

# OPTIMIZATION OF ENERGY CONSUMPTION IN RESIDENTIAL BUILDINGS

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**Abstract:** The increase in energy consumption in the residential sector represents a major global challenge due to rising costs and environmental impact. Energy optimization in residential buildings aims to reduce energy losses, improve system efficiency and integrate renewable energy sources. This paper analyzes the main methods and technologies used to enhance energy efficiency in residential buildings, focusing on modern solutions applicable under current regulatory and sustainability requirements.

**Key words:** efficiency, residential buildings, energy consumption, building automation, renewable energy.

## 1. INTRODUCTION

The building sector is responsible for a significant share of global energy consumption and greenhouse gas emissions. Residential buildings account for a large portion of this consumption, mainly due to heating, cooling, lighting and the use of electrical appliances [1].

In recent years, energy optimization has become a priority, supported by European regulations promoting nearly Zero Energy Buildings (nZEB). Civil engineers play a key role in implementing technical solutions that reduce energy demand while maintaining indoor comfort and functionality.

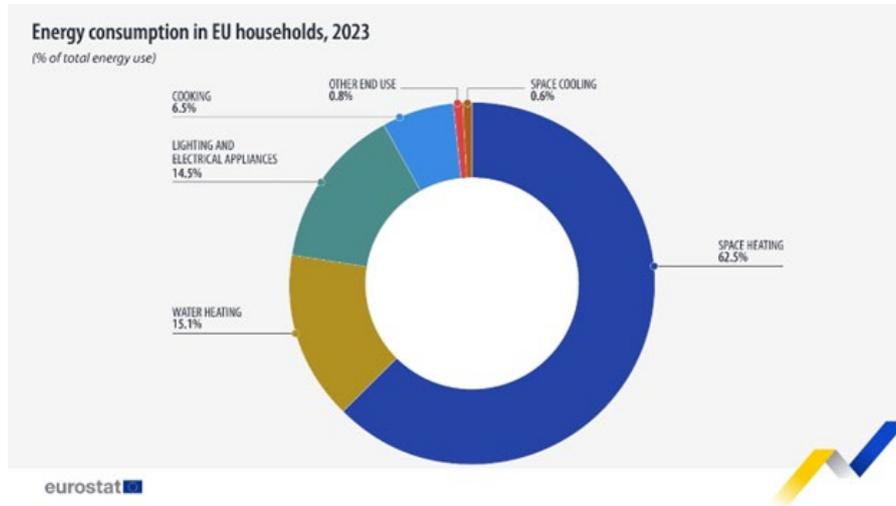
## 2. ENERGY CONSUMPTION IN RESIDENTIAL BUILDINGS

Energy consumption in residential buildings is primarily associated with the following systems:

- space heating and domestic hot water preparation;
- cooling and air conditioning systems;
- lighting installations;
- household appliances and electronic equipment.

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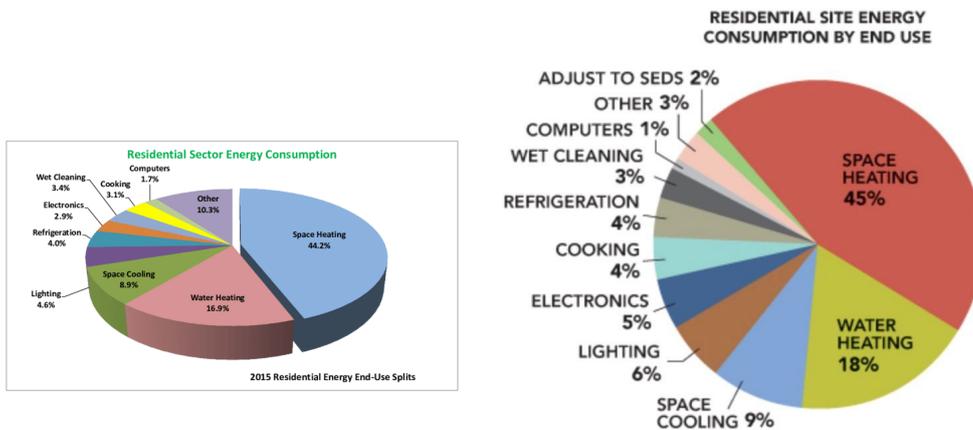


Fig.1. Main energy consumption categories in residential buildings

### 3. METHODS FOR ENERGY CONSUMPTION OPTIMIZATION

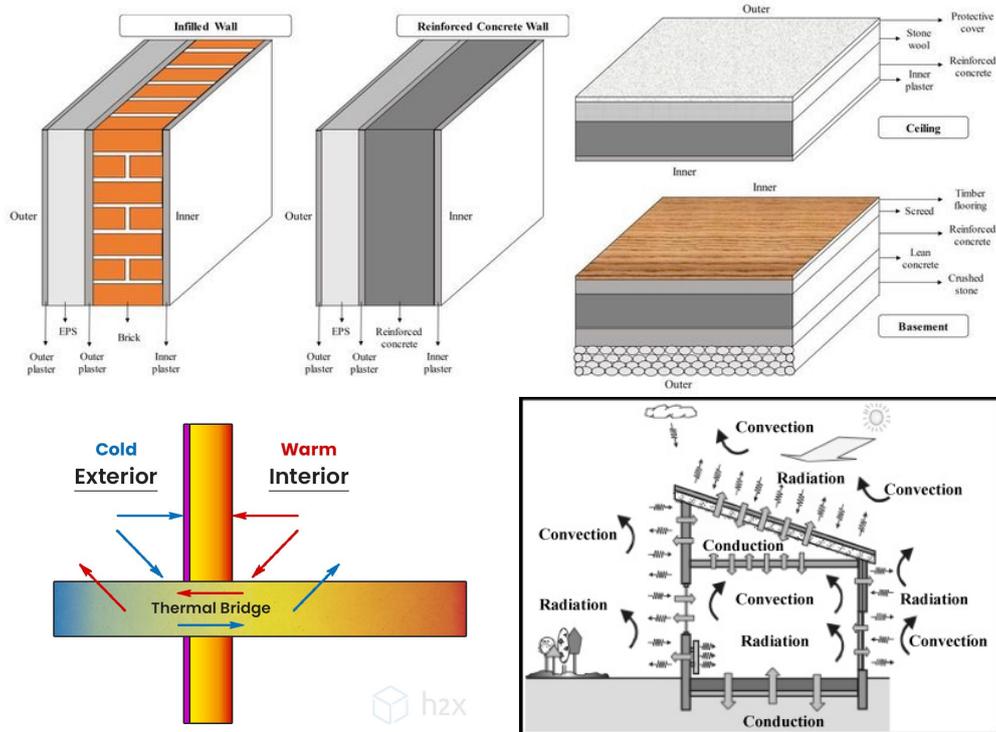
#### 3.1. Improvement of the Building Envelope

Energy optimization begins with reducing heat losses through the building envelope. Effective measures include thermal insulation of external walls, roof and floors, the use of high-performance thermal windows and the elimination of thermal bridges.

These passive measures can reduce heating energy demand by up to 30–50%, depending on the initial building condition [3].

The energy performance of buildings is significantly influenced by the quality of the building envelope. Improving the envelope represents an effective solution for reducing energy consumption, enhancing thermal and acoustic comfort, and extending

the service life of buildings. This paper presents the main strategies for improving building envelopes, the materials used, insulation methods, and thermal bridge control techniques, as well as their impact on energy efficiency and building sustainability. Implementation challenges and future development perspectives are discussed in the context of the European regulatory framework for nearly zero-energy buildings (NZEB).



**Fig.2.** Building envelope improvement measures for energy efficiency

The building envelope represents the external layer that separates the indoor environment from outdoor conditions and plays a crucial role in controlling energy and mass transfer. In the field of civil engineering, the energy efficiency of a building is directly related to the thermal and acoustic performance of its envelope. In the context of increasing energy costs and stricter environmental regulations, improving the building envelope has become a necessity for reducing energy losses, ensuring structural protection, and enhancing occupant comfort.

