve zero-emission buildings, the following are used: solar heat and solar energy, considered to be the most abundant renewable resource on our planet [16] (photovoltaic panels, solar collectors, heat pumps), geothermal energy, using heat from the ground, water energy (well water, groundwater, use of river water, etc.), heat pumps, wind energy (wind turbines) and biomass systems [8]. Their great advantages are availability, purity, and renewability. They are considered to be much more sustainable than many traditional energy sources [16]. The most popular in zero-emission buildings are heat pumps, which allow one to use free solar energy accumulated in the atmosphere, ground, or groundwater all year round, which are most often located at the point of energy consumption.

The provision within the definition of a zero-emission building, which mandates that renewable energy be generated in close proximity to the building, presents a constraint on the utilization of some renewable energy sources, including biomass. Transporting them to the place of use, especially from remote regions, causes additional, unnecessary greenhouse gas emissions. Therefore, a strategy focusing solely on on-site energy generation would be suitable mainly for new and relatively small installations, which is why zero-emission buildings use the most renewable sources available in given conditions and climate. For example, in the Mediterranean climate, solar energy and photovoltaics are used more often, while in countries with colder climates, heat pumps (geothermal energy, earth heat) and possibly biomass (taking into account the costs of transporting the raw material) are more often utilized [6].

Poland faces a significant challenge in improving the energy efficiency of its building stock. Much of the existing infrastructure is outdated and energy intensive, contributing to high greenhouse gas emissions and energy costs. However, with growing awareness of climate change and the increasing availability of advanced technologies, Poland has a significant opportunity to transition towards a more sustainable built environment.

Poland has made strides in recent years to align its building codes with European Union directives on energy performance. Key regulations and standards include:

- EPBD (Energy Performance of Buildings Directive): This EU directive sets minimum energy performance requirements for new and renovated buildings, promoting energy efficiency and the use of renewable energy sources.
- WT 2021 (Technical Conditions 2021): Poland's technical conditions for buildings, updated in 2021, define requirements for energy efficiency, including insulation, ventilation, and heating systems. These standards aim to reduce primary energy consumption in buildings.
- NZEB (Nearly Zero-Energy Buildings): Poland is progressively moving towards the NZEB standard, which requires buildings to have very high energy performance and cover a significant portion of their energy needs with renewable sources.

Building upon the existing standards, we need to implement further strategies to realize our ambitious energy efficiency objectives. Potential strategies include:

- Renovating existing buildings to significantly reduce their energy consumption. This can involve upgrading insulation, replacing windows, and installing efficient heating and cooling systems.
- Adopting the Passive House standard, which focuses on maximizing energy efficiency through passive measures like airtight construction, superinsulation, and heat recovery ventilation.
- Increasing the use of renewable energy sources in buildings, such as solar photovoltaic panels, solar thermal collectors, and heat pumps.
- Implementing smart building technologies to optimize energy use, including building management systems, smart meters, and automated controls.
- Raising awareness among building professionals, homeowners, and policymakers about the benefits of energy efficiency and the available technologies and incentives.

By addressing the challenges and capitalizing on the opportunities, Poland can significantly focus on achieving the best possible energy performance.

The Energy Performance of Buildings Directive (EPBD) is a document enacted in 2010 (2010/31/EU) [17]. It was revised in 2018 (2018/844/EU) [18] with a view to sending a strong political signal that the EU's goal was to modernize the building sector based on technological progress as well as to increase the scope of building retrofitting. The latest directive on the energy performance of buildings is Directive (EU) 2024/1275 [19] of the European Parliament and of the Council of 24 April 2024. It entered into force on 28 May 2024 and introduced a number of significant changes regarding the energy efficiency of buildings. The latest EPBD directive is a significant step towards a more sustainable and energy-efficient building sector in Europe. It sets ambitious targets and provides a framework for action, which should contribute to achieving the EU's climate and energy goals. The EPBD revision was part of the Renovation Wave strategy, which itself is an element of the European Green Deal. Presented in October 2020, the strategy aimed as a minimum at doubling the rate of energy-efficient building retrofitting and providing support to comprehensive retrofitting projects by the year 2030. It was noted that existing legislative measures for buildings would not be sufficient to achieve the increased EU climate target for 2030, with an emissions reduction target of at least 55%, the planned ambitious energy efficiency targets, or climate neutrality by the year 2050. Until now, the increasingly stringent energy efficiency requirements for buildings have only applied to newly constructed buildings, but the latest EU law will also affect already existing buildings. Thermal modernization and energy efficiency will also affect the well-being of residents and users [20–22]. The amendment of the Energy Performance of Buildings Directive (EPBD), known also as the "Buildings Directive", aims to significantly reduce greenhouse gas emissions and energy consumption of buildings in the European Union by retrofitting all existing buildings, both residential and public ones. Under the guidelines of the EPBD, it will not be long before every building in Poland will be assigned its own energy class (see Figure 1), within a framework of a system similar to that used for household appliances and consumer electronics.

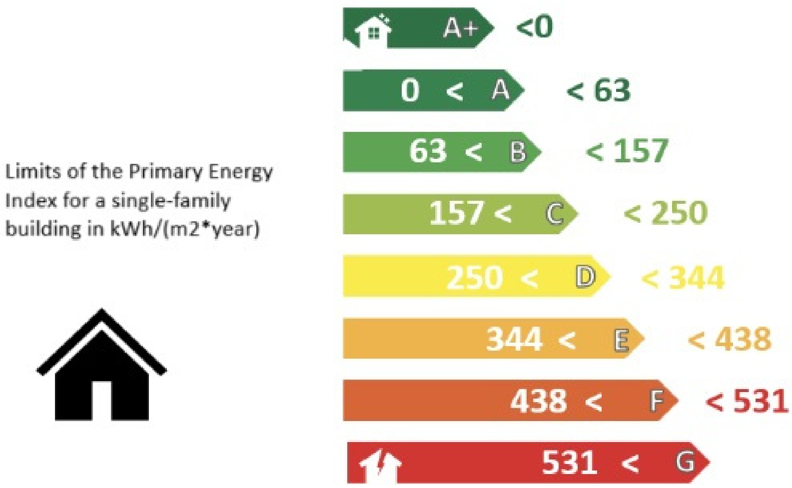

Figure 1. Energy classes of buildings proposed by the National Energy Conservation Agency for single-family houses (according to the EP index in kWh/m^2 per year). Source: the author's own work based on: https://termomodernizacja.pl/polskie-klasy-energetyczne-jak-beda-charakteryzowane-budynki-od-2024-roku/ (accessed on 17 November 2024) [23].

A building's energy class determines how much energy a building uses over the course of one year (for heating, ventilation, domestic hot water, cooling, and lighting) and how much it costs to maintain it. The EPBD will divide residential buildings into classes from the best (A+) to the worst (G), the latter expected to include 15% of the buildings with the worst energy performance in the country (so-called "energy vampires"). The Ministry of Development and Technology intends to introduce such a system for the classification of buildings as early as 2024. The introduction of the building energy classification system will provide a number of benefits for home and flat owners. First and foremost, it will allow them to get to know the factual energy status of their buildings and plan renovation projects that will translate into a better quality of life, energy savings, and lower property maintenance costs. The cost of heating a building with energy class A can be up to six times lower than that of a building with energy class F or G. However, the aim of the amended Directive is not just to introduce energy classes for buildings, but to systematically improve their condition in order to eliminate those with the worst energy performance. Accordingly, the Directive requires non-residential buildings and public buildings to achieve at least energy efficiency class E by 2027 and class D by 2030. Residential buildings will have to achieve the same classes by 2030 and 2033 respectively. In the subsequent years, individual buildings should achieve increasingly higher classes, so that ultimately, in 2050, the entire national building stock is zero emission and climate neutral. The proposal to amend the EPBD is highly controversial in the EU, primarily because of the scale of the undertaking. The implementation of its provisions will require the mobilization of huge financial resources, both private and public. The EPBD project provides for all new buildings in the EU to achieve zero-emission status by 2028. Public buildings, on the other hand, are to be zero emission by 2026. From 2028, where feasible and economically justifiable, all new buildings should be equipped with solar (RES) installations, while for buildings undergoing renovation and refurbishment, this provision will apply from 2032. For the renovation wave to succeed, it will be crucial for the government to efficiently implement support mechanisms, especially taking into account the capacity of the poorest to bear such costs. EU funds will help, with a huge portion of both the National

Recovery Plan (NRP) and regional funds earmarked for the support of energy efficiency and green transformation.

In 2026, another source of funding will become available, namely the Social Climate Fund. In the NRP alone, EU funds are reserved for Poland to co-finance almost 800,000 new heat sources and 700,000 thermal upgrading projects for residential buildings by 2026. The fund's operational period is established as 2026–2032, with eligible expenditures commencing on 1 January 2026. An initial allocation of 50 million allowances will be auctioned in 2026 to ensure adequate support in the initial phase. The new ETS is designated as the primary funding mechanism for the fund from 2027 forward [24,25].

In an effort to achieve carbon neutrality by 2050, the EU has introduced further requirements to reduce emissions in the construction sector. To ensure that the energy transition is fair and inclusive, the European Commission has proposed the establishment of a Social Climate Fund. The fund will help vulnerable households, small businesses, and transport users who are particularly affected by energy and transport poverty.

It is part of the Ready for 55 legislative package [26], which aims to achieve the European Green Deal targets of reducing greenhouse gas emissions by 55% by 2030.

The Social Climate Fund [27] should finance specific measures to address energy and transport poverty, in both short and long-term perspectives, including:

- reducing energy taxes and charges or providing other forms of direct income support to counteract rising road transport and heating fuel prices;
- providing incentives to renovate buildings and switch to renewable energy sources in buildings;
- providing incentives to switch from private to public transport, car sharing or cycling;
- supporting the development of a second-hand electric vehicle market.

The mandatory EU climate target is enshrined in the European climate law: to reduce EU emissions by at least 55% by 2030. EU Member States are working on new legislation to achieve this target and to make the EU climate neutral by 2050.

With the goal of a 55% reduction in greenhouse gas emissions by 2030, the Council and the European Parliament have set ambitious climate targets. To achieve these targets, the "Ready for 55" package introduces a collection of legislative proposals, modifying existing EU laws and establishing new initiatives to ensure policy alignment. One of the ways to obtain external funding that will help to reduce one's own contribution to a thermal upgrading project is a thermal upgrading bonus. Such a bonus constitutes a contribution towards the costs of a thermal upgrading project. It can be spent, for example, on the replacement of windows, doors, or heat sources.

A bonus may be used by investors regardless of their legal status, excluding budgetary units and local government budgetary establishments, e.g., housing communities and cooperatives, local government units, social housing associations, social housing initiatives, commercial companies, and natural persons (including owners of single-family houses). A thermal upgrading can be granted to a project owner who has completed a thermal upgrading project and has obtained a credit for that purpose. It is intended for project owners using credits (project owners using their own funds only are not eligible for a bonus). The amount of a credit must constitute at least 50 percent of a particular thermal upgrading project and not less than the amount of a bonus. The amount of a thermal upgrading bonus is 26 percent of the costs of a thermal upgrading project, and 31 percent of the total costs of a thermal upgrading project including an RES element, namely the purchase, installation, construction, or modernization of a renewable energy source (the costs of a RES system must constitute at least 10 percent of the total costs of a thermal upgrading project). Additional support of 50 percent of the costs of strengthening a prefab-concrete-panel building is available if such a procedure is combined with a thermal upgrading project such as The Thermal Upgrading Support Act [28]. Incentives to invest in renewable energy sources include rebates, subsidies, or preferential loans from both EU and national funds. These are very popular, as appropriate support can significantly reduce the cost of a thermal upgrading project and thus shorten the time it takes for the money spent to pay off. "Clean

Air" is a nationwide subsidy program that allows for the replacement of heat sources and the thermal upgrading of buildings.

Since April 2024, new regulations have been in effect for the "Clean Air" program. Beneficiaries can receive funding for:

- replacing an old, inefficient solid fuel heating source with a new, efficient, and eco-friendly boiler;
- upgrading the heating system;
- insulating the building;
- replacing windows and doors;
- purchasing a heat recovery system (mechanical ventilation with heat recovery);
- installing a photovoltaic system (solar panels).

Beneficiaries can receive up to PLN 135,000 for the highest level of funding with comprehensive thermal modernization, up to PLN 99,000 for the increased level, and up to PLN 66,000 for the basic level. Additionally, an energy audit, up to PLN 1200, will be considered a qualified expense [29].

3. Methodology and Analysis of a Selected Case Study

3.1. Methodology

The growing ecological awareness and the need to counteract climate change present new challenges and goals for the construction sector. In response to these challenges, the European Union is introducing increasingly stringent regulations and targets related to reducing greenhouse gas emissions and the sustainable use of natural resources. In this context, the concept of zero-emission buildings is becoming not only a priority but also an integral part of the future of construction.

