E3S Web of Conferences **667**, 01002 (2025) https://doi.org/10.1051/e3sconf/202566701002
*AEE2025*

# Survey of available technologies for zero carbon and energy balance houses

*Kristián* Mičko[1,*] and *Tatiana* Soľaková[1,**]

[1]Technical University of Košice, Center of Circular and Low-Emission Construction, Vysokoškolská 4, 040 01 Košice

**Abstract.** The decarbonization of industry is important to minimize the negative aspects of climate changes. One of the industrial direction is the civil engineering industry, including construction and building flats, houses, and commercial property. The commercial and private hauses has a significant impact to production of greenhause gases including $CO_2$. This paper surveys the available renewable sources of energy usable for making comfort living conditions in the buildings. This kind of energy could significantly reduce the greenhause gases compared to fosil fuels. This study also shows the methodology how can be measured and modelled the potential behavior of houses with zero energy balance gained by in-site installed renewable energy sources. Comparison of each technology, we can analyse the strength and weakness of each energy sources. According to analysis, it could be choosen the optimal solution on implementing of decarbonization strategy in new buildings.

## 1 Introduction

In recent years, the scientific community has shown strong interest in zero-energy buildings and homes. A crucial strategy for addressing climate change is to reduce greenhouse gas emissions, with the construction industry playing a significant role in global $CO_2$ output. Assessing a building's environmental footprint typically involves analyzing its energy consumption, calculating emissions, and comparing the results with those of other structures [1].

Zero-energy buildings are specifically designed to consume minimal energy while generating their own power from on-site renewable sources. This has led to a growing body of research focused on developing new technologies and methods to enable the creation of such buildings. Studies suggest that the first step toward achieving zero-energy performance is minimizing overall energy demand. Subsequently, a comprehensive strategy for energy conservation and environmental protection should be implemented. However, the effectiveness of these buildings depends on the integration of advanced renewable energy systems and sophisticated building technologies. Therefore, reliable evaluation methods are essential to guide their development and ensure long-term performance. [2].

This paper is structured as follows: Sect. 2 describes the kind of renewable sources. In Sect. 3, there is a description of energy storage. The concepts of and methodology to measure

*e-mail: kristian.micko@tuke.sk
**e-mail: tatiana.solakova@tuke.sk

of level decarbonization the buildings is described in Sect. 4. The examples for each concept is written in Sect. 5. The knowledge of this paper are concluded in Sect. 6.

## 2 Renewable energy sources

Comfortable living conditions in houses, apartments, and commercial buildings require both electrical and thermal energy sources. In the 20th century, the most commonly used sources for generating heat and electricity were derived from fossil fuels. These fuels affected the environment not only at mining sites but also during the energy production process. The fossil fuel market crisis caused by the Iranian Revolution in 1979 and the subsequent sanctions on Iran's exports forced Western countries to develop new types of energy sources. Climate change has also reinforced this trend toward seeking sustainable energy alternatives [3] (Figure 1).

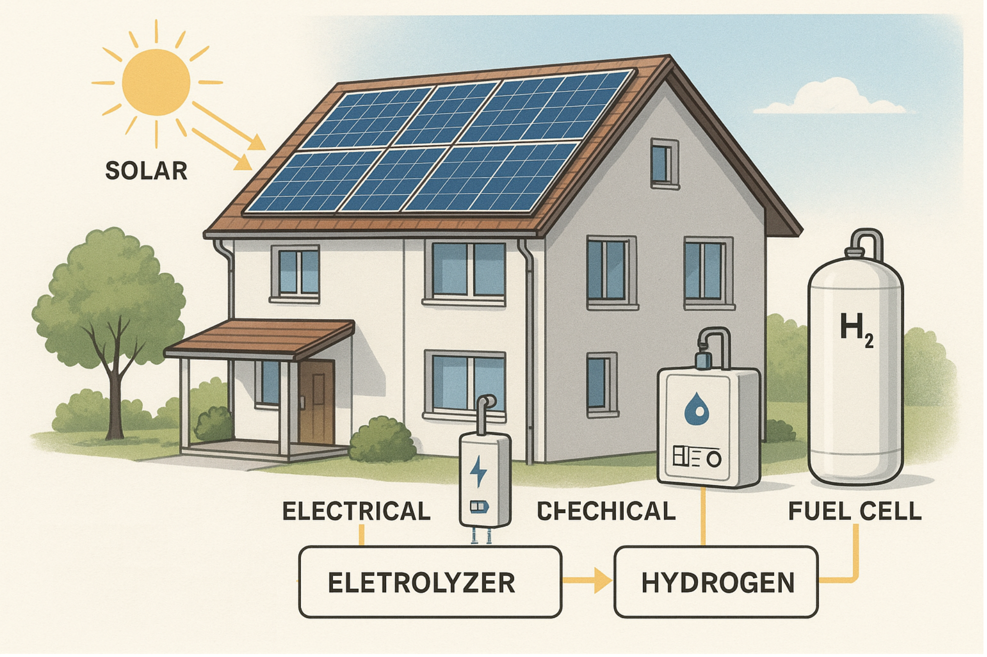


**Figure 1.** Ilustration of house with renewable energy sources

Renewable energy sources can be divided into several groups:

1. Chemical energy sources,
2. thermogenerators,
3. photovoltaic panels,
4. wind power,
5. bacterial-origin source,
6. hydropower,

7. biomass,

8. geothermal energy.

**Chemical energy sources** - these sources generate electrical energy through chemical reactions. One of the most widely used chemical sources is the hydrogen-powered generator. Hydrogen fuel cell generators are a clean alternative to fossil fuels; however, they are technically demanding to construct due to the high reactivity of hydrogen in open air, particularly with oxygen [4].

**Thermogenerators** - they convert heat energy into electricity. A Peltier module is one of the fundamental components used in the construction of thermogenerators. This module is also commonly used in low-cost cooling devices, such as small portable freezers designed for outdoor (camping) use. Thermogenerators have a low efficiency coefficient and, therefore, are not widely used for large-scale electricity generation. However, they can serve as a supplementary source of electrical energy in cases where waste heat cannot be utilized for other practical purposes [5].

**Photovoltaic panels** - they generate electricity from light, most commonly from sunlight. The first generation of photovoltaic cells was not efficient enough for widespread use. These cells were primarily developed for devices sent into space, such as probes and orbital satellites, where sunlight is abundant. However, research in the field of photovoltaic cell chemistry has increased their efficiency to more than 30%. This progress allows for the generation of more electricity using a smaller surface area compared with first-generation photovoltaic cells [6].

**Wind power** – this type of power has historically been used in various applications, including sailboats, as well as for tasks such as water pumping and grain milling. In modern times, other energy sources are often employed for these purposes. However, wind power continues to be utilized for electricity generation, although its use is limited by suitable climatic conditions in specific geographical regions. On the other hand, wind turbines installed across large areas can pose ecological challenges, particularly by disrupting the migration routes of endangered bird species. Another concern is the environmental impact associated with the manufacturing and lifecycle of turbine blades [7].

**Hydropower** – water influences weather in many ways. Energy can be obtained from water through dams, reservoirs, or sea wave generators. Hydropower plants require large areas for construction and significant material investments. However, they are a clean, renewable source of energy with a high efficiency coefficient. On the other hand, hydropower plants have limited geographical availability [8].

**Biomass** – waste from agricultural and woodworking industries can be effectively processed to generate heat and electrical energy. This renewable energy source helps reduce greenhouse gas emissions and mitigate other negative environmental impacts. However, the production of biomass energy remains costly, and inappropriate agricultural policies could create challenges for the food industry due to the higher profitability of cultivating biomass crops instead of food [9].

**Geothermal energy** – this is one of the most efficient renewable sources of thermal energy. Heat extracted from the Earth can also be converted into electrical energy using thermogenerators. However, the utilization of geothermal energy is limited by geographical availability, and the initial investment required for constructing geothermal power systems is relatively high [10].

# 3 Energy storage

Electrical and thermal energy have limitations in terms of storage. Electrical energy cannot be stored efficiently over long periods. Certain engineering solutions make it possible to convert and store electrical energy in mechanical form. However, the conversion from one form of energy to another always involves some losses. Thermal energy can be stored more efficiently than electrical energy, but its storage capacity and efficiency depend on the engineering design of the system's insulation from external conditions. This section discusses the available technologies for energy storage.

## 3.1 Heat storage

Heat storage is a mechanism that allows to maintain thermal energy for a certain period of time. This kind of storage can be divided into two categories:

1. Short-time period,

2. long-time period.

**Short-time period of heat storage** - this type of storage maintains its temperature for a period of one to two days. Water boilers are widely used as short-time heat storage systems due to their low construction costs and the favorable thermal properties of water. One limitation of water, however, is that its physical properties vary with changes in pressure and temperature, which are related to the specific volume of the stored water. [11].

**Long-time period of heat storage** - this type of storage can maintain its temperature for a period of one month or even longer. For this purpose, sand heat batteries have been proposed. With appropriate design, such heat batteries can retain thermal energy for several months, thereby reducing the operating costs of residential houses and buildings. The main limitation of this storage technology is the high initial investment required for its construction and installation [12].

## 3.2 Electrical storage

Electrical storage systems can be divided into two main categories: electrochemical and mechanical. Electrochemical storage systems are rechargeable batteries. They have a high efficiency coefficient but consist of critical metals such as lithium and cobalt. The mining of these metals causes numerous environmental problems, including soil degradation and the pollution of water sources.

Mechanical energy storage systems can be categorized into several groups, including gravitational and gyroscopic (flywheel) batteries, each with different design configurations. Gravitational batteries utilize surplus energy (for instance, from solar panels) to lift heavy concrete blocks to a defined height. When electrical energy is required, these blocks are lowered, releasing stored potential energy that is converted back into electricity. The main operating principle is based on the use of mechanical potential energy. Conversely, gyroscopic batteries, such as flywheels, store energy in the form of mechanical kinetic energy. The surplus energy is used to accelerate the rotating mass to its maximum speed, thereby reaching peak kinetic energy. When electricity is needed, the flywheel's rotational motion is coupled with a generator to produce electrical power [13].

## 4 Net zero building concept

The construction of buildings has an impact on the energy and material consumption. The life cycle of usage buildings depends on architectural design, placement in the terrain, and the construction or insulation materials. An unsuitable type of construction increases the demands for heating or cooling the building. It causes the increased electrical or gas energy consumption [14].

Sustainable constructions require an analysis of the microclimate of the selected terrain to design and construct the building process. If the analysis is taken into account, then the building significantly reduces the energy demands. The building's energy demand can be analysed via the various metrics such as *Energy Use Intesity (EUI)*. The *EUI* is defined as:

$$EUI = \frac{E}{A \cdot t}$$

where:

$$E = \text{energy}$$
$$A = \text{area}$$
$$t = \text{time}$$

Basic unit of *EUI* is:

$$\left(\frac{\text{kWh}}{\text{m}^2 \cdot \text{year}}\right)$$

Another metric is *Thermal Energy Demand Intesity (TEDI)* defined as follows:

$$TEDI = \frac{Q_{heating}}{A \cdot t}$$

where:

$$Q_{heating} = \text{energy for heating or cooling building}$$

The basic unit of measurement for *TEDI* is the same as that used for *EUI*. The difference between *TEDI* and *EUI* is in the usage of energy. In the case of *EUI* metric, there is included the energy used for lights, electric devices, water boiling and maintaining habitable temperature. *TEDI* is the energy only for maintaining habitable temperature.

Aforementioned metrics measure the kind of energetical consumption. There are also metrics for energy production of buildings from renewable energy sources. *Renewable Energy Generation (REG)* is measured via $kWh/m^2 \cdot year$ that is the same unit as for *EUI* and *TEDI*. The calculation of this value depends on the source of energy mentioned in Sect. 2. If we compare consumed and produced (from renewable sources) $E$, then we can calculate the next metric *Net Energy Balance (NEB)*. The formula is:

$$NEB = \sum E_{consumed} - \sum E_{produced}$$

When we $E$ multiply by the energy tariff, we get *Net Cost Energy Balance (NCEB)*. *NCEB* defines the economical efficiency of buildings. The production and consumption $E$ makes greenhause gases emissions that are measured by *greenhause gases emissions intensity (GHG Emissions Intensity)*. The measure unit is $kg\ CO_2/m^2 \cdot year$. The calculation of *GHG Emissions Intensity* depends on the type of each energy source. The formula is:

$$GHG\ Emissions\ Intensity = \frac{\sum Emissions\ from\ all\ sources}{A \cdot t}$$

where:

$$Emissions = E \cdot Emission\ Factor\ of\ energy\ source$$

Based on these metrics, we can categorize the buildings into the following groups. Nearly Zero Energy Buildings (NZEnB) where is *NEB* close to zero, but in low negative values. There are buildings with significant on-site production of *E* from renewable sources, but these buildings still have to import part of *E* from public utilities. However, *E* from renewable sources noticeably reduces the *GHG Emissions Intensity* or cost operation of those buildings. Zero Energy Buildings (ZEnB) have zero value difference between the consumption and production of *E* because renewable sources of *E* on-site are efficiently used for the operation needs of the buildings. The construction of these buildings are rare. Passive buildings are buildings where $Q_{heating}$ is close to zero or zero value. They reduce operation cost, but use imported *E* for eletrical devices and light. Zero Emissions Buildings (ZEmB) are buildings constructed from recyclable materials and using the *E* for their operation from clean sources including imported *E* from public utilities. Zero Energy Cost Buildings (ZEnCB) are buildings where the *NCEB* is value of zero. ZEnCBs produce the *E* from renewable sources in suitable year period (for example, summer for solar panels) to monetize the *E* and profit use to buy *E* when the renewable sources not produce the *E*. Proficit Energy Buildings (PEnB) are buildings with positive *NEB* value.