**a). Objectives of Building Envelope Improvement:**

The main objectives pursued through building envelope modernization are:

1. Reduction of heat losses during the cold season and limitation of heat gains during summer.
2. Improvement of thermal and acoustic comfort within the building.
3. Extension of structural durability by protecting the building against moisture, condensation, and weather exposure.

4. Reduction of environmental impact through decreased energy consumption and lower CO<sub>2</sub> emissions.

**b). Methods for Improving the Building Envelope:**

✓ **Thermal Insulation:**

- Internal insulation is achieved by applying thermal insulation materials to the interior side of walls. This solution preserves the exterior appearance of the building but reduces usable interior space.

- External insulation (ETICS – External Thermal Insulation Composite Systems) involves installing insulation boards on the façade, covered with decorative plaster, thereby preventing thermal bridges and protecting the building structure.

- Roof and floor insulation is carried out using mineral wool, expanded or extruded polystyrene, or polyurethane foam.

✓ **Thermal Bridge Control:**

Thermal bridges are critical areas where heat transfer is intensified. They commonly occur at corners, structural joints, and around window openings. Mitigation solutions include:

- Thermally insulated window frames and profiles.
- Additional insulation at corners and joints.
- Prefabricated elements with optimized thermal performance.

✓ **High-Performance Windows and Doors:**

- Windows with insulating glazing units consisting of double or triple panes filled with inert gas.

- Frames made of PVC, laminated wood, or aluminum with thermal break.
- Airtight seals to prevent air infiltration.

✓ **Ventilation and Airtightness:**

- Vapor diffusion membranes to prevent condensation.
- Mechanical ventilation systems with heat recovery (HRV).
- Careful sealing of joints and gaps to enhance energy efficiency.

Materials Used:

The main modern materials used to improve building envelopes include:

- Expanded polystyrene (EPS) and extruded polystyrene (XPS) – good thermal insulation properties and moisture resistance.

- Basalt and glass mineral wool – effective acoustic insulation and fire resistance.

- Polyurethane foam (PUR/PIR) – spray-applied, adaptable to irregular surfaces.

- Innovative materials, such as aerogels and phase-change materials for thermal energy storage.

**c). Benefits of a High-Performance Building Envelope:**

- Reduction of energy consumption by 30–50%.
- Increased occupant comfort through stable indoor temperatures and improved sound insulation.

- Prevention of mold formation and structural degradation.
- Increase in the market value of the building.

- Contribution to sustainability goals and compliance with NZEB requirements.

**d). Challenges and Future Perspectives:**

The implementation of building envelope improvement technologies may be limited by:

- High initial investment costs.
- Compatibility issues with existing structures, particularly historic buildings.
- The need for accurate design to prevent condensation-related problems.
- Appropriate material selection based on climatic zone and environmental exposure.

Future perspectives include the use of materials with superior thermal performance, the integration of renewable energy solutions, and the development of smart buildings with adaptive envelopes that automatically respond to external conditions and building energy demands.

**Conclusions:**

Improving the building envelope represents a key strategy for enhancing energy efficiency, comfort, and durability in civil engineering constructions. Proper material selection, effective thermal bridge control, and the optimization of windows and doors significantly contribute to improved thermal and acoustic performance. In the context of modern regulations and sustainability objectives, building envelope modernization constitutes a strategic step toward the development of energy-efficient and durable buildings.

### **3.2. Efficient Heating and Cooling Systems**

The use of modern heating and cooling systems significantly contributes to energy savings. Common solutions include air-to-water and ground-source heat pumps, condensing boilers, ventilation systems with heat recovery and high-efficiency air conditioning units [4].

#### **Ventilation Systems with Heat Recovery:**

Ventilation systems with heat recovery play a crucial role in ensuring adequate indoor air quality while minimizing energy losses in modern buildings. These systems are particularly important in energy-efficient and airtight constructions, where natural infiltration is insufficient to meet ventilation requirements.

A heat recovery ventilation (HRV) system operates by supplying fresh outdoor air to interior spaces while simultaneously extracting stale indoor air. The defining characteristic of such systems is the presence of a heat exchanger, which enables the transfer of thermal energy from the exhaust air stream to the incoming supply air without mixing the two airflows. As a result, a significant portion of the thermal energy that would otherwise be lost through ventilation is recovered.

During the heating season, the warm exhaust air transfers heat to the colder incoming air, thereby preheating it before it enters the occupied spaces. Conversely, during the cooling season, the process helps reduce the cooling load by transferring

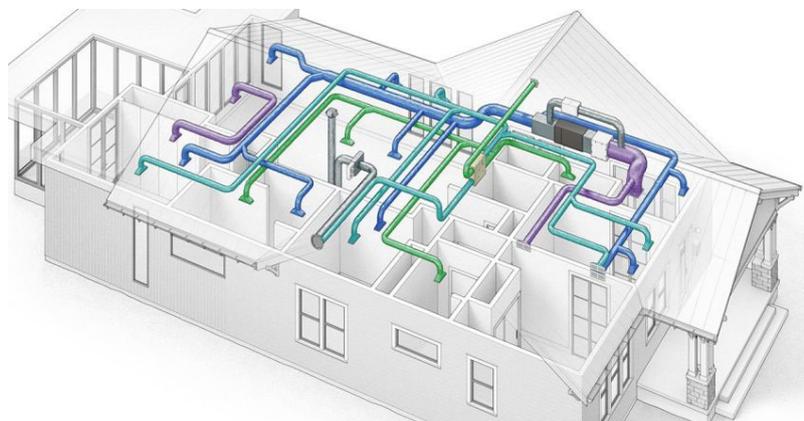
heat from the incoming warm air to the cooler exhaust air. Modern heat exchangers, particularly counterflow and cross-counterflow designs, can achieve heat recovery efficiencies ranging from 60% to over 90%, depending on system configuration and operating conditions.

Two main categories of heat recovery ventilation systems are commonly used: heat recovery ventilators (HRV) and energy recovery ventilators (ERV). HRV systems recover only sensible heat, whereas ERV systems also allow for the transfer of latent heat, enabling partial moisture exchange between the air streams. Consequently, HRV systems are generally more suitable for cold or temperate climates, while ERV systems are preferred in warm or humid regions where indoor humidity control is essential.

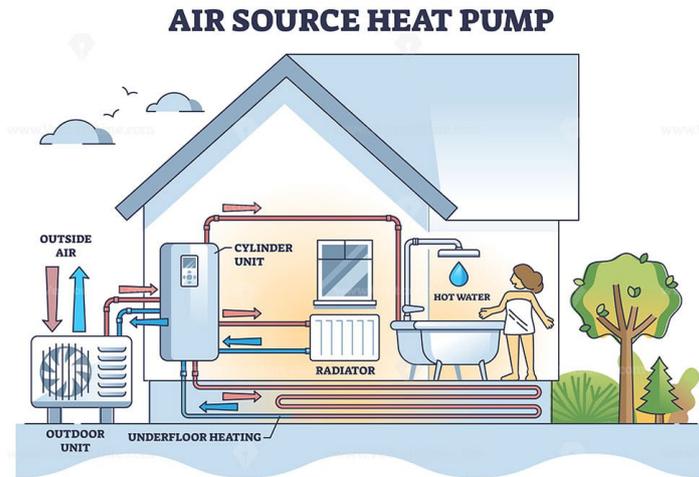
The implementation of ventilation systems with heat recovery offers multiple benefits. From an energy perspective, these systems significantly reduce heating and cooling demand, contributing to lower operational energy consumption and compliance with nearly zero-energy building (NZEB) requirements. From an indoor environmental quality standpoint, continuous mechanical ventilation ensures the removal of carbon dioxide, volatile organic compounds, excess moisture, and odors, thereby enhancing occupant health and comfort. Furthermore, by controlling indoor humidity levels, these systems reduce the risk of condensation and mold formation, contributing to improved building durability.

Despite their advantages, the effectiveness of heat recovery ventilation systems depends strongly on proper design, installation, and operation. Key factors include adequate airtightness of the building envelope, correct airflow rates, balanced supply and exhaust volumes, well-insulated ductwork, and regular maintenance of filters and mechanical components. Inadequate design or poor installation may result in reduced efficiency, increased noise levels, or compromised indoor air quality.

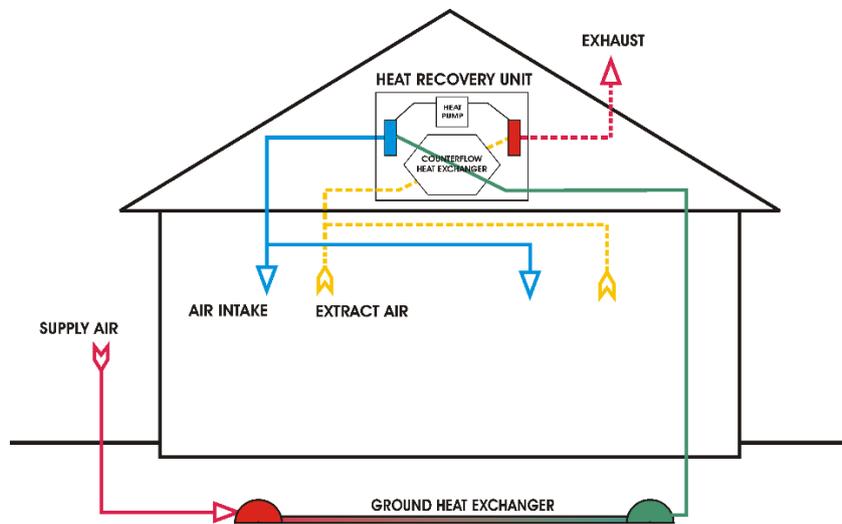
In conclusion, ventilation systems with heat recovery represent a fundamental component of modern energy-efficient building design. By combining controlled ventilation with high energy performance, these systems support sustainability objectives, enhance indoor environmental quality, and extend the service life of building components. Their integration is therefore essential in contemporary civil engineering practice, particularly in low-energy and nearly zero-energy buildings.



a).



b).



c).

**Fig.3.** Efficient heating, cooling and ventilation systems in residential buildings

### 3.3. Energy-Efficient Lighting

Replacing conventional lighting systems with LED technology, combined with presence sensors and automatic daylight control, leads to substantial energy savings. Energy consumption for lighting can be reduced by up to 70% using modern control solutions [5].

### 3.4. Building Automation and Smart Systems

Smart Home and Building Management Systems enable automatic control of lighting, heating and cooling based on occupancy and predefined schedules. These systems rely on sensors, controllers and IoT technologies, allowing real-time monitoring and optimization of energy use [6].