A Nearly Zero-Energy Building (NZEB) is one that has a very high energy performance, with nearly zero or very low energy demand largely covered by renewable energy sources, including those generated on-site or nearby. A zero-emission building is characterized by zero net energy consumption. This means that the total amount of energy it consumes annually is equal to the amount of renewable energy produced on-site. According to the European Commission [17,30], a zero-emission building is defined as a building with very high energy performance. It is distinguished by very low energy consumption, entirely covered by renewable energy sources. As the name suggests, the operation of such a building occurs without local carbon dioxide emissions from fossil fuels. To achieve zero-emission buildings, the European Commission follows the principle of "energy efficiency first." In addition to contributing to the reduction of fossil fuel consumption and increasing independence and security of supply, this principle also emphasizes the importance of reducing energy production. The concept of zero-emission buildings is therefore based on a revolutionary approach to the design, construction, and operation of buildings, aiming to completely eliminate greenhouse gas emissions associated with their use. This involves not only energy efficiency but also the use of renewable energy sources, as well as the implementation of innovative technologies and materials with low environmental impact.

Nearly Zero-Energy Buildings (NZEB) and zero-emission buildings present a combination of solutions illustrated in a diagram developed by the European Commission. These solutions include various elements [17,30], such as:

- Air filtration and ventilation systems—ensuring a clean and healthy indoor environment.
- Efficient and energy-saving lighting and heating systems—minimizing energy consumption.
- Installed photovoltaic panels—harnessing solar energy and converting it for building use.
- High-performance windows—effectively insulating the interior against heat loss.
- Energy-efficient electronic and household appliances—consuming less energy.
- Smart thermostat—optimizing temperature regulation.
- Electric vehicle charger—supporting sustainable transportation solutions.

Starting in 2028, new buildings in the European Union will be required to meet zero-emission standards. If technically and economically feasible, such properties will be obligated to install solar panels and heat pumps. For public buildings, this requirement will take effect even earlier, in 2026. Residential buildings undergoing major renovations will need to be zero emission by 2032. Another significant change associated with EU requirements is the introduction of energy certificates for buildings, which will classify properties on a scale from Class A (zero-emission building) to Class G (low energy efficiency) [30].

The proposed case study demonstrates how a standard single-family house with specific energy efficiency indicators, in line with current technical requirements in Poland, can be transformed into a zero-emission building using renewable energy sources. The goal is to generate the greatest possible energy savings and achieve zero greenhouse gas emissions. Energy requirements encourage users to conserve significant amounts of energy. A viable strategy for enhancing energy efficiency in buildings involves implementing comprehensive thermal upgrades and integrating renewable energy systems. These actions are in accordance with the Energy Performance and Efficiency Act and the regulation on building specifications and siting, which, since 2021, has established standards for nearly zero-energy buildings [31]. The subject building is a detached residential dwelling located in Krakow. Climate data for the study were sourced from the Krakow—Balice meteorological station, the closest facility with comprehensive long-term records and a representative typical meteorological year. The mean annual ambient temperature for the period 1971–2000 was 7.6 °C, while the design outside temperature for this climatic region is −20 °C [32,33].

Recent Polish legislation concerning energy audits and financial incentives for building renovations mandates that thermal calculations for modernization projects adhere to the PN EN 12831 standard. This standard delineates Poland into five distinct climatic zones, each characterized by unique design outdoor temperature values for calculation purposes (Table 1) [32].

Table 1. Design outdoor and mean annual air temperature in Poland according to PN EN 12831.

Climatic Zone	Design Outdoor Temperature [°C]	Mean Annual Air Temperature [°C]
I	−16	7.7
II	−18	7.9
III	−20	7.6
IV	−22	6.9
V	−24	5.5

Apart from the design heat load (Φ_H), the annual energy demand for space heating ($Q_{H,nd}$) is also calculated. This is also known as usable energy and represents the net energy delivered to the building's heating system to cover a given energy need (consumed directly) after accounting for distribution and generation losses. This is calculated using the quasi-steady-state monthly method of the EN ISO 13790 standard [33]. This method simplifies the calculation by assuming steady-state conditions for each month, while still capturing the dynamic behavior of the building and its heating system throughout the year. The method remained almost unchanged in the newly introduced EN ISO 52016-1 standard, ensuring continuity and facilitating the comparison of energy performance assessments across different versions of the standard.

The calculation procedure for a heated space is as follows:

(a) determination of the design value of the external temperature and the annual average external temperature;
(b) determination of the status of each space (whether it is heated or not) and the design value of the internal temperature for each heated space;
(c) determination of the dimensional and thermal characteristics of all building elements for all heated and unheated spaces;

(d) calculation of the design heat loss coefficient by transmission and then the design heat loss by transmission for the heated space;
(e) calculation of the design ventilation heat loss coefficient and ventilation heat loss for the heated space;
(f) calculation of the total design heat loss;
(g) calculation of the heat surplus for the heated space, which is the additional heating power needed to compensate for the effects of heating interruptions;
(h) calculation of the total design heat load for the heated space.

The calculation method was developed based on the following assumptions:

- uniform distribution of air temperature and design temperature (the height of the rooms does not exceed 5 m);
- the values of air temperature and operative temperature are the same (well-insulated buildings);
- steady-state conditions (constant temperature values);
- constant properties of building elements as a function of temperature.

The PN-EN ISO 13790:2008 standard, in conjunction with other standards related to the energy properties of buildings, should allow its application in various situations, such as:

(a) verifying whether newly constructed buildings meet national requirements expressed as energy performance indicators;
(b) comparing the energy performance of alternative design variants;
(c) determining the energy characteristics of existing buildings, based on an analytical assessment of the building's energy demand, calculated for standard usage conditions and a typical meteorological year;
(d) calculating the energy effects when existing buildings undergo thermal modernization;
(e) planning future energy demand at regional, national, or international levels by applying statistical methods to the energy performance results of buildings representative of the building stock in a given region.

Given these assumptions, the PN-EN ISO 13790:2008 standard [33] is flexible and includes three different types of calculation methods:

- A quasi-steady-state monthly method with a special option—the seasonal method;
- A simplified dynamic hourly method;
- Calculation procedures for detailed dynamic simulation methods with varying time steps (e.g., hourly).

Both the monthly method and the simple hourly method have fully normative status. The monthly method provides accurate annual energy demand results, but results for individual months, especially near the beginning and end of the heating and cooling seasons, may have significant relative errors [33].

The alternative simple hourly calculation method, which simplifies the process by using linearized equations for heat transfer calculations, was introduced into the standard to facilitate calculations that take into account hourly building usage schedules. These schedules include factors such as:

- Presence of building occupants;
- Artificial lighting and equipment usage;
- Temperature settings and ventilation modes;
- Deployment of movable sun shades;
- Hourly control options based on external or internal climatic conditions;
- And other relevant factors.

The results obtained through this method provide hourly data for each hour of the year. However, the results for individual hours have not been validated due to the lack of measurement data in this area. Consequently, individual hourly values may have large relative errors, which may affect the reliability of analyses and forecasts based on this data. Despite these limitations, the hourly calculation method offers a valuable tool for detailed analysis of the variability of parameters over time, e.g. temperature, pressure, solar radiation, energy consumption, and you can precisely track changes occurring during the day, perform more accurate modeling and simulations along with the optimization of these indicators.

3.2. Analysis of a Selected Case Study

Using the PN-EN 12831 climate classification system, Krakow is categorized as Zone III. This designation, coupled with regulatory requirements, shaped the design criteria adopted for this location (Table 2) [32–34]. The pursuit of zero energy and zero emissions standards (NZEB) involved rigorous analysis of energy performance and environmental impacts, with an emphasis on exploring the viability of select renewable energy sources.

Table 2. Defined Thermal Conditions for the Considered Location [27,28].

Parameter	Value	Unit
Design External Temperature	−20.0	°C
Room Air Temperature—Living Spaces	20.0	°C
Room Air Temperature—Staircase	16.0	°C
Room Air Temperature—Basement	12.0	°C
Heating Degree Days—External Walls (20.0 °C)	4538.3	K·d
Heating Degree Days—External Walls (16.0 °C)	3078.3	K·d

The building, constructed using traditional masonry technology, features 3 stories (a basement and 2 above-ground levels) and has a rectangular layout (see Figure 2).

Figure 2. Visualization of the Building [Own Preparation].

Constructed in 1983, it has a total heated volume and heated floor area of 1100 m^3 and 485 m^2, respectively.

Building Characteristics:

- External Wall Construction: Cellular concrete walls, plastered on both sides, 45 cm thick, insulated with 14 cm of thermal insulation material (thermal transmittance coefficient U = 0.139 W/(m^2·K)).

- Roof: Pitched roof with a wooden structure covered with sheet metal, insulated with 20 cm of thermal insulation material (U = 1.628 W/(m^2·K)).
- Windows: New PVC profile windows with double glazing, with a thermal transmittance coefficient depending on the window size, U = 0.9 W/(m^2·K).
- Entrance Doors: Glazed doors made of unplasticized polyvinyl chloride (UPVC) with a thermal transmittance coefficient U = 1.3 W/(m^2·K).
- Ventilation System: Mechanical ventilation system with heat recovery.

The building is heated by a 12 kW condensing gas boiler. The central heating system utilizes a floor heating system with fully automatic regulation and control. A high-efficiency condensing boiler provides hot water throughout the building via a centralized system with continuous circulation. In addition to central heating and hot water, the building has all necessary utilities: water supply, sewage disposal, electrical wiring, and a lightning protection system. The building is in good overall condition; however, to enhance energy performance and meet the 2021 Technical Conditions, a complete thermal upgrade of the exterior walls is advisable.

The initial phase of energy analysis involves evaluating the building's current performance. This encompasses examining on-site assessments and technical records to ascertain the efficacy of the systems and the heating requirements during a typical heating season. The derived parameters construct a mathematical model that necessitates comparison with actual operational conditions. Any deviations necessitate modifications and supplementary investigations.

A crucial subsequent step in a comprehensive audit is exploring potential enhancements and modernizations. Proposed interventions address not only technological facets but also encompass organizational (e.g., personnel training) and regulatory (e.g., modifications in energy tariffs) dimensions.

Following these steps, the analysis proceeds to evaluate the return on investment. The primary stage entails determining investment expenditures based on prevailing market dynamics. Subsequently, the savings accrued through the proposed measures are computed. Both these figures constitute integral components of the investment feasibility assessment. An energy audit is fundamental for making informed decisions regarding energy cost optimization in the building. Often, conducting an audit at the initial level allows for implementing simple changes with minimal or no cost, leading to significant energy savings and, in practice, lower building maintenance costs [35,36].

A comprehensive improvement plan is developed once the most cost-effective measures are identified. This plan encompasses a series of recommended investments, prioritizing those with the greatest financial return. However, the selection process takes a holistic approach, considering not only economic factors but also improvements to thermal comfort, the elimination of thermal bridges, enhancements to heating system safety and reliability, ease of use, and environmental impact. The plan also accounts for existing building conditions and the need for integrated solutions to ensure effectiveness. In conjunction with other standards related to energy performance (see Figure 3, which outlines the computational procedure and its connections with other standards related to energy performance), it helps ensure a comprehensive approach to evaluating and improving building energy efficiency.

The main objective of energy analyses is to pinpoint opportunities for energy efficiency improvements, assess costs, and guide the Investor in prioritizing and scheduling upgrades for maximum impact. The audit's scope is collaboratively defined with the Investor. For insulation projects, the optimal thickness of thermal insulation is calculated based on cost-effectiveness criteria. Once cost-effective actions are identified, the optimal scope of work is established, which is a set of recommended investments for implementation. The selection of the scope of work is mainly based on economic criteria, but other factors are also considered, such as improving thermal comfort, eliminating wall cold bridging, increasing the safety and reliability of central heating, simplifying device operation, and ecological benefits. Technical conditions and the necessity of integrating some improvements to achieve the expected results are also taken into account [29,37].

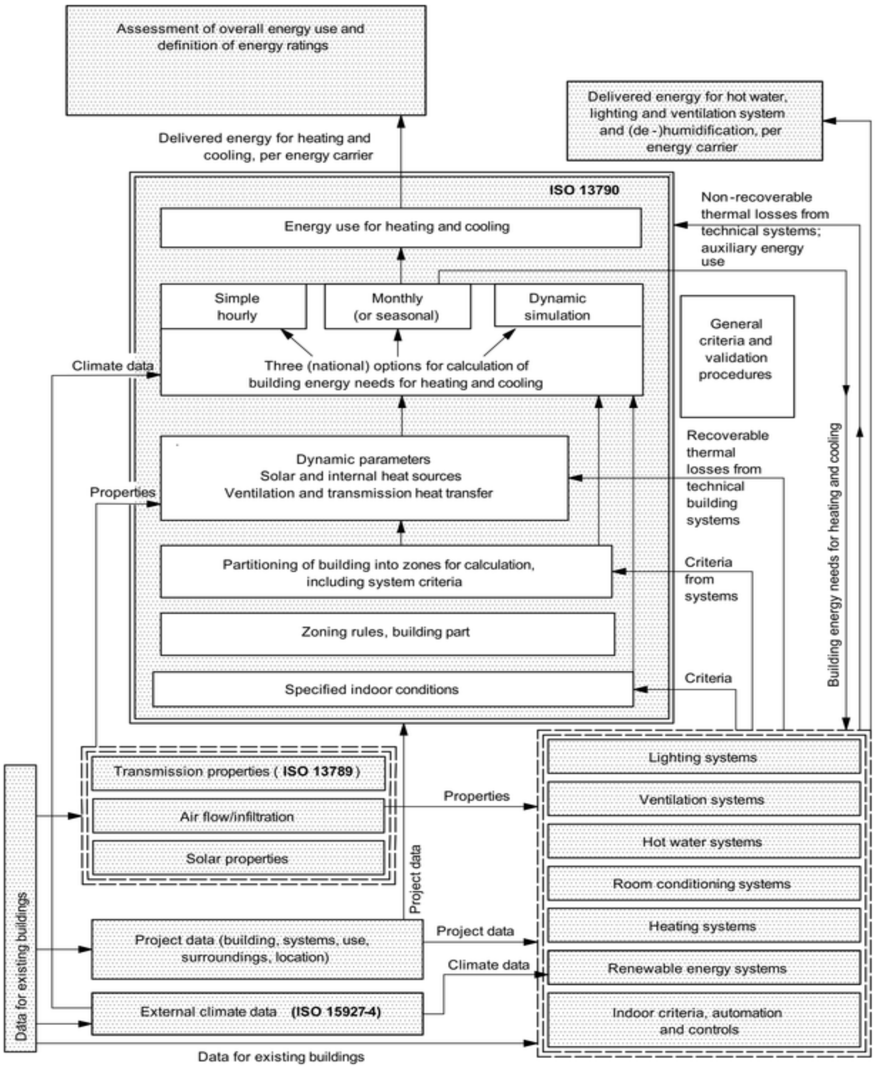

Figure 3. Block Diagram of the Computational Procedure and Its Connections with Other Standards [31,33,38].

This International Standard (EN ISO 13790) is part of a series of computational methods for designing and assessing the thermal and energy performance of buildings. It provides a consistent set of calculation methods with varying levels of detail, addressing energy consumption for heating and cooling of building spaces and the impact of recoverable heat losses from building technical systems, such as heating and cooling systems [33,35,36].

In conjunction with other standards related to energy performance (see Figure 3, which outlines the computational procedure and its connections with other energy performance-related standards), it ensures a comprehensive approach to evaluating and improving building energy efficiency.

To accurately determine the building's design thermal load and assess its energy efficiency, a virtual 3D model was generated using Audytor OZC software (version 7.0 Pro, Sankom). This model, shown in Figure 4, was meticulously created to reflect the design specifications and actual site conditions. The energy performance analysis followed the PN-EN ISO 13790 standard, employing the monthly calculation method [31,37].

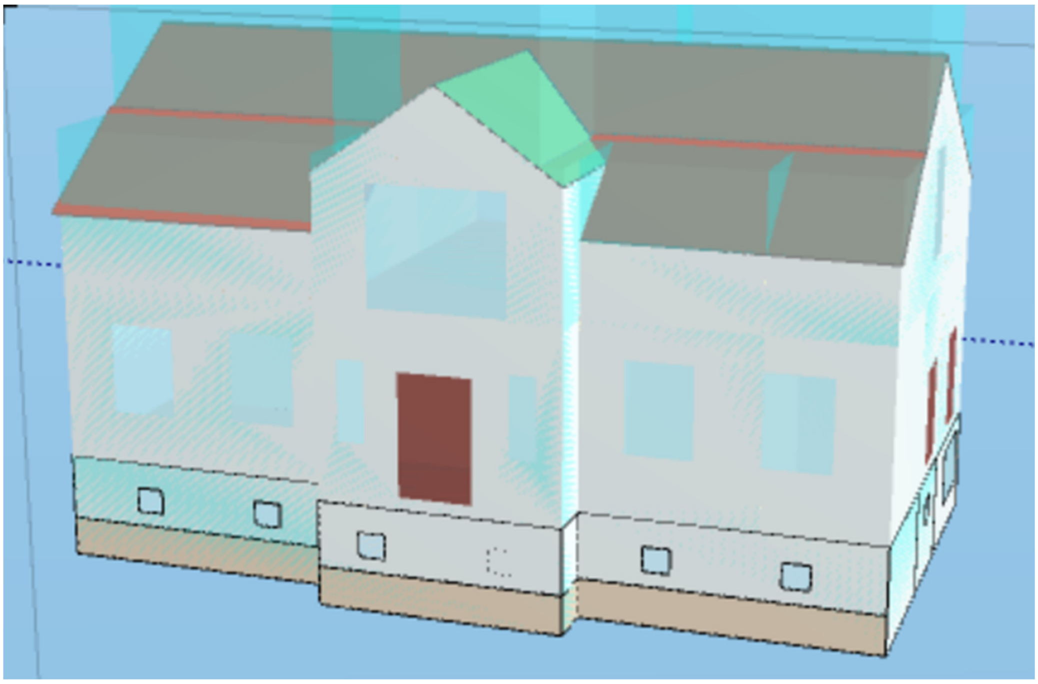

Figure 4. Building View in Audytor OZC Software [Own Preparation].

The annual design heating demand amounted to 111.95 GJ/year (31,099 kWh/year). The largest heat losses occurred through the ventilation system, totaling 50.21 GJ/year, and through the external walls, amounting to 24.48 GJ/year (see Table 3).

Table 3. Summary of energy losses through partitions—heating after thermal modernization (own elaboration).

Description	[GJ/Year]	[kWh/Year]	[%]
External doors	5.26	1460	4.7
Exterior window	14.34	3983	12.8
Basement floor	5.31	1474	4.7
Ventilated flat roof	4.83	1343	4.3
Ceiling Heat Loss	3.87	1074	3.5
Exterior wall at ground level	0.81	225	0.7
Interior wall	2.85	791	2.5
Exterior wall	24.48	6801	21.9
Heat for ventilation	50.21	13,948	44.9
Total	111.95	31,099	100.0

By analyzing the relationships between key indicators, we can easily gauge the effectiveness of measures such as envelope insulation, thermal bridge elimination, and airtightness enhancement in improving a building's overall quality. The most crucial element in deciding on the appropriate thermal modernization solution is determining three key indicators in the energy efficiency classification: the primary energy demand coefficient (EP), the useful energy demand coefficient (EU), and the final energy demand coefficient (EK) [31,39].

To calculate the final energy demand, we analyze the annual useful energy demand in relation to the typical efficiency of the heating system throughout the year. This analysis allows us to determine the specific energy required for heating, which can be expressed through the following equation:

$$Q_{K,H} = \frac{Q_{H,nd}}{\eta_{H,tot}} \left[\frac{kWh}{year}\right] \quad (1)$$

where:

$Q_{H,nd}$—useful energy demand to heat a residential building (useful heat),
$\eta_{H,tot}$—average seasonal efficiency of the building's heating system.

The next element is the energy used to prepare domestic hot water, and its demand is determined using the following formula:

$$Q_{K,W} = \frac{Q_{W,nd}}{\eta_{W,tot}} \left[\frac{kWh}{year}\right] \quad (2)$$

where:

$Q_{W,nd}$—demand for preparation of domestic hot water;
$\eta_{W,tot}$—average annual efficiency of devices preparing domestic hot water.

The determination of the final energy demand coefficient (EK) is facilitated by the preceding equations. It is essential to note that EK, EU, and EP are expressed in kilowatt-hours per square meter of floor area annually, representing the heating energy requirement. The calculation of the required final energy (EK) for the building is detailed in the following equation:

$$EK = \frac{Q_{K,H} + Q_{K,W}}{A_f} \left[\frac{kWh}{m^2 \times year}\right] \quad (3)$$

where:

A_f—heated or cooled space in the building with a specific temperature, expressed in [m^2].

The annual energy requirements for thermal comfort (heating and domestic hot water), cooling, and illumination determine the calculated demand for non-renewable primary energy sources. The EP index is calculated from the relationship:

$$EP = \frac{Q_P}{A_f} \left[\frac{kWh}{m^2 \times year}\right] \quad (4)$$

where:

Q_P—annual demand for primary energy [kWh/year].

Of which the annual primary energy demand is calculated according to the formula:

$$Q_P = Q_{P,H} + Q_{P,W} + Q_{P,C} + Q_{P,L} \left[\frac{kWh}{year}\right] \quad (5)$$

where:

$Q_{P,H}$—annual primary energy demand through the heating and ventilation system for heating and ventilation;
$Q_{P,W}$—annual primary energy demand by the domestic hot water preparation system;
$Q_{P,C}$—annual primary energy demand for the space ventilation and cooling system;
$Q_{P,L}$—annual demand for a lighting system (calculated only for public buildings).

Usable energy efficiency index is calculated from the following dependence:

$$EU = \frac{Q_U}{A_f} \left[\frac{kWh}{m^2 \times year}\right] \quad (6)$$

where:

Q_U—annual demand for usable energy [kWh/year].

$$Q_U = Q_{H,nd} + Q_{W,nd} + Q_{C,nd} \left[\frac{kWh}{year}\right] \quad (7)$$

where:

$Q_{H,nd}$—annual usable energy demand for heating and ventilation;
$Q_{W,nd}$—annual demand for usable energy for preparation domestic hot water;
$Q_{C,nd}$—annual usable energy demand for cooling.

To assess the unit value of CO_2 emissions associated with a building or a specific area within a building equipped with technical systems, the following calculation is used:

$$E_{CO2} = \frac{E_{CO2,H} + E_{CO2,W} + E_{CO2,C} + E_{CO2,L} + E_{CO2,P}}{A_f} \left[\frac{MgCO_2}{m^2 \times year}\right] \quad (8)$$

where:

$E_{CO2,H}$—the amount of CO_2 emissions from the combustion of fuels by the heating system;
$E_{CO2,W}$—the amount of CO_2 emissions from the fuel combustion process by the domestic hot water preparation system;
$E_{CO2,C}$—the amount of CO_2 emissions from the combustion of fuels by the cooling system;
$E_{CO2,L}$—the amount of CO_2 emissions from the combustion of fuels by the built-in lighting system;
$E_{CO2,P}$—the amount of CO_2 emissions from the combustion of fuels by auxiliary devices in technical systems.

4. Results and Conclusions of the Conducted Analysis of the Selected Case Study

While using 100% renewable energy is a crucial step towards achieving zero-emission buildings, it doesn't automatically guarantee a completely zero-emission building in every case. Even if a building operates on 100% renewable energy, it is essential to consider the embodied carbon emissions associated with the materials used in its construction and the construction process itself. Manufacturing building materials like concrete, steel, and glass requires energy and often releases greenhouse gases. Transportation of materials to the construction site also contributes to emissions. Demolition and disposal of building materials at the end of the building's life cycle can also release embodied carbon. In many cases, buildings with 100% renewable energy still rely on grid connections or backup generators for times when renewable energy generation is low. If these backup systems use fossil fuels, they will contribute to emissions. Occupant behavior significantly impacts a building's energy consumption and emissions. Even with renewable energy sources, inefficient use of appliances, heating, and cooling can lead to higher energy demand and potentially reliance on non-renewable backup systems. While 100% renewable energy use is a significant step towards zero-emission buildings, it is not the only factor to consider. Embodied carbon, operational emissions, and the definition of "zero-emission" all play a role. By adopting a holistic approach that considers the entire life cycle of the building and incorporates strategies to minimize emissions at every stage, we can move closer to truly zero-emission buildings and a more sustainable built environment.

Integrating heat pumps and photovoltaic (PV) systems in buildings offers a powerful synergy that unlocks significant energy and environmental benefits. This combination harnesses renewable energy sources to provide efficient heating, cooling, and electricity, reducing reliance on fossil fuels and minimizing carbon emissions. Heat pumps are highly efficient heating and cooling systems that can deliver several units of heat for every unit of electricity consumed. By extracting heat from the air, water, or ground, they significantly reduce energy consumption compared to traditional fossil fuel-based systems. PV systems generate clean electricity that can be used directly to power the heat pump. This increases the self-consumption of solar energy, reducing reliance on the grid and maximizing the utilization of renewable resources. Heat pumps and PV systems significantly reduce greenhouse gas emissions compared to conventional heating and electricity generation technologies. This contributes to mitigating climate change and improving air quality.

The proposed system for analysis is a hybrid system consisting of an air-source heat pump powered by a photovoltaic installation with an annual balance. This means that the solar energy produced throughout the year is sufficient to cover the electricity demand of the heat pump.

In the existing condition, the building exhibits the following energy efficiency indicators (see Table 4):

Table 4. Summary of Energy Efficiency Indicators for the Existing Building [Own Preparation] based on: [31,39].

Assessment of the Energy Characteristics of the Building		
Energy Performance Index	**Building Being Assessed**	**Requirements According to Technical and Construction Regulations 2021**
Annual useful energy demand indicator	EU = 118.0 [kWh/m^2 year]	
Annual final energy demand indicator	EK = 131.3 [kWh/m^2 year]	
Annual demand for non-renewable primary energy	EP = 182.3 [kWh/m^2 year]	EP = 75.0 [kWh/m^2 year]
Unit amount of CO_2 emissions	E_{CO2} = 0.032 [$MgCO_2/m^2$ year]	
Heat demand indicator for heating	$Q_{H,nd}$ = 111.95 [GJ/year]	

To achieve the nearly zero-energy building standard, an air-to-water heat pump was installed, which operates in both the central heating and domestic hot water systems. Additionally, a photovoltaic system was implemented to supply the building with electrical energy.

The energy analysis proposes the use of a 12 kW air-source heat pump with the following COPs:

- COP = 4.14 at +7 °C (heating water temperature 35 °C)
- COP = 3.44 at +2 °C (heating water temperature 35 °C)
- COP = 2.23 at −7 °C (heating water temperature 35 °C)

and photovoltaic panels with a total capacity of 14 kW (25 panels × 560 W) and an installation area of approximately 66 m^2.

These two measures significantly impacted the building's energy performance. The indicators for primary energy, final energy, and useful energy, as specified by the regulations, were substantially reduced. This example clearly demonstrates how transitioning to renewable energy sources can help reduce dependence on external energy supplies and make a building more resilient to rising operational costs.

The use of these two renewable energy sources in the heating and electrical systems of the building allowed for a reduction in primary energy consumption to zero, and consequently, a reduction in greenhouse gas emissions to zero as well. The adoption of highly efficient devices, with very high annual energy efficiency, also led to a reduction in final energy by more than 50%. The summary of the building's energy efficiency indicators after implementing renewable energy sources is presented below in Table 5 [31,39]:

Table 5. Summary of Energy Efficiency Indicators After Building Modernization [Own Preparation].

Assessment of the Energy Characteristics of the Building		
Energy Performance Index	**Building Being Assessed**	**Requirements According to Technical and Construction Regulations 2021**
Annual useful energy demand indicator	EU = 118.0 [kWh/m^2 year]	
Annual final energy demand indicator	EK = 63.1 [kWh/m^2 year]	
Annual demand for non-renewable primary energy	EP = 0.00 [kWh/m^2 year]	EP = 75.0 [kWh/m^2 year]
Unit amount of CO_2 emissions	E_{CO2} = 0.00 [MgCO_2/m^2 year]	
Heat demand indicator for heating	$Q_{H,nd}$ = 111.95 [GJ/year]	

The energy analysis for the aforementioned building clearly demonstrates that we can achieve our goal of adapting the building to a zero-emission class by utilizing 100% renewable energy sources.

In this case, this was made possible by employing a highly efficient air-source heat pump with very strong annual performance and photovoltaic panels to supply all electrical components of the building (see Table 6).

Table 6. Summary list of energy efficiency indicators for the state after modernization of the building (own elaboration).

Assessment of the Energy Characteristics of the Building		
Energy Performance Index	**Differences in the Group Before and After Thermomodernization**	**Percentage Saving of Individual Indicators**
Annual useful energy demand indicator	EU = 0.00 [kWh/m^2 year]	0.00 [%]
Annual final energy demand indicator	EK = 68.2 [kWh/m^2 year]	51.94 [%]
Annual demand for non-renewable primary energy	EP = 182.3 [kWh/m^2 year]	100.00 [%]
Unit amount of CO_2 emissions	E_{CO2} = 0.032 [MgCO_2/m^2 year]	100.00 [%]
Share of renewable energy sources in the annual final energy demand	U_{RES} = 100.00 [%]	100.00 [%]
Heat demand indicator for heating	$Q_{H,nd}$ = 0.00 [GJ]	0.00 [%]

Indicators of energy efficiency related to non-renewable primary energy are entirely irrelevant in this context because the building uses 100% renewable energy sources, specifically heat pumps and photovoltaic panels. Consequently, there is also a reduction in the unitary carbon dioxide emissions. The utilization of renewable energy in the building amounts to 100%. By adopting such assumptions for building analysis, it is directly possible to achieve a design-level zero-emission building using 100% renewable energy.

Table 6 and Figure 5 demonstrate that the thermal modernization of the building envelope, particularly the exterior walls and ventilated roof, combined with the integration of renewable energy sources (heat pumps and photovoltaic installation), resulted in a 51.94% reduction in thermal energy consumption. This translates directly to lower operating costs.

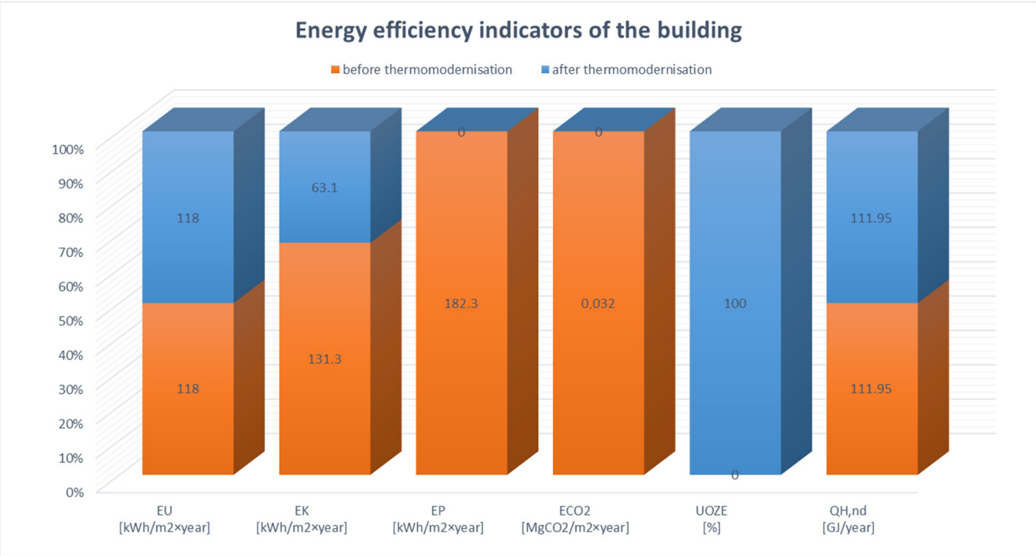

Figure 5. Summary list of energy efficiency indicators for the state after modernization of the building (own elaboration).

5. Discussion & Conclusions

Despite the technological and economic challenges associated with building and maintaining zero-emission buildings, including the availability of suitable materials and technologies, their construction is increasing worldwide, contributing to reduced carbon emissions, improved air quality, and increased energy independence in cities and societies.

The use of renewable energy sources contributes to reducing reliance on fossil fuels and minimizing pollution emissions. Implementing renewable energy sources (RES) requires an economic analysis to assess project costs and benefits. As the prices of renewable energy systems continue to decline, the profitability of RES implementations increases. However, the actual savings achieved depend on many factors and are often lower than initially anticipated. The use of RES results in reduced operating costs and less negative environmental impact, particularly in terms of smog reduction, leading to tangible improvements in comfort, quality of life, and increased market value of the building.

This publication analyzes the feasibility of transforming a standard building, as defined by current regulations (Technical Conditions 2021), into a zero-emission building powered entirely by renewable energy sources. In this case, the renewable sources are air-to-water heat pumps and photovoltaic installations for electricity production.

Improving energy efficiency and promoting the rational use of energy resources are crucial for Poland's sustainable development, especially in the face of rising energy demand. With growing awareness of climate change and the economic benefits of energy conservation, businesses, government entities, and individual consumers are increasingly seeking solutions to enhance energy efficiency.

Buildings are the primary energy consumers in modern society, making them a key target for energy-saving initiatives. Implementing energy efficiency measures is essential to achieve significant cost savings and reduce greenhouse gas emissions.

Conducting energy audits is a crucial first step. Audits help identify areas for improvement and provide data to determine the most effective energy-saving measures.

- Upgrading building envelopes: Improving insulation, replacing windows, and ensuring airtight construction to minimize energy loss.
- Optimizing HVAC systems: Implementing efficient heating, ventilation, and air conditioning systems, such as heat pumps, and ensuring regular maintenance for optimal performance.
- Utilizing energy-efficient lighting: Switching to LED lighting and incorporating daylighting strategies to reduce electricity consumption.

- Implementing smart building technologies: Using building management systems and smart grids to optimize energy use and monitor performance.

Monitoring and supervising implemented measures are vital to ensure long-term effectiveness. Regular maintenance of equipment, for example, ensures optimal technical conditions and maximum efficiency. Furthermore, promoting efficient use of infrastructure elements, such as ensuring proper operation of lighting and HVAC systems, contributes to overall energy savings.

Rational energy use and actions to reduce consumption yield numerous benefits:

- Economic benefits: Lower energy bills for businesses and households, increased competitiveness for industries, and reduced energy imports.
- Environmental benefits: Reduced greenhouse gas emissions, improved air quality, and decreased reliance on fossil fuels.
- National security benefits: Enhanced energy independence and reduced vulnerability to energy price fluctuations.

Many countries recognize the multifaceted benefits of energy efficiency and are implementing policies and programs to encourage its adoption. Poland, with its ambitious goals for sustainable development, should prioritize energy efficiency as a key strategy for achieving economic growth, environmental protection, and energy security. By investing in energy-efficient technologies, promoting responsible energy use, and continuously monitoring progress, Poland can pave the way for a more sustainable and prosperous future.

Zero-emission buildings and net-zero energy buildings represent crucial steps towards sustainable development and the mitigation of climate change. These building types, while sharing the common goal of minimizing environmental impact, differ slightly in their approaches.

Advanced building designs prioritize the reduction of carbon emissions during their operational phase. This goal is achieved through the implementation of cutting-edge energy-efficient technologies, the incorporation of renewable energy systems, and the careful selection of sustainable building materials. By minimizing fossil fuel consumption and optimizing energy performance, these buildings play a crucial role in curbing greenhouse gas emissions and promoting cleaner air. Net-zero energy buildings, on the other hand, take a broader approach by aiming to balance the total amount of energy consumed with the amount of renewable energy generated on-site over a specific period, typically a year. This approach not only eliminates carbon emissions but also promotes energy independence and reduces operational costs.

Achieving net-zero energy status requires a comprehensive strategy that encompasses both advanced technologies and conscious energy management.

Key components include:

- High-performance building envelope: Minimizing energy consumption by utilizing advanced insulation, high-performance glazing, and airtight construction techniques.
- Energy-efficient systems: Utilizing efficient heating and cooling systems, such as heat pumps, and minimizing energy consumption through the use of LED lighting and Energy Star appliances.
- Renewable energy integration: Achieving energy independence through the implementation of on-site renewable energy production, such as solar photovoltaic panels and solar thermal systems.
- Smart building technologies: Implementing building management systems and smart grids to optimize energy consumption and grid interaction.

While the construction of zero-emission and net-zero energy buildings may require advanced solutions and higher initial investments, the long-term benefits are substantial. These benefits include:

- Reduced environmental impact: Minimized carbon emissions, reduced reliance on fossil fuels, and improved air quality.

- Lower operating costs: Significant savings on energy bills due to reduced energy consumption and on-site renewable energy generation.
- Improved occupant comfort and health: Enhanced indoor environmental quality, thermal comfort, and reduced exposure to pollutants.
- Increased property value: Energy-efficient and sustainable buildings tend to have higher market values.

Despite the numerous advantages, the widespread adoption of zero-emission and net-zero energy buildings faces challenges, including:

- Higher upfront costs: The initial investment for advanced technologies and sustainable materials can be significant.
- Technological complexity: Designing and constructing these buildings requires specialized expertise and careful integration of various systems.
- Regulatory barriers: Building codes and regulations may need to be updated to accommodate innovative technologies and approaches.

Overcoming these challenges requires a collaborative effort from policymakers, industry professionals, and building owners. Accelerating the transition towards zero-emission and net-zero energy buildings requires enacting supportive policies, nurturing innovation, and expanding public awareness. This will ultimately cultivate a more sustainable and resilient built environment. The construction industry is undergoing a transformation towards greater sustainability, and net-zero buildings serve as a model that can and should be emulated. With increasing environmental awareness and technological progress, striving for net-zero emissions is becoming more feasible and economically viable. By supporting the development of such solutions, we not only contribute to the protection of our planet but also create healthier, more comfortable, and cost-effective living spaces.

In the face of global climate challenges, net-zero buildings offer a path to a future where responsible energy management becomes the norm rather than the exception. It is time to invest in innovative solutions that will benefit both us and future generations.

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