Review of optimization solutions for zero-energy buildings with the approach of using renewable energies

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ABSTRACT

In recent years, environmental concerns and increasing energy demand have promoted the idea of zero-energy buildings. These types of buildings are designed to be efficient in fossil energy consumption and decarbonization, and operate by combining optimization strategies and renewable technologies. In this research, by reviewing the latest research in the field of zero-energy buildings, emerging technologies such as photovoltaic-thermal panels, multi-generation systems, solar energy integration with thermal storage, and fuel cells are reviewed and evaluated. Valid research also demonstrates the fact that the use of hybrid approaches and appropriate design can lead to high efficiency, pollution reduction, and economic optimization. The aim of this article is to determine the research and design paths towards buildings with net zero energy consumption and can help researchers and designers in the process of developing sustainable buildings and looking to the future.

Keywords: Zero energy building, energy consumption optimization, multigenerational system, photovoltaic thermal system, exergy analysis, sustainable design

1. INTRODUCTION

Carbon-neutral buildings are buildings that do not rely on any fossil fuel sources and do not emit carbon emissions. These buildings are considered modern buildings. A carbon-neutral building is designed and managed in such a way that it not only emits no carbon dioxide but also, at some stage, is synonymous with negative emissions over a year. After the optimization modifications are implemented and the energy demand is reduced, the remaining balance is provided by renewable energy technologies [1].

These buildings combine energy efficiency and renewable energy generation such that, over a given horizon, no more energy is consumed than is produced from on-site renewable sources. Achieving carbon neutrality is an ambitious and currently achievable goal, and is rapidly expanding in diverse geographies and markets [2]. Researchers are increasingly looking at designing and deploying these buildings in a way that reduces dependence on fossil fuels, and in response to regulatory authorities, many local governments are developing and moving towards the goal of carbon neutrality in buildings [3].

The transition to zero-energy buildings will, in the long term, reduce environmental damage, lower operating and maintenance costs, increase resilience to outages and natural events, and enhance energy security [4]:

During the design and construction or renovation of such buildings, different approaches can be used, including: integrated design, updating equipment and systems, reducing electrical loads, and utilizing energy-saving programs [5].

Zero-energy buildings make it simple and inexpensive to intelligently reduce energy consumption and meet their needs from renewable sources [6]. These buildings have significant potential to transform energy consumption habits, and more and more are being used due to the combination of people who want to achieve this philosophy of updating and increasing monitoring.

Non-renewable energy sources have always been inherently limited. However, in the current era, with the increase in population and the subsequent expansion of energy needs in residential buildings, this limitation has become increasingly noticeable. Gas and oil reserves are rapidly decreasing, and this trend has sounded a serious alarm. Therefore, the use of wind and solar energy to meet human needs is not only a choice, but a necessity. If countries can use these renewable resources wisely, on the one hand, the process of global warming will slow down, and on the other hand, the costs imposed by the consumption of fossil fuels will be reduced. For this reason, solar energy is increasingly popular in the design and construction of buildings today and is recognized as one of the most efficient ways to provide energy in residential homes [7].

Given the growing demand for sustainable energy sources in the construction industry, the aim of this article is to collect and carefully analyze the latest research in the field of optimizing zero-energy buildings and to examine new technologies used in this regard. The innovation of this study is to present a combined approach to various technologies, compare the findings of reputable research, and highlight the role of multigenerational systems and sustainable design in the future development of smart and sustainable buildings.

2. REVIEW OF THE RESEARCH BACKGROUND

In 2024, Assareh et al. designed a solar multigeneration system for a 120-unit residential complex in Sydney. Over the course of a year, the residential building consumed 36,728 kWh of electricity, 133,123 kWh of heating and 17,902 kWh of cooling. Notably, their proposed system was capable of producing 166,164 kWh of electricity, 467,945 kWh of heating and 183,370 kWh of cooling annually. The system achieved an energy efficiency of 25.18% with a cost rate of 46.6$/h. The cycle schematic is shown in Fig. 1 [8].

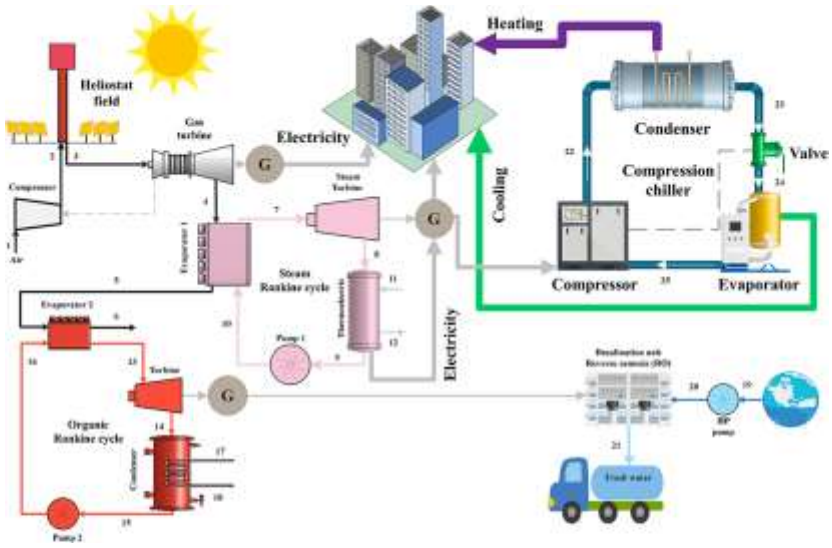

Fig. 1. Schematic of the proposed cycle [8].

In 2020, Khan Mohammadi et al. designed and analyzed a smart hybrid system including a photovoltaic-thermal (PVT) module and a reverse osmosis (RO) unit that generates both electricity, heating, and drinking water. To simulate this system, real data from the cities of Tehran, Doha, and Stockholm were used, and computational operations were performed in EES and TRNSYS software. The results showed that the annual net power of the system at a mass flow rate of 40 kg/h was 588.09, 12556.35, and 2656.83 kW, respectively. Also, the cost of producing fresh water in these three cities was reported to be 0.24, 0.16 and 0.88 €/m3, respectively. In terms of overall costs, Doha had the lowest rate at 19.85 $/h, and the highest exergy destruction of all regions was related to PVT modules. The cycle schematic is shown in Fig. 2 [9].

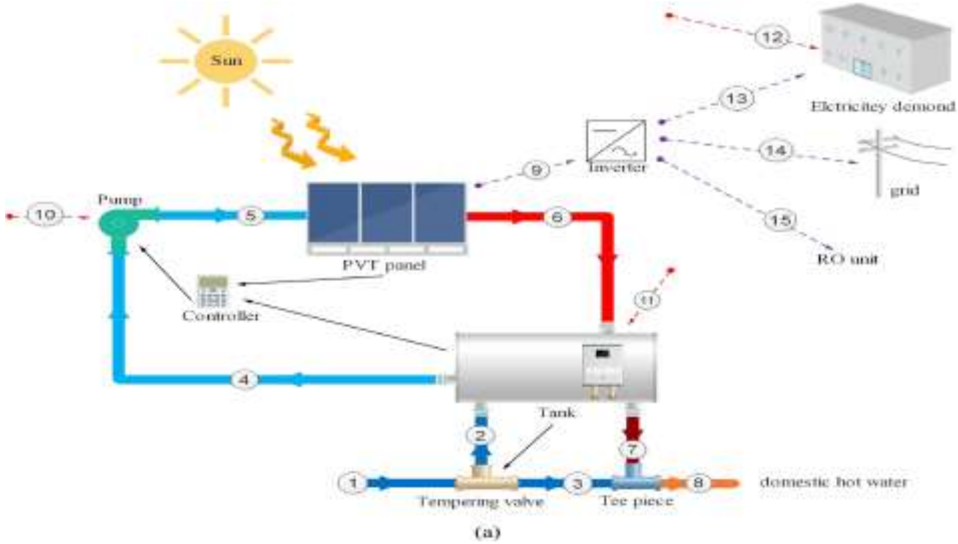

Fig. 2. Schematic of the proposed cycle [9].

In 2020, Behzadi et al. designed a new solar system for a building that integrates into electricity and district heating networks without using batteries and heat pumps. The results showed that the very low temperature model is the most suitable option; in this simulation, over 400 cubic meters of hot water were delivered to the heating network over the course of a year, and approximately 1940 kWh of surplus electricity was injected into the electricity distribution network. Additionally, it produced the highest amounts of electricity and heat, with 3647.4 and 9118.5 kWh, respectively, and the highest overall efficiencies were achieved for ultra-low temperature (74.51%), low temperature (62.35%), and third generation (52.35%) district heating. The cycle schematic is shown in Fig. 3 [10]

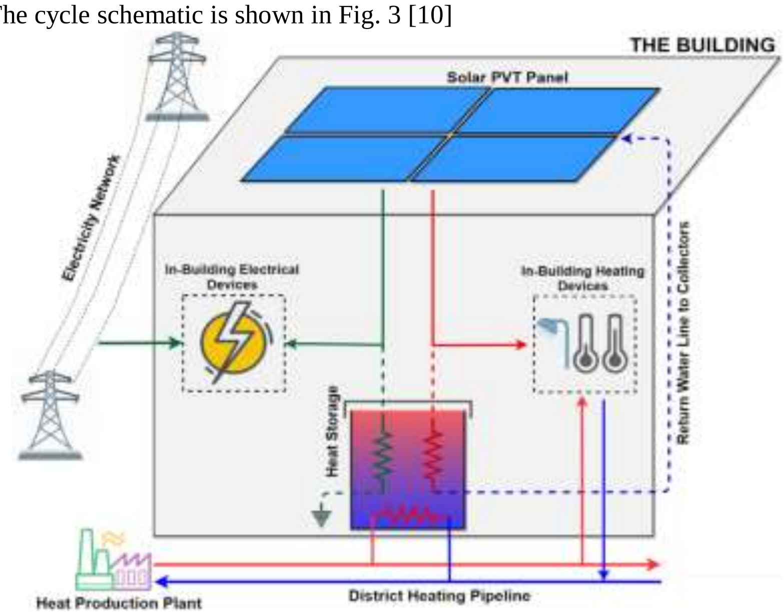

Fig. 3. Schematic of the proposed cycle [10].

In 2022, Ahmad et al. addressed the importance of reducing carbon emissions in the building sector, especially in combating climate change. Considering that this sector accounts for approximately 40% of energy consumption and 36% of global greenhouse gas emissions, the design of net zero energy buildings has been proposed as an effective solution. Additionally, the role of renewable energy sources, including hydroelectricity, wind energy, solar energy, heat pumps, and bioenergy, in the development of this category of buildings was examined. The cycle schematic is shown in Fig. 4 [11].

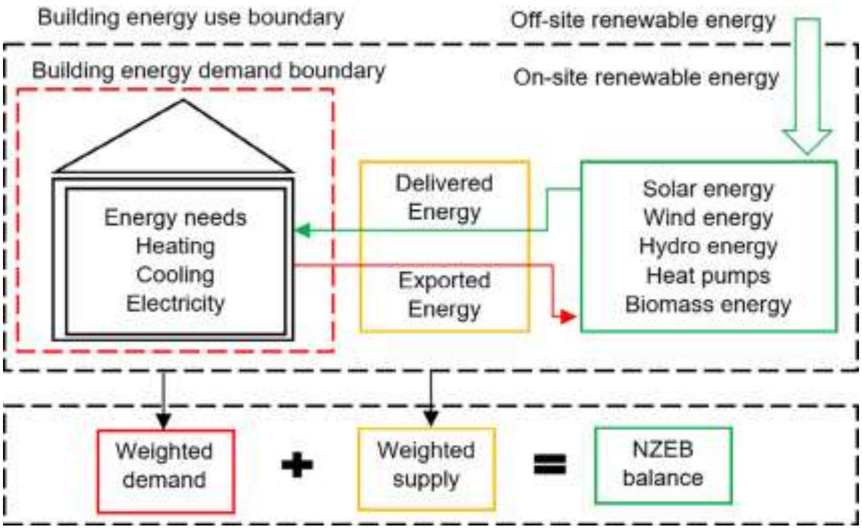

Fig. 4. Definition of a net zero energy building [11].

In 2022, Salameh et al., focusing on the significant increase in energy demand in the United Arab Emirates, designed and optimized a solar absorption cooling system based on LiBr–H_2O solution to reduce the electrical loads associated with air conditioning in residential and industrial sectors. They used TRNSYS to simulate the most critical weeks of the year and in real conditions of a residential unit. The results showed that the coefficient of performance (COP) of the system was about 0.793. The optimization results also showed that the optimal angle of the evacuated tubes is approximately equal to the latitude of the UAE and, considering the solar coefficient of 0.73, a surface area of 40 m2 for the collectors and a volume of 1 m3 for the hot water storage tank are considered the most suitable options. On the other hand, based on life cycle analysis, the introduced solar cooling system has only 43.2% of the economic cost, 8.5% of the energy consumption, and 8.7% of the carbon footprint of the conventional vapor condensation system. The cycle schematic is shown in Fig. 5 [12].

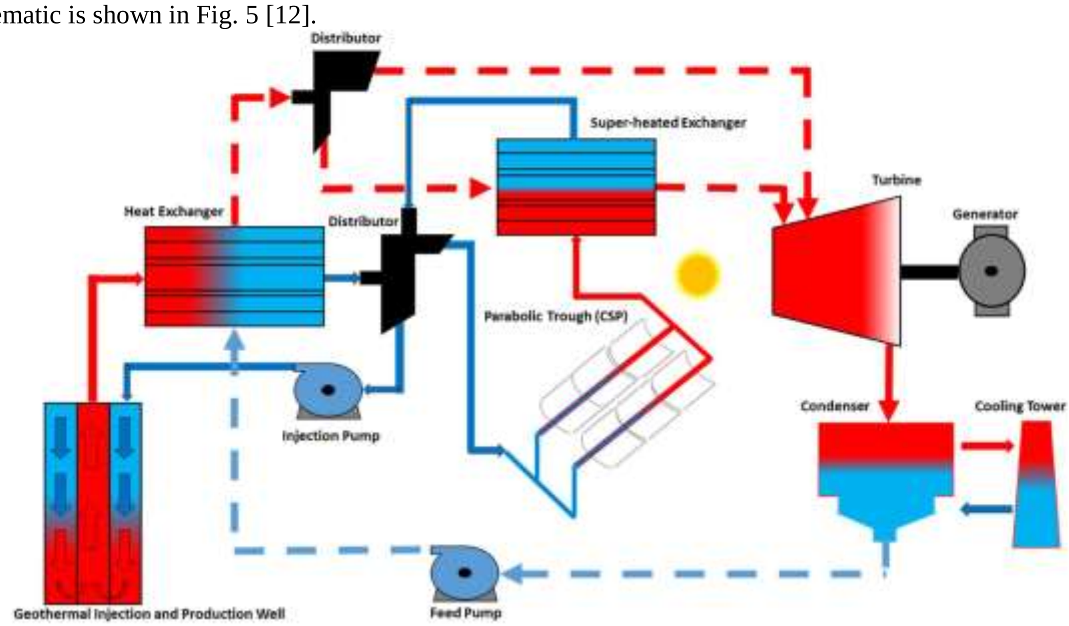

Fig. 5. Schematic of the proposed cycle [12].

Bahramian et al. In 2022, conducted a comprehensive evaluation of an integrated power, heating, and cooling system based on a smart solar-hydrogen hybrid configuration. Their findings showed that under optimal operating conditions, the system achieved significant energy cost reductions of up to 8.46 $/GJ and greenhouse gas emissions of up to 0.37 tons/MWh, while maintaining an annual efficiency of 37.28%. These results highlight the significant potential of advanced micro-scale solar CCHP systems for permanent residential applications, offering environmental and economic benefits. The cycle schematic is shown in Fig. 6 [13].

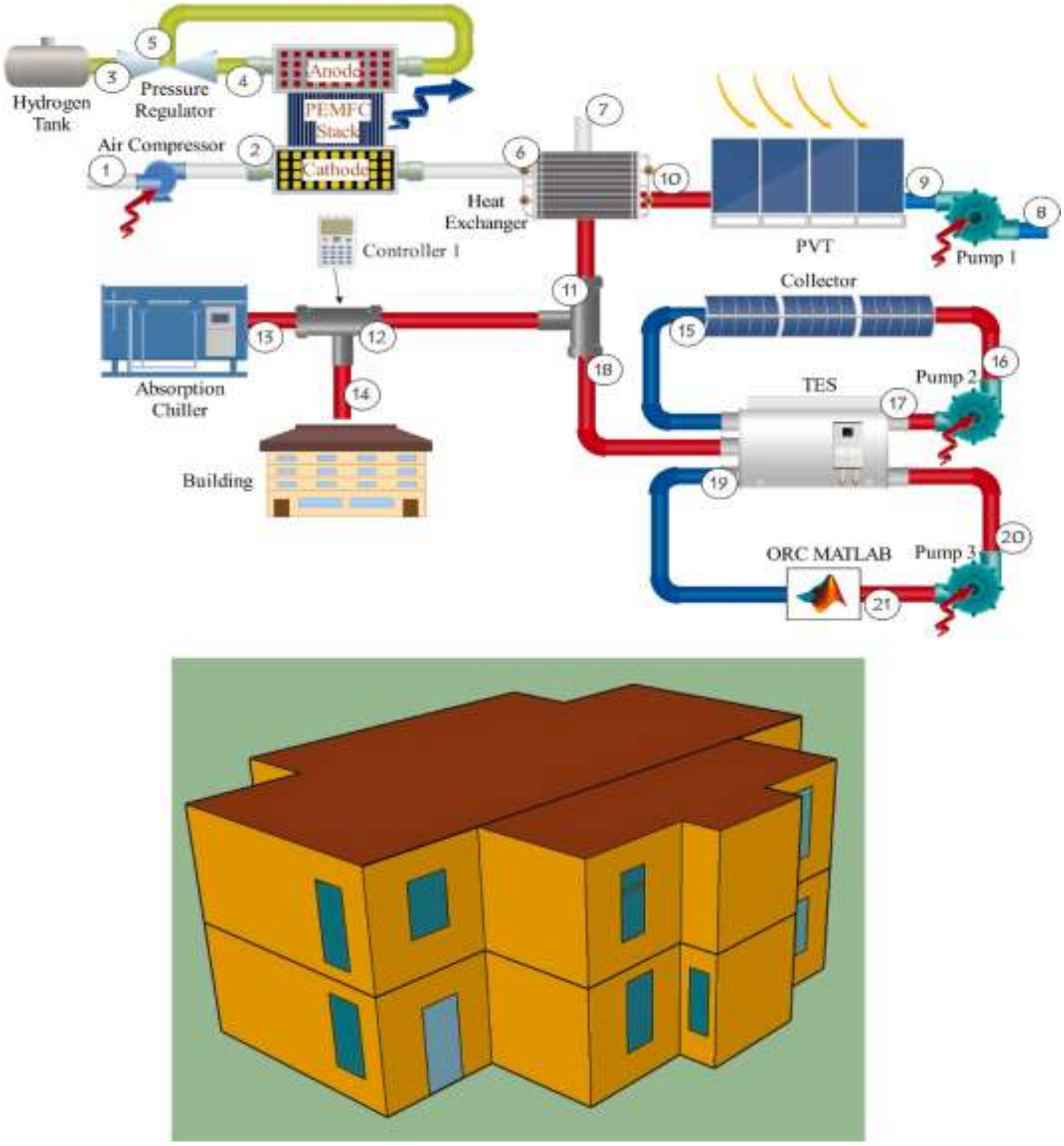

Fig. 6. Schematic of the proposed cycle [13].

Moghadam et al. In 2023, analyzed and evaluated a multi-purpose and sustainable system consisting of a biomass-fired external combustion gas turbine and a double-effect absorption chiller. Also, in the optimization, an advanced combination of neural network and multi-criteria algorithm is used to optimize the performance and dimensional parameters in the best possible conditions. The results showed that the highest economic exergy cost belongs to the gas turbine and gasifier system, respectively, at 40% and 23 % of the total exergy cost. Also, the proposed cycle, under optimal conditions, provides output power, heating, cooling and carbon dioxide emission reduction of 514 kW, 2052 kW, 2650 kW and 1.33 kg/kWh, respectively. The cycle schematic is shown in Fig. 7 [14].

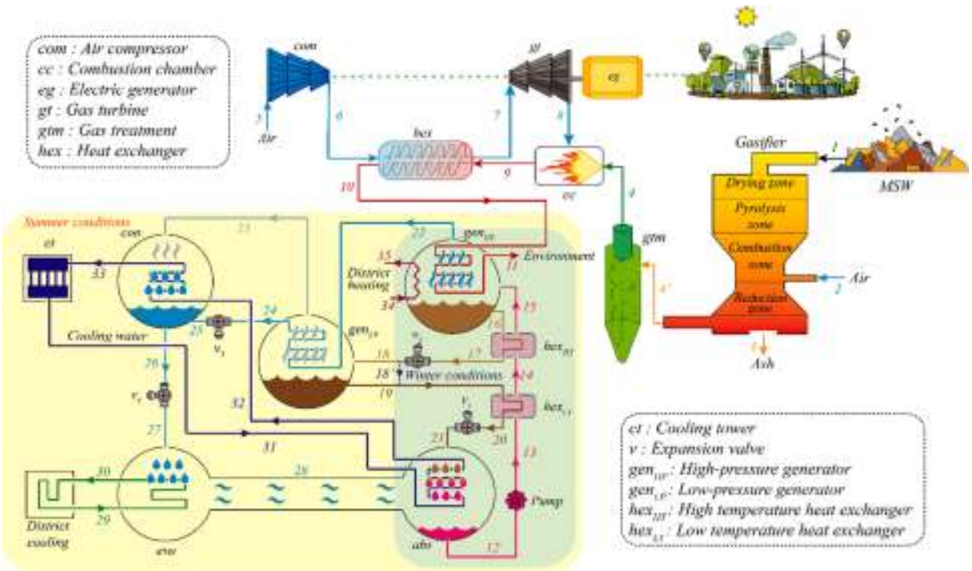

Fig. 7. Schematic of the proposed cycle [14].

Qu et al. In 2022, designed and evaluated a comprehensive energy, exergy, environmental and economic analysis for an integrated water heating system based on photovoltaic-thermal panels and a water source heat pump. The results show that the PV/T-WSHP system has 25.3% higher power conversion efficiency, an energy efficiency ratio (EER) of 3.71, and a significant reduction in annual exergy loss compared to the PV+ASHP hybrid system. The annual cost of the studied cycle is 217.7 yuan lower than the reference system, and the annual consumption of standard coal is saved by 0.62 and 0.50 tons, respectively. The cycle schematic is shown in Fig. 8 [15].

Fig. 8. Schematic of the proposed cycle [15].

In recent years, the use of substandard building materials and poor thermal insulation has led to an increase in the consumption of fossil fuels in the construction sector. This has not only led to an increase in air pollution and global warming, but also to a rapid decrease in limited fossil energy resources. Therefore, optimizing the type of materials and increasing the quality of construction can play an important role in reducing energy consumption and improving energy efficiency in residential buildings. In this regard, the use of solar energy, as one of the cleanest and most economical renewable resources, is an efficient option for providing the energy needed by buildings.

In addition, multi-purpose systems designed based on new energies have the ability to simultaneously provide the electricity, heat, and cooling needed by a building. Such systems are also very desirable from an environmental perspective due to the use of natural and sustainable resources and can play a significant role in reducing pollution from fossil fuel consumption.

3. CONCLUSION

A review of existing studies shows that achieving zero-energy buildings is not only possible, but also that high efficiency and significant savings in energy consumption can be achieved by integrating renewable technologies and smart design. Hybrid systems such as multi-generation solar farms, energy storage, and smart energy management methods play a key role in providing heating, cooling, and electrical load to buildings. Technical, economic, and environmental studies also show that the use of these systems not only helps reduce pollution, but is also economically justified. Therefore, it is suggested that a systemic approach to energy and an emphasis on the use of clean resources be prioritized in the design of future residential units. The use of multi-criteria simulation and optimization tools can also assist designers and policymakers in the decision-making process.

4. FUTURE OF RESEARCH

- Use of Artificial Intelligence in Building Energy Design
- The Role of Government Policies in the Development of NZEB Buildings
- Iran's Climate Challenges in Implementing These Buildings

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