Enhancing net-zero energy buildings: a comprehensive critical review of Passivhaus design in the UK

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Abstract

In the effort to reach the UK's goal of having zero carbon emissions by 2050, this study offers a detailed review of Passivhaus designs in the UK's housing area. This research tries to fill in the gaps in existing studies by closely looking at how much energy and carbon Passivhaus homes use compared to other homes in the UK. Focusing on energy efficiency and carbon emissions, this research plans to set a strong basis for further study stages, including creating a user-friendly online tool for easy access and understanding of the results. Using a step-by-step approach, the study gathers information from a wide range of scholarly articles, showing the Passivhaus design as a new way to create energy-saving homes. Initial findings highlight the great potential of Passivhaus designs in significantly lowering the need for space heating compared to the average UK home. However, the review also points out the lack of research on indoor air quality and the comfort of residents, marking an important area for further study. Additionally, the study emphasizes the urgent need to update current databases and approach to include a broader view of the energy embodied in materials and its related carbon emissions. As this PhD research moves forward, it plans to deepen the understanding of the sustainability of Passivhaus homes in the UK, with the goal to suggest changes in current Passivhaus standards to fully address the carbon emissions from embodied energy, leading the way towards a cleaner, more sustainable future in the UK's building industry.

Keywords - Passive Houses, Net Zero Energy Homes, Whole-Life Carbon Footprint, Embodied Carbon Footprint, Operational Carbon Footprint

1. Introduction

In a rapidly urbanizing world, the pressing demand for energy-efficient housing cannot be understated. As the effects of climate change intensify, the onus falls on the global community to undertake significant measures to curb the escalating levels of greenhouse gas emissions, a significant portion of which is attributed to the building sector [1]. The United Kingdom has embraced this challenge head-on, aligning its policy framework to achieve net-zero carbon emissions by the year 2050, a visionary step that underscores the nation's commitment to ushering in a sustainable future [2] [3]–[5]. Integral to this ambitious endeavour is the emergence and growth of the Passivhaus or 'Passive House' standard in the UK, a groundbreaking approach that seeks to radically diminish the energy footprint of homes [6]. This study embarks on a meticulous journey to scrutinise the various dimensions of the Passivhaus design within the UK's context, laying bare its strengths and pinpointing areas where it can potentially evolve to become an even more potent tool in the fight against climate change.

Originating from a German prototype developed in the early 1990s, the Passivhaus standard has metamorphosed into a globally acknowledged blueprint for energy efficiency in building design [7] [4]. The foundational philosophy of this approach rests on principles such as superior insulation, stringent air tightness requirements, and mechanical ventilation heat recovery (MVHR), elements that are engineered to significantly lower the energy demands of a dwelling [8]. In the UK, this design standard has gradually cemented its place as a preferred choice for eco-conscious property developers and homeowners alike [6], [9], [10]. However, as the reach of Passivhaus expands, it becomes increasingly pertinent to dissect its performance critically, paying special attention to its implications for embodied carbon emissions – domains that have previously remained somewhat underexplored in the broader academic and policy discourse [11].

As we stand at the cusp of a potentially transformative era in the realms of building science and environmental sustainability, it is incumbent upon researchers to delve deeper, analysing the efficacy of Passivhaus designs from multiple angles [12], [13]. It is no longer sufficient to merely highlight the remarkable reductions in space heating energy demands that these structures facilitate [14]–[16]. The discourse must evolve to encompass a more nuanced understanding of the life cycle impacts of Passivhaus homes, dissecting the embodied energy associated with construction materials and scrutinising the actual indoor air quality experienced by the occupants [17]–[19]. It is within this context that the present study situates itself, seeking to bridge the existing gaps in literature and thereby facilitating a comprehensive appraisal of the Passivhaus standard in the UK [10].

Moreover, the critical review presented herein ventures beyond a theoretical analysis of existing literature, aspiring to contribute tangibly to the ongoing efforts to enhance the sustainability of buildings in the UK. One of the cornerstone innovations of this research is the envisaged development of a cloud-based visualization tool, a platform designed to democratise access to research findings and foster a culture of informed decision-making amongst various stakeholders, including policy makers, builders, and the general populace. Through this tool, the study aims to propel the discourse on sustainable building design into a new frontier, where data-driven insights guide the evolution of building standards and practices.

Simultaneously, this research acknowledges the complex web of considerations that influence the transition towards net-zero energy buildings. While the Passivhaus standard offers a promising pathway, it is essential to scrutinise it critically, identifying potential areas of improvement and adaptation to the unique climatic and socioeconomic context of the UK houses [11]. The question of occupant comfort and the potential issues of overheating, particularly in the face of changing climate patterns, are pertinent aspects that demand deeper exploration [20]. Similarly, a focussed investigation into the embodied carbon emissions of Passivhaus homes can unearth insights that can further refine the approach, making it more aligned with the overarching goals of environmental sustainability [21], [22].

1.1. Core Principles and Technical Aspects of Passivhaus Design

1.1.1. Foundational Principles

In the vanguard of sustainable building designs, the Passivhaus standard stands distinguished, underscored by its meticulous alignment with principles that prioritize both energy efficiency and inhabitant comfort [23]. This section embarks on a profound exploration of the foundational principles that underlie the Passivhaus standard, scrutinizing how these principles harmonize to radically decrease the energy demands of a residence.

A linchpin of the Passivhaus standard is the deployment of superior insulation, often perceived as the foremost strategy in energy conservation [19] [24] [25] [26]. This insulation extends beyond merely outfitting buildings with thicker layers of insulating material. It necessitates the incorporation

Table 1: Overview of the main Passivhaus certification criteria [4], [6], [24]

Criteria	Details
Space Heating Demand	Not more than 15 kWh/(m²yr)
Cooling Demand	Matched to the heating demand plus an additional allowance for dehumidification.
Primary Energy Demand	Not exceeding 120 kWh/(m²yr) for all energy used in the building
Airtightness	Maximum of 0.6 air changes per hour at 50 Pascals pressure (n50 ≤ 0.6 /hr)
Thermal Comfort	Should not exceed 25°C for more than 10% of hours in a year
Window Performance	U-value not exceeding 0.80 W/(m²K)
Ventilation System Efficiency	Minimum 75% efficiency

of high-performance insulation materials that bear a remarkable ability to restrict heat transfer, thereby enabling a stable interior climate irrespective of external weather conditions [19] [24] [25] [26]. The goal is not merely to minimize energy loss but to create a buffer that separates the conditioned indoor environment from the fluctuating outdoor climate, enhancing the comfort and health of the occupants [19] [24] [25] [26].

Complementing the insulative strategy is a stringent air tightness requirement that seeks to mitigate uncontrolled air leakage, a potential conduit for energy loss [19] [27]. Buildings designed as per Passivhaus standards are equipped with airtight layers that prevent the infiltration of cold drafts in winter and the intrusion of hot air in summer, thereby sustaining a comfortable indoor environment year-round [19] [27]. This strategy extends beyond energy conservation; by preventing damp and cold spots, it mitigates the risk of mould growth, thus fostering healthier living spaces [19] [27].

The next piece in this synergistic puzzle is the Mechanical Ventilation Heat Recovery (MVHR) systems [28], [29]. These are designed to enhance indoor air quality without compromising on energy efficiency. In essence, the MVHR systems operate by extracting stale air from the building and replacing it with fresh, filtered air from the outside, a process which, incidentally, recovers a substantial portion of the heat energy from the expelled air to warm the incoming fresh air [28], [29]. This cyclical process ensures a continuous flow of fresh air, facilitating a healthier indoor environment while maintaining a high level of energy efficiency [28], [29].

Together, these foundational principles create a delicate ballet of technical elements that work synergistically to establish residences with markedly reduced energy demands, fostering a harmonious balance between human comfort and environmental sustainability.

2. Methods: Unveiling the Research Process

Choosing a systematic literature review over a wider literature review for this scholarly discussion is grounded in the need to provide a thorough and unbiased analysis that aligns with scientific rigor and truth [30]. A systematic literature review demands the use of scientific strategies to carefully identify, evaluate, and synthesize relevant studies that address a specific research question [30]. It strives to present a complete and unbiased collection of evidence, strictly following methodological guidelines. In comparison, wider literature reviews offer a broad overview of existing narratives but miss the structured approach and accuracy that systematic reviews encompass [30].

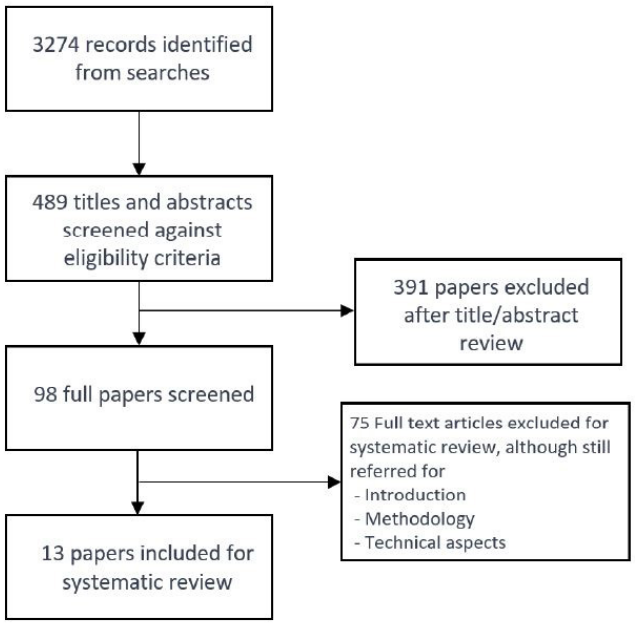

Figure 1: Chart explaining systematic review process for literature review.

2.1. Literature Search and Selection

To sift through the vast amount of existing literature, a combination of modern tools and platforms were used. The process began with the use of applications like "Connected Papers", a novel tool that visually groups research papers based on their similarities and thematic connections, helping to discover hidden links and fostering a deeper understanding. In addition, platforms such as "Google Scholar", "ResearchGate", and "Elsevier" were fertile sources from which numerous papers were gathered, exploring a variety of terms including "passive houses in the UK", "whole-life energy consumption", "embodied carbon passive houses", and "net zero UK".

To ensure a deep and comprehensive analysis, the research initially embraced over 150 peer-reviewed articles. This large body of work was carefully analysed, using both qualitative and quantitative approaches to select the most central works to the research objectives.

2.2. Rationale for Selection

Central to this research is a refined selection of thirteen notable papers, chosen with a steadfast commitment to depth, relevance, and a range of perspectives. This chosen corpus seeks to furnish a well-rounded view of the Passivhaus design scene in the UK, with each paper adding a unique yet harmonized voice to the scholarly conversation. The process of selecting these papers was anything but arbitrary; it was the outcome of a relentless pursuit for quality and pertinence. The existing literature specifically addressing the topic of "whole-life energy consumption and carbon footprints in UK Passivhaus residences" is notably sparse. A meticulous investigation revealed a gap in the literature; studies extensively covering the whole-life energy consumption in passive houses, particularly in any specific geographic locale, are conspicuously absent. Most extant studies veer towards discussions on embodied or operational carbon, without encompassing the entire spectrum of whole-life energy consumption.

Moreover, focusing specifically on the UK market introduces additional layers of complexity, as literature addressing the carbon footprint specific to passive house studies in this region is even more limited. Therefore, the research adapted by integrating various studies that cast light on diverse, yet interconnected facets: comparisons between passive and conventional houses, insights into the UK market's stance on low carbon houses, and investigations into embodied carbon studies in passive houses, among others.

Each paper was therefore scrutinized through a series of stringent criteria evaluating the depth of content, methodological robustness, and the extent to which it contributes to the existing knowledge base. These thirteen papers, which form the foundation of this research, offer a rich array of insights that resonate well with the delineated research objectives, facilitating a comprehensive analysis.

By honing in on these thirteen studies, this research seeks to weave a narrative that is both in-depth and sharply focused, illuminating understudied facets of the Passivhaus sector in the UK. It aspires to construct a discourse that is not only illuminating but also inspires further explorations and discussions in this emerging field.

3. Critical Examination of existing literature and research for Passivhaus Design in the UK's Context

At the start of this intensive research journey, this section carefully explores a collection of thirteen vital research papers that are crucial to understanding the current scenario of Passivhaus design in the UK. Through detailed observation, it will cover a variety of analyses and findings, while also pointing out the shortcomings present in each study. This thorough examination hopes to build a strong route towards a deeper understanding of Passivhaus implementation in the UK, encouraging an academic discussion that is as thoughtful as it is progressive, and making a significant contribution to the growing story of sustainable residential designs in the UK.

Table 2: Overview of 13 papers selected for literature review.

	Source	Location	Study's Focus	Reason of analysing this source
2020	R. Mitchell and S. Natarajan [6]	UK	Investigating the Passivhaus standard's effectiveness in reducing the UK's housing energy performance gap through post-occupancy analysis.	Aids in understanding energy performance gaps in passive houses, fostering a sustainable transformation in UK's residential sector.
2017	X. Liang et al. [31]	UK	Comparative analysis of energy efficiency between conventional and passive houses in Northeast England.	Offers empirical data crucial for analysing energy consumption trends in UK passive houses for my PhD thesis.
2013	A. Stephan et al. [5]	Belgium	Evaluates life cycle energy demands of passive houses, comparing a Belgian passive house with other housing models.	Offers insights into neglected aspects of passive house energy demands, aiding in developing more comprehensive UK policies.
2012	Rosa M. Cuéllar-Franca et al. [32]	UK	Analysing environmental impacts of UK's prominent housing types through life cycle assessment to propose net-zero energy transition strategies.	Guides in-depth study on environmental impacts and energy consumption patterns in UK housing types for my PhD research.
2018	N.G. Fernando et al. [33]	UK	Analyses embodied carbon emissions in various structural elements of a newly constructed apartment building in Sunderland, UK.	Guides efforts to minimize energy consumption in UK passive houses, fostering alignment with contemporary sustainability goals
2023	M. Keyhani et al. [34]	UK	Examines disparities in embodied carbon databases affecting UK's Passivhaus designs; highlights potential emissions reductions through sustainable practices.	Essential for understanding and improving carbon emissions calculations in UK passive houses, aiding in focused, sustainable research development.
2022	L. Jankovic et al. [21]	UK	Analysing Birmingham Zero Carbon House's retrofit process, highlighting material choices and paths to net-zero emissions by 2050.	Guides my PhD thesis on energy consumption in UK passive houses, facilitating net-zero strategies and renewable technology integration.
2017	Zr. Larasati et al. [35]	Indonesia	UK's adoption of refined Embodied Energy calculations in Passivhaus design, using insights from Indonesia's low-cost housing strategy.	Enhances understanding of material production's environmental impact in UK passive houses, aiding in effective strategy development.
2022	N. Anderson et al. [36]	UK	Evaluating and strategizing to reduce embodied energy in the UK's affordable social housing sector.	Informing strategies to reduce whole life energy consumption in UK passive houses for my PhD thesis.
2023	D. Arslan et al. [37]	UK	Exploring prefabrication techniques' role in reducing carbon emissions in UK high-rise residences, using Portland's Place case study.	Guides strategies for minimizing energy consumption in UK passive houses, highlighting gaps in current LCA tools and guidelines.
2020	B. Derbi et al. [38]	UK	Analysing MgO SIPs' environmental impact in UK's nearly Zero Energy Buildings through a North England single-family house case study.	Informing material sourcing strategies for lower energy consumption in passive houses aligning with UK's nZEB goals.

2014	Rosa M. Cuéllar-Franca et al. [40]	UK	Analyses life cycle costs of UK housing stocks, advocating for Passivhaus strