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ENHANCING BUILDING ENERGY EFFICIENCY THROUGH THE IMPLEMENTATION OF RENEWABLE ENERGY SOURCES

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Abstract: Considering increasing sustainability requirements and the urgent need to reduce greenhouse gas emissions, improving the energy efficiency of buildings has become a key challenge in the construction sector. One of the most promising approaches involves the integration of renewable energy sources (RES) as alternatives to traditional, high-emission energy systems. This paper presents an analysis of the potential for using RES – such as solar, geothermal, and biomass energy – to enhance the energy efficiency of residential and public buildings. The economic and environmental benefits of implementing modern energy technologies are discussed, along with examples of technical solutions and hybrid system models. Legal, technical, and social aspects related to the implementation of such systems are also considered. The results of the analysis indicate that well-designed and properly managed RES systems can significantly reduce the demand for primary energy and CO_2 emissions while increasing the energy independence of buildings.

Keywords: renewable energy, RES, geothermal energy, wind and solar energy

1. Introduction

Building energy efficiency refers to the reduction of energy consumption while maintaining or even improving the thermal comfort, health, and well-being of occupants. It encompasses the use of advanced building materials, thermal insulation, energy-efficient systems (such as HVAC and lighting), and intelligent building management solutions. Enhancing energy efficiency not only lowers operational costs but also contributes to climate change mitigation and increased energy security.

Renewable energy sources (RES), such as solar, wind, geothermal, biomass, and hydropower, play a crucial role in improving energy performance in buildings. These sources are sustainable, have a low environmental footprint, and significantly reduce greenhouse gas emissions compared to fossil fuels Integrating RES into buildings – through technologies such as photovoltaic panels, solar thermal systems, ground-source heat pumps, or biomass boilers – allows for the partial or complete substitution of conventional energy sources. This integration not only supports decarbonization efforts but also increases the resilience and self-sufficiency of buildings in the face of growing energy demands and fluctuating energy prices [1].

2. Various types of renewable energy sources

Various types of renewable energy sources (RES) are increasingly being integrated into buildings to enhance their energy performance, reduce operational costs, and limit environmental impact. Photovoltaic (PV) systems, which convert solar radiation into electricity, are among the most widely adopted technologies, offering potential reductions in annual electricity bills of up to 70% [2]. These systems are often integrated into rooftops or building facades, sometimes combined with energy storage to increase self-consumption. Heat pumps, which extract thermal energy from the air, ground, or water, provide an efficient and low-emission alternative to traditional heating systems, with coefficients of performance (COP) typically ranging between 3 and 4. They are also capable of providing cooling during summer, making them suitable for year-round energy optimization.

Solar thermal collectors offer another effective solution, primarily for domestic hot water heating. When properly dimensioned and installed, they can meet 60–70% of the annual hot water demand, significantly lowering reliance on conventional energy sources. Biomass systems, using fuels such as wood pellets, firewood, or biogas, are commonly employed in detached houses and rural areas. Compared to fossil fuels, they contribute to a reduction in CO_2 emissions by up to 70%, especially when the biomass is sourced sustainably. Small wind turbines, although more location-dependent, can be highly effective in rural or coastal areas with adequate wind resources, offering energy independence and reducing grid dependence.

Beyond their direct energy benefits, the integration of RES supports climate change mitigation, energy diversification, and long-term economic savings. Additionally, hybrid systems that combine multiple sources – such as PV with heat pumps and battery storage – can enhance resilience and optimize energy use throughout the year. When combined with smart building technologies and energy management systems, RES enable buildings to become nearly zero-energy (nZEB) or even energy-positive, contributing to national and EU climate goals.

3. Benefits of using renewable energy sources

The implementation of renewable energy systems in buildings brings both economic and environmental advantages. One of the key benefits is the **reduction in building operating costs** – investments in renewable energy technologies, such as heat pumps, can typically pay off within 5 to 15 years, depending on the type and scale of the installation. In addition to financial savings, renewable energy sources contribute significantly to **reducing greenhouse gas emissions**. For an average household, modernization involving RES can lower CO_2 emissions by approximately 1–3 tons annually. To illustrate the impact: a conventional home without any renewable energy installations may emit around 4 tons of CO_2 per year, whereas a home equipped with RES technologies can reduce that to as little as 1–2 tons annually [6, 11]. This not only supports household sustainability but also contributes to broader climate change mitigation efforts.

3.1. Improved comfort

Renewable energy systems (RES) such as heat pumps can significantly enhance the thermal comfort of the occupants of buildings. These systems provide stable indoor temperatures throughout the year, regardless of external weather conditions. For example, heat pumps not only offer efficient heating during the winter months but also enable cooling during summer, acting as a versatile all-season solution. This results in improved living conditions and contributes to the overall well-being of residents by maintaining a consistent and pleasant indoor climate.

3.2. Reduced dependence on external energy sources

The implementation of renewable energy systems decreases reliance on conventional energy suppliers and imported fossil fuels. By producing energy on-site – through solar panels or other RES technologies – buildings become more self-sufficient and resilient to fluctuations in energy prices and potential supply disruptions. This independence is especially valuable in times of geopolitical instability or rising energy costs.

3.3. Benefits of using renewable energy sources

According to recent studies [4] integrating RES into buildings leads to a significant reduction in electricity consumption from the grid. One example is the application of photovoltaic (PV) systems:

- before modernization: 100% of electricity consumption sourced from the power grid;
- after modernization: 70% of electricity generated by RES, only 30% drawn from the grid.

This not only translates into lower energy bills but also contributes to reducing the building's carbon footprint. A diagram of the benefits of using RES is presented in Figure 1.

4. Challenges of implementing renewable energy systems

4.1. High initial investment costs

One of the most commonly cited barriers to the adoption of renewable energy systems (RES) are the high upfront costs. While the long-term operational savings are often significant – thanks to lower energy bills and reduced maintenance – many individuals, businesses, or municipalities struggle with the initial capital required for installation. These costs typically include: purchase of equipment (e.g., solar panels, batteries, inverters, heat pumps, or wind turbines), installation services by certified technicians, permits, inspections, and regulatory compliance, potential upgrades to existing infrastructure (e.g., roof reinforcement, new electrical wiring, integration with smart grid systems).

Although financial incentives such as subsidies, tax credits, and low-interest loans are available in many regions, they are not always sufficient to fully offset the investment or may not be accessible to all demographics. This barrier is particularly acute in low-income households or in developing countries, where access to financing is limited. An example of the estimated costs of installation ground-source heat pumps in Poland is presented in Table 1.

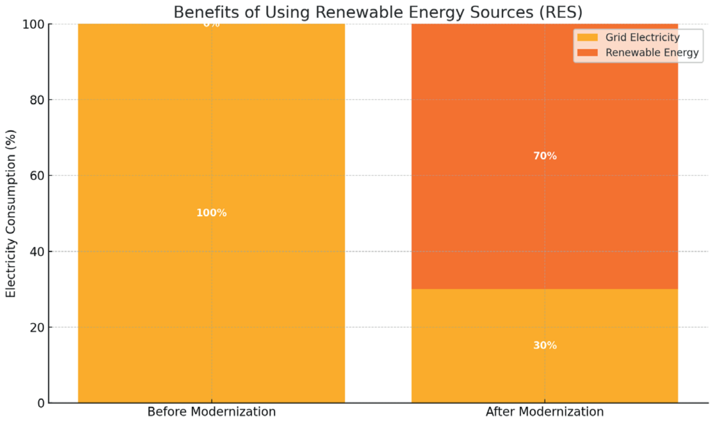

Fig. 1. Benefits of using renewable energy sources [1–3]

Table 1. Estimated installation costs of ground-source heat pumps in Poland (2020–2025) [6–10]

Year	Estimated cost (PLN)	Estimated cost (EUR)	Notes
2020	60,000–90,000	13,000–19,500	Including drilling and installation
2021	60,000–90,000	13,000–19,500	Stable prices
2022	60,000–90,000	13,000–19,500	High demand, no cost increase
2023	60,000–90,000	13,000–19,500	GSHP market growth (+28%)
2024	60,000–90,000	13,000–19,500	Drilling: 160–250 PLN/m
2025	60,000–100,000	13,000–22,000	Slight rise due to inflation

4.2. Technical constraints and location-specific issues

The feasibility of deploying renewable energy systems is highly dependent on the technical characteristics of the building or site, as well as its geographical location. Some of the main challenges include: *limited space availability*: In urban environments, rooftop space may be restricted or shared (e.g., in apartment buildings), making it difficult to install enough solar panels to meet energy demands. *Shading and orientation*: Trees, taller buildings, or structural features can cast shadows on solar installations, reducing efficiency. Additionally, optimal orientation and tilt are needed to maximize sunlight exposure.

Wind turbines require consistent and strong wind speeds to operate efficiently. In cities, wind conditions are often irregular due to obstructions and turbulence caused by buildings.

Some buildings may not be structurally sound enough to support the additional load of solar panels or heavy battery systems without reinforcement.

From the aesthetic side, local regulations or historical preservation codes may limit or prohibit visible modifications to rooftops or facades, especially in culturally protected areas.

In rural areas, while space is generally less of an issue, the lack of grid infrastructure or professional service providers can make installation and maintenance more complicated or expensive.

4.3. Seasonal and weather dependence

Renewable energy production is naturally variable. Solar energy, for example, is highly dependent on sunlight availability, which fluctuates with weather and seasons. This intermittency often requires **energy storage systems** (e.g., batteries) or **hybrid systems** with backup sources to ensure a stable supply – further increasing the overall system cost and complexity.

4.4. Maintenance and technical know-how

Although RES generally require less maintenance than traditional systems, they are not maintenance-free, for example: panels need to be cleaned and occasionally inspected, inverters have a limited lifespan and must be replaced after 10–15 years and battery systems may degrade faster depending on usage patterns.

Furthermore, many users lack the technical expertise to maintain or troubleshoot these systems themselves, necessitating professional services which may not always be locally available.

5. Subsidies and support programs

European Union programs supporting investments in renewable energy sources (RES) offer substantial financial assistance for the modernization of buildings using green technologies. In Poland, well-known initiatives include *Clean Air* (*Czyste Powietrze*) and *My Electricity* (*Mój Prąd*) [3, 5] and the others, which provide grants and rebates for installing solar panels, heat pumps, and improving energy efficiency. Table 2 presents a comparison of the main renewable energy funding programs available to households in Poland, including the scope of support, maximum funding amounts, and key eligibility criteria.

Table 2. Support programs for renewable energy in Poland (2025) [3, 5]

Program name	Eligible measures	Support level	Timeline / Notes
Mój Prąd 6.0	PV systems, battery storage, energy management systems, EV chargers	Up to PLN 16,000 per household	Open from Sep 2, 2024, to Aug 2, 2025, or until funds are depleted. Expanded scope beyond solar panels.
Czyste Powietrze 2025	Heat pump installation (non-gas), boiler replacement, insulation, building modernization	Up to PLN 170,000 (tiered by income)	Relaunched Mar 31, 2025. Requires energy audit and excludes gas systems.
Moje Ciepło	Heat pumps (air-to-water, ground-source), hybrid systems	Varies by technology and household income	Ongoing program under NFOŚiGW. For newly built, energy-efficient homes.
Ulga Termo-modernizacyjna	All RES-related upgrades and thermal modernization	Tax deduction up to 53,000 PLN per owner	Permanent income tax relief for single-family homeowners. Stackable with grants.
Energia dla Wsi	Rural RES installations, community cooperatives, agricultural buildings	Depends on project scope and location	Active from Feb 3 to Dec 19, 2025. Focus on rural energy autonomy.
BGK TERMO	Multi-family building RES systems (collective PV, heat pumps)	Covers up to 50% of net investment	For housing cooperatives, communities, and managers. Managed via BGK bank.

In addition to direct subsidies, tax incentives also play a significant role. Homeowners and building owners may deduct the costs of RES investments from their income taxes, making such projects more accessible and financially attractive.

The process of applying for funding to install renewable energy sources (RES) in Poland – such as photovoltaic systems, heat pumps, or energy storage – begins with selecting the appropriate support program, such as *My Electricity* (*Mój Prąd*), *Clean Air* (*Czyste Powietrze*), or *My Heat* (*Moje Ciepło*). The choice depends on the type of planned investment, the condition of the building (new or undergoing renovation), and the household's income level. The applicant then prepares the complete documentation, which typically includes the application form, a cost estimate, invoices or contractor offers, documents confirming property ownership, and in some cases, an income certificate as well as an **energy audit of the building**. The energy audit is particularly required in programs such as *Clean Air*, especially when applying for higher levels of support or when the investment involves comprehensive thermal modernization. Its purpose is to assess the energy efficiency of the building before the upgrade and to recommend optimal technical solutions eligible for funding. The application can be submitted electronically (e.g., via the gov.pl platform or dedicated program portals), in person at an office, or by mail. Once submitted, the application undergoes a formal and substantive evaluation. The funding authority (e.g., the Provincial Fund for Environmental Protection) may request additional information or conduct a technical inspection. Upon a positive decision, a grant agreement is signed. In refund-based programs, the applicant first completes the project – purchasing and installing the system – and then submits documentation confirming its completion (e.g., invoices, handover protocols). In some cases, a portion of the funds may be paid in advance, prior to installation. The final stage involves settling the grant and receiving the payment. The entire process may take several weeks to a few months, depending on the quality of the documentation, compliance with program requirements, and the availability of funds.

Although the application process can be time-consuming and administratively demanding, the **benefits of investing in RES are tangible** – including long-term savings on energy bills, improved energy efficiency, and greater independence from external energy suppliers.

6. Conclusions

Implementing renewable energy source (RES) technologies in buildings is a forward-looking investment that not only reduces utility bills but also supports environmental protection and sustainable development. Long-term financial savings and improved energy independence are among the most important benefits for property owners. Through systems such as photovoltaic panels, energy storage, and heat pumps, households gain the ability to produce and manage their own energy, often covering most or even all of their daily needs. This significantly reduces dependence on external electricity or heating suppliers and enhances resilience to fluctuating energy prices, power outages, and energy crises. Stored surplus energy can be used during periods of low production or high demand, ensuring energy continuity and security. Moreover, this autonomy contributes to a cleaner environment by lowering CO_2 emissions and reducing the overall ecological footprint. National and EU support programs – such as subsidies, grants, and tax incentives – play a crucial role in making these technologies more accessible, lowering the financial barrier to entry. In the long run, investing in RES enhances not only economic efficiency but also household stability, self-sufficiency, and environmental responsibility. Figure 2 presents a model of a self-sufficient household, illustrating a vision of the future centered around sustainable and energy-independent living.

Fig. 2. Model of a self-sufficient household

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Conflicts of Interest: The author of this paper declares no conflicts of interest.

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