Zero Energy Homes: Definitions, Design Considerations, Challenges, and Real-world Applications

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Introduction

In the pursuit of sustainable living and environmental responsibility, the concept of Zero Energy Homes (ZEHs) has emerged as a promising avenue for reducing the carbon footprint of residential housing. However, the lack of standardized definitions has led to a diverse landscape of interpretations surrounding ZEHs, necessitating a comprehensive exploration of these definitions and their implications (Torcellini et al., (2006). This review paper aims to delve into the multifaceted realm of Zero Energy Homes, examining various definitions, design considerations, challenges, and real-world applications.

Understanding ZEHs requires a nuanced exploration of the diverse definitions that have surfaced in research. From homes that achieve net-zero energy consumption through a combination of thermal efficiency and renewable energy sources to the concept of Zero Carbon Homes (ZCH) emphasizing carbon emissions neutrality, and Carbon Positive Homes (CPH) producing a surplus of renewable energy, each definition brings a unique perspective to the discourse (Pipkorn et al., n.d.). Additionally, the emergence of Zero Energy Solar Homes highlights the specialized use of solar power as the sole renewable energy source (Pipkorn et al., n.d.).

As the demand for Zero Energy Buildings (ZEB) rises due to affordability and reduced maintenance costs, the design of such structures becomes paramount (Neves et al. 2022; U.S. Department of Energy, n.d.-b). Key considerations include energy efficiency and renewable energy integration, with a focus on energy infrastructure (Parker, 2009; U.S. Department of Energy, n.d.-a; Wu & Skye, 2021) Geothermal heating, facilitated by ground source heat pumps (GSHP) or air source heat pumps (ASHP), emerges as a crucial component, tailored to specific climatic conditions. Window improvements and innovative energy management through internet monitoring further contribute to the overall energy efficiency of ZEBs.

Despite the potential benefits, challenges persist in the realization of ZEBs. Human-building interaction, miscellaneous energy needs, and heating efficiency demand specific attention (Sparn et al., 2016; Nikdel et al., 2022). Internet monitoring proves instrumental in mitigating miscellaneous energy and enhancing overall energy efficiency while addressing human-building interaction requires lifestyle changes.

Examining practical applications, this review highlights successful implementations of ZEBs, such as a 3-bedroom ZEH in Denver surpassing net-zero capabilities through envelope efficiency, efficient equipment, and solar technologies (Norton & Christensen, 2007). The exploration extends to the establishment of Zero Energy Communities (ZED) in Denver, emphasizing resource sharing among ZEBs (Polly et al., 2016). Real-life examples, including a decade-long study on a ZEH, provide insights into challenges faced and lessons learned.

Specific considerations for ZEBs in cooler climates are explored, acknowledging the limitations of solar energy during long winters. Solar thermal electric systems offer a potential solution for meeting heating energy needs. In contrast, geothermal heating emerges as a viable option for overcoming challenges in achieving net-zero energy goals in colder climates (Al Faris et al., 2017).

Finally, the paper examines the broader implications of ZEBs/ZEHs, outlining environmental benefits, reduced fossil fuel consumption, economic development, and employment opportunities (Maradin, 2021). While solar energy presents advantages in terms of cost, safety, and accessibility, challenges such as weather dependence, efficiency concerns, and high initial investments are also discussed (Brostrom & Howell, 2008).

In synthesizing these varied facets, this review seeks to provide a comprehensive understanding of Zero Energy Homes, offering valuable insights for researchers, policymakers, and practitioners involved in the pursuit of sustainable and energy-efficient residential structures.

Methods

In the pursuit of gathering comprehensive and diverse information for this review paper, a team of four dedicated researchers collaborated to explore various aspects of Zero Energy Homes (ZEHs). This section provides an overview of the methodologies employed, challenges faced, and adaptations made during the information retrieval process.