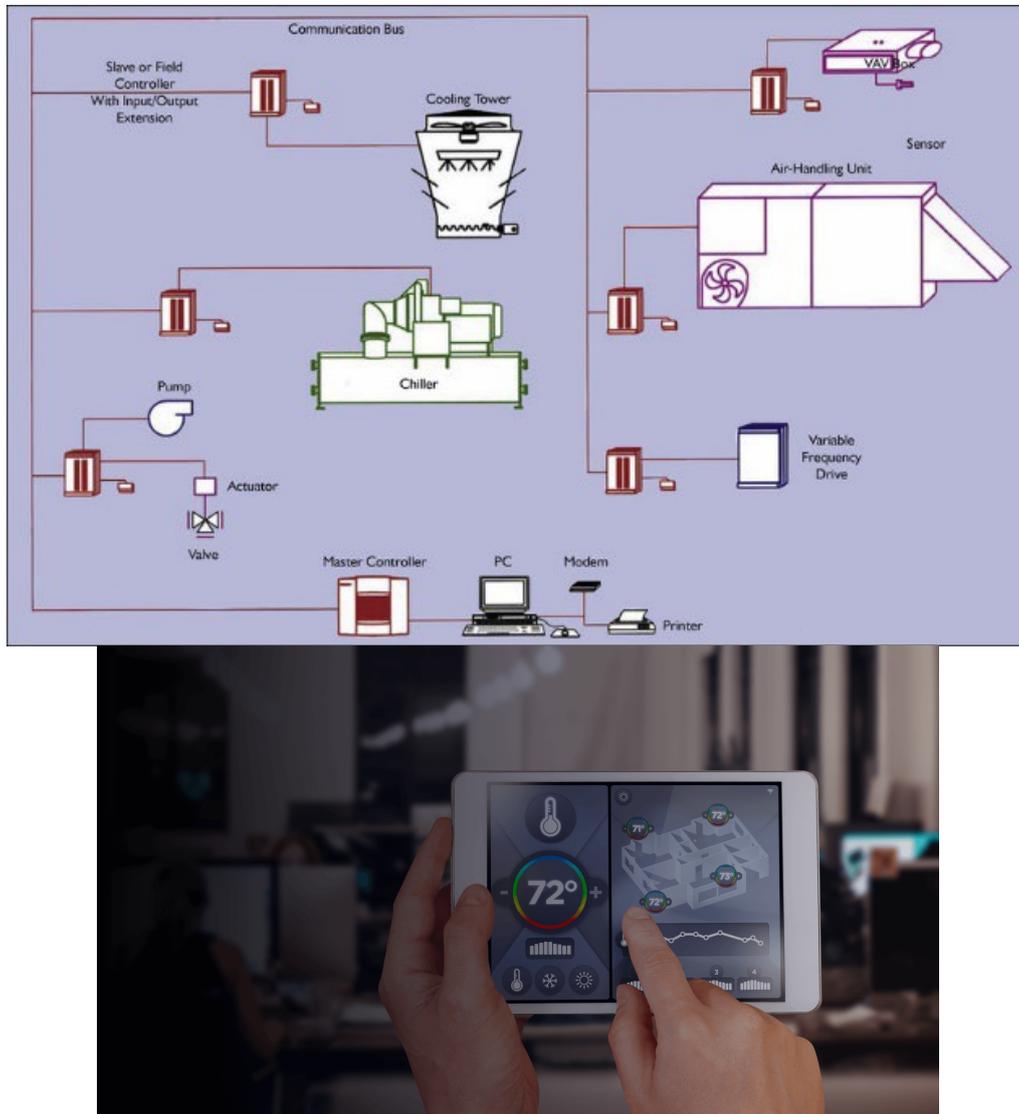


Fig.4. Smart Home system architecture for energy optimization

### 3.5. Integration of Renewable Energy Sources

Renewable energy systems play an essential role in reducing dependence on conventional energy sources. Photovoltaic panels, solar thermal collectors and hybrid grid-connected systems contribute to lower CO<sub>2</sub> emissions and reduced operating costs [7].

#### 4. MONITORING AND ANALYSIS OF ENERGY CONSUMPTION

Energy monitoring is performed using energy meters, sensors and data acquisition systems connected to software platforms. Continuous monitoring allows the identification of inefficiencies and supports data-driven decision-making for energy optimization [8].

#### 5. CASE STUDY: ENERGY OPTIMIZATION IN A RESIDENTIAL BUILDING

##### 5.1 Building Description

The case study analyzes a multi-family residential building equipped with thermal insulation, LED lighting, a heat pump system and a basic Smart Home solution for energy monitoring.

##### 5.2 Results and Discussion

The implementation of passive and active measures resulted in an overall energy consumption reduction of approximately 35%, with improved thermal comfort and lower operational costs.



Fig.5. Energy consumption before and after optimization – case study

## 6. BENEFITS OF ENERGY CONSUMPTION OPTIMIZATION

Optimizing energy consumption in residential buildings provides multiple benefits, including reduced operating costs, improved indoor comfort, lower environmental impact, increased property value and compliance with current regulations.

## 7. CONCLUSIONS

Energy consumption optimization in residential buildings represents a key strategy for sustainable development. By combining passive measures, efficient technologies and intelligent control systems, significant energy savings can be achieved. The integration of renewable energy sources further enhances building performance and contributes to environmental protection and improved quality of life.

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