## 5 Discussion

Sustainable and ecological buildings offer many benefits. However, the construction of them requires many efforts from the side of environmental, architectural engineers and economist. Passive houses are a great choice for low-cost construction with low level of *GHG Emissions Intensity*. However, imported *E* could expensive for operation needs of this houses. These houses could be built from straw briquette.

The highest rate of NZEnB built houses or buildings in the EU holds in France, Germany, Italy, UK, and Poland, but many countries in the EU have to prepare the strategy to increase them. The biggest challenge for these countries is to reconstruct existing buildings to this standard.

ZEnCB are focused on improving the owners family budget. However, a house design with suitable construction material enables indirectly to reduce greenhause gases emissions from the operational living cycle. The installation of this system is costly and requires some grants from the government. However, the investments are returned in several years according to volatility of *E* tarrif in the market.

The combination of various renewable energy sources and storages mentioned in Sect. 2 and Sect. 3 could be used for construction of ZEnB. ZEnB also needs the suitable geographical area to implement. The good news is that every country has some natural conditions to use one of the renewable source combination and implement at least NZEnB. Japan as the country with ocean access and vulcanic mountains built the prototype of ZEnB. This ZEnB use the combination of hydrogen fuel cells, solar panels and geothermal energy.

PEnB and houses are rarity, but this is property when the environmental goals to be used as form of passive income. The higher value of produced *E* over consumed *E* lead to sell the *E* into public utilities. The monetization of *E* is important to return investment in a short period. Many environmental solutions have long-period time to return of investments, but this Heliotrop building is the example for realizing this ambitious concept.

Based on the case studies reported by [15], *EUI* and *NEB* can be quantified directly from annual energy flows and floor area. For example, the Adam Joseph Lewis Center (1260 $m^2$, 160 $kW$ PV) achieves an estimated *EUI* of about 152 $kWh/m^2{\cdot}year$ and a net energy balance close to zero, assuming typical PV yields. Similarly, the Aldo Leopold Legacy Center (1100 $m^2$, 39.6 kW PV) produces approximately 10% more electricity than it consumes annually, yielding a positive NEB of 0.1·E use, while the Montreal R-2000 dwelling reduces its annual electricity demand from 24.1 *MWh/year* to 13.6 *MWh/year* by using a ground source heat pump and reaches NEB 0 when coupled with an 85.4 $m^2$ PV array.

According to aforementioned examples and Section 2 we can summarise these results in SWOT analysis (Table 1).

| **Energy Source** | **Strengths** | **Weaknesses** | **Opportunities** | **Threats** |
|---|---|---|---|---|
| **Chemical energy sources** | High energy density, controllable output | Complex storage, safety risks, high costs | Development of safe storage and green hydrogen | Public safety concerns, expensive production |
| **Thermogenerators** | Simple, reliable, no moving parts | Very low efficiency, costly materials | Use of waste heat, nanomaterial improvements | Competition from more efficient technologies |
| **Photovoltaic Panels** | Clean, scalable, rapidly improving efficiency | Weather-dependent, large area required | Integration in buildings (BIPV), cost reduction | Waste and recycling issues, lifespan degradation |
| **Wind Power** | Mature, low operating cost, high potential | Intermittent generation, visual/noise impact | Offshore wind farms, hybrid systems | Environmental impact on fauna, high capital cost |
| **Hydropower** | High efficiency, stable output, long lifespan | High construction cost, environmental impact | Modernization of dams, micro-hydro systems | Climate change, sedimentation, ecosystem damage |
| **Biomass** | Renewable, uses waste, carbon-neutral | Competes with food, land-intensive | Biofuel and biogas development | Deforestation, high logistics cost |
| **Geothermal Energy** | Constant, efficient, low emissions | Geographically limited, expensive drilling | Deep drilling innovations, hybrid systems | Geological risks, high initial investment |

**Table 1.** Comparison of Different Energy Sources

## 6 Conclusion

Modern houses and commercial buildings need to reduce negative environmental impact. The effective way is via the adoption of ZEnBs. Renewable energy sources such as solar, wind, biomass, and geothermal power, along with innovative technologies like microbial fuel cells, and decreasing the usage of fossil fuels can significantly minimize the *GHG Emissions Intensity*. Furthermore, improved building insulation and design can reduce *E* losses and promoting long-term sustainability.

Optimizing the *E* consumption process to *NEB* or near-zero energy balance presents challenges: such as demanding input costs, geographical, and technological limitations; we can overcome these barriers through supportive government policies, financial support, and ongoing research and innovation. Self-sufficient buildings are characterized by a combination of smart architectural design, renewable *E* integration, and advanced *E* storage solutions.

Ultimately, ZEnBs do not only contribute to climate changes, but also provide long-term economic benefits for their providers. The progress of technology enabling the widespread implementation of these sustainable construction concepts. These concepts can play a key role in achieving global *E* efficiency and emission reduction targets.

Every building has the potential to reduce its carbon and greenhouse gas emissions. It cannot be guaranteed that climatic conditions will always be suitable for all buildings and houses to achieve a net-zero energy balance and thereby become carbon neutral. However, there are always technologies available that can significantly reduce energy consumption and the overall carbon footprint. In future research, we will focus on analyzing climatic phenomena affecting existing buildings and propose strategies to reduce their carbon footprint through the installation of appropriate technologies for generating thermal and electrical energy suited to specific climatic conditions.

## Acknowledgments

This paper is part of a project titled “DEKAST: Research and innovation for the decarbonization of construction activities through low-emission construction processes and materials in the circular economy” under number of 09I04-03-V02-00051 and the Scientific Grant Agency of the Ministry of Education, Science, Research and Sport of the Slovak Republic (VEGA - 1005724).

## References

[1] M. Shirinbakhsh, L.D. Harvey, Net-zero energy buildings: The influence of definition on greenhouse gas emissions, Energy and Buildings **247**, 111118 (2021).

[2] S. Schimschar, K. Blok, T. Boermans, A. Hermelink, Germany’s path towards nearly zero-energy buildings—enabling the greenhouse gas mitigation potential in the building stock, Energy Policy **39**, 3346 (2011).

[3] P. Esmaeili, M. Rafei, M. Salari, D. Balsalobre-Lorente, From oil surges to renewable shifts: Unveiling the dynamic impact of supply and demand shocks in global crude oil market on us clean energy trends, Energy Policy **192**, 114252 (2024).

[4] L. Tkáč, F. Schauer, Ž. Gerhátová, Chemical energy sources transformations by remote experiment, International Journal of Online Engineering (iJOE) **10**, 35 (2014).

[5] M. Neska, M. Mrozek, A. Majcher, Modular thermoelectric conversion system for low-temperature thermal energy, in *E3S Web of Conferences* (EDP Sciences, 2025), Vol. 636, p. 05002

[6] P.K. Nayak, S. Mahesh, H.J. Snaith, D. Cahen, Photovoltaic solar cell technologies: analysing the state of the art, Nature Reviews Materials **4**, 269 (2019).

[7] A.M. Foley, P.G. Leahy, A. Marvuglia, E.J. McKeogh, Current methods and advances in forecasting of wind power generation, Renewable energy **37**, 1 (2012).

[8] K.P. Garrett, R.A. McManamay, A. Witt, Harnessing the power of environmental flows: Sustaining river ecosystem integrity while increasing energy potential at hydropower dams, Renewable and sustainable energy reviews **173**, 113049 (2023).

[9] N.E. Benti, G.S. Gurmesa, T. Argaw, A.B. Aneseyee, S. Gunta, G.B. Kassahun, G.S. Aga, A.A. Asfaw, The current status, challenges and prospects of using biomass energy in ethiopia, Biotechnology for Biofuels **14**, 209 (2021).

[10] R. Rohit, D.C. Kiplangat, R. Veena, R. Jose, A. Pradeepkumar, K.S. Kumar et al., Tracing the evolution and charting the future of geothermal energy research and development, Renewable and Sustainable Energy Reviews **184**, 113531 (2023).

[11] N. Kanojia, S. Kaushik, S. Ali, A. Joshi, S. Singh, A. Kumar, B.K. Rewani, P.K. Gupta, S. Alam, Review on sustainable thermal energy storage technology with packed bed regenerator, Neuro Quantology **20**, 2324 (2022).

[12] P. Niksiar, C. Rogillio, H. Torab, S. Tiari, Experimental study of a silica sand sensible heat storage system enhanced by fins, Energies **17**, 5402 (2024).

[13] M.E. Amiryar, K.R. Pullen, A review of flywheel energy storage system technologies and their applications, Applied Sciences **7**, 286 (2017).

[14] S. Deng, R. Wang, , Y. Dai, How to evaluate performance of net zero energy building–a literature research, Energy **71**, 1 (2014).

[15] M. Kapsalaki, V. Leal, Recent progress on net zero energy buildings, Advances in Building Energy Research **5**, 129 (2011).