We spearheaded the research by focusing on obtaining a thorough understanding of the components and intricacies of zero-energy homes. Utilizing Google Scholar we successfully amassed a collection of 20 unique sources, specifically favoring those that culminated in PDF formats for ease of reference (AlFaris et al., 2017; Arasteh et al., 2003; Brostrom & Howell, 2008; Charron & Athienitis, 2006; Commonwealth of Massachusetts, n.d.; D'Agostino & Mazzarella, 2019; Liu et al., 2015; Maradin, 2021; Neves et al., 2021; Nikdel et al, 2022; Norton & Christensen, 2007; Parker, 2009; Pipkorn et al., n.d.; Polly et al., 2016; Sparn et al., 2016; Stevanović et al., 2022; Torcellini et al., 2006; U.S. Department of Energy, n.d.-a; U.S. Department of Energy, n.d.-b; Wu & Skye, 2018). Beginning with a foundational search on zero-energy home components, we expanded our exploration by delving into multimedia content, such as a relevant YouTube video. This immersive approach allowed him to unearth deeper insights into zero-energy concepts related to homes, buildings, and ultimately, biomass energy. However, we encountered challenges in tracking down information year by year, coupled with occasional restrictions posed by paywalls when accessing certain details.

Our research focused on the global impact of zero energy on buildings, extending beyond the United States to encompass 280 international structures. Employing Google Scholar as our primary research tool, we sought to understand how zero-energy technology influenced not only civilian structures but also its implications for the U.S. military. Exploring the financial aspects, we investigated the costs associated with constructing and maintaining zero-energy buildings. Recognizing the unique nature of zero-energy compared to other energy sources, we concluded our research by examining the technology's future plans and potential variations in zero-energy building designs. This strategic approach aimed at providing valuable insights for constructing persuasive arguments and guiding future advancements. We compiled the 5 relevant studies and sorted them into categories in Table 1 in the discussion section of this paper. We also identified the most relevant figures in each of these 5 studies.

We collaborated in our research efforts, concentrating on the identification and analysis of Zero Energy Homes (ZEHs) in the United States, particularly in Colorado. Our collective focus aimed to ensure the consistency of data across diverse sources and geographical locations. By investigating the current landscape of ZEHs, they sought to glean insights into the future trajectory of this technology. Their research culminated in an examination of the pros and cons associated with zero-energy buildings, offering a nuanced perspective on the potential impacts on the occupants of such structures. This collaborative approach provided a holistic view of ZEHs, emphasizing the importance of considering both advantages and challenges in the ongoing development and adoption of zero-energy technologies (AlFaris et al., 2017; Arasteh et al., 2003; Brostrom & Howell, 2008; Charron & Athienitis, 2006; Commonwealth of Massachusetts, n.d.; D’Agostino & Mazzarella, 2019; Liu et al., 2015; Maradin, 2021; Neves et al., 2021; Nikdel et al, 2022; Norton & Christensen, 2007; Parker, 2009; Pipkorn et al., n.d.; Polly et al., 2016; Sparn et al., 2016; Stevanović et al., 2022; Torcellini et al., 2006; U.S. Department of Energy, n.d.-a; U.S. Department of Energy, n.d.-b; Wu & Skye, 2018).

Discussion

SI No.	Title of paper	Category	Relevant figures/tables	Citation
1	The challenges of designing and building a net zero energy home in a cold high-latitude climate	Zero Energy in Homes	Figure 2. Illustration of Optimum Point for Choosing between Employing Additional Energy Efficiency or Employing Additional Renewable Energy	(Brostrom & Howell, 2008)
2	Pairing geothermal technology and solar photovoltaics for net-zero energy homes	Zero Energy in Homes	Figure 5. Results of NZE System Payback Comparison	(Neves et al., 2021)

3	Performance result from a cold climate case study for affordable zero energy homes	Zero Energy in Homes	Figure 5. Daily and cumulative net site electricity use	(Norton & Christensen, 2007)
4	Performance result from a cold climate case study for affordable zero energy homes	Zero Energy in Homes	Table 1. Summary of NREL/Habitat ZEH Attributes	(Norton & Christensen, 2007)
5	Performance result from a cold climate case study for affordable zero energy homes	Zero Energy in Homes	Table 3. 1212-Montherformance Summary of NREL/Habitat ZEH	(Norton & Christensen, 2007)

Table 1: Data Summary and Analysis

Optimizing Net Zero Energy Goals

This study provides a representation of the delicate balance Zero Energy Homes (ZEHs) strive to achieve (Brostrom & Howell, 2008). The figure elucidates the concept of finding the optimum point where the combined cost of increasing energy efficiency and renewable energy is minimized. This optimization is crucial for reaching net-zero energy goals economically. The study underscores the challenge of balancing increased renewable energy and enhanced energy efficiency, illustrating that pushing one aspect to an extreme—relying solely on renewable energy or maximizing energy efficiency—becomes cost-prohibitive. The essence of ZEHs lies in finding the equilibrium, where both renewable energy and energy efficiency are optimized to achieve net-zero energy consumption cost-effectively. This optimization ensures the feasibility of ZEHs by minimizing the financial burden associated with achieving energy neutrality.

Payback Period Analysis

This study provides an analysis of payback periods for different systems in various locations. It also provides valuable insights into the economic viability of Zero Energy Homes (Neves et al., 2021). The study specifically highlights the shorter payback period achieved with specific systems, such as the baseline + PV system in Miami, Florida, and the GHP + PV system in Duluth, Minnesota. In several cases, the payback periods for different systems are comparable, emphasizing the complexity of choosing an optimal system. For instance, the marginal difference in payback periods between the baseline + PV system and the GHP + PV system in Reno, NV illustrates the nuanced decision-making required in selecting a system. Such economic considerations become pivotal for homeowners and policymakers alike, influencing the widespread adoption of Zero Energy Homes.

Solar Water Heating System Design

Turning attention to the solar water heating system, as depicted in this study, the use of TRNSYS modeling software allowed for a detailed exploration of design assumptions and trade-offs (Norton & Christensen, 2007). Tilt angle, collection size, and storage tank size were evaluated, leading to the inclusion of a drain-back system with specific specifications in the final design. This study underscores the importance of leveraging modeling tools to optimize the performance of renewable energy systems, ensuring efficient utilization in real-world applications.

Performance Attributes of NREL/Habitat ZEH

Table 1, sourced from "Performance Results from a Cold Climate Case Study for Affordable Zero Energy Homes," provides a summary of the attributes of a specific ZEH located in Wheat Ridge, Colorado (Norton & Christensen. 2007). This NREL and Habitat for Humanity collaboration outperformed the national average, positioning itself not just as a consumer but as a producer of energy. The attributes encompass square footage, bedroom count, occupant number, and various components of the house, highlighting the successful integration of sustainable features.

In summary, the figures and table discussed contribute to a nuanced understanding of the multifaceted landscape of Zero Energy Homes. From the delicate balance between energy efficiency and renewable energy to the economic considerations of system payback periods, these visuals provide key insights into the challenges and opportunities inherent in the quest for sustainable living through Zero Energy Homes.

Conclusion

In the pursuit of sustainable living, Zero Energy Homes (ZEHs) emerge as a beacon of innovation, embodying the collective efforts to redefine the paradigm of residential energy consumption. This comprehensive review has delved into the intricate facets of ZEHs, presenting a tapestry of insights gleaned from various studies and figures.

The optimization challenge illustrated in Brostrom, M., & Howell, G.'s study (2008) underscores the essence of ZEHs—finding the delicate equilibrium between increased energy efficiency and renewable energy adoption. The pursuit of net-zero energy goals necessitates a strategic approach that minimizes costs while maximizing the efficiency of both energy systems. The review emphasizes that ZEHs are not about singularly favoring energy efficiency or renewable energy by achieving an optimal synthesis that ensures economic feasibility.

This study sheds light on the economic viability of different Zero Energy Home systems, emphasizing the importance of payback periods in decision-making. The nuanced analysis of locations and systems reveals the intricacies involved in selecting the most appropriate technology for specific contexts. This economic lens is pivotal for fostering broader adoption and integration of ZEHs into diverse geographical and economic landscapes.

The exploration of a solar water heating system, as depicted in Figure 5, highlights the significance of advanced modeling tools in optimizing renewable energy systems. The detailed trade-offs in tilt angle, collection size, and storage tank size underscore the importance of leveraging technology to enhance the efficiency of sustainable solutions.

Table 1 provides a tangible example of success in the form of an NREL and Habitat for Humanity ZEH in Wheat Ridge, Colorado. Outperforming the national average, this case study exemplifies the transformative potential of ZEHs to not only meet but exceed energy efficiency expectations, ultimately becoming energy producers rather than consumers.

As we conclude this review, it becomes evident that the journey toward sustainable living through Zero Energy Homes is nuanced and multifaceted. The delicate balance, economic considerations, technological advancements, and real-world success stories collectively weave a narrative of promise and opportunity. The insights gained from this review serve as a compass for researchers, policymakers, and homeowners navigating the path toward a future where ZEHs play a central role in fostering sustainable and resilient living. By unveiling the intricacies and successes of ZEHs, we hope to inspire a collective commitment to embrace and propel the evolution of sustainable living into a tangible reality.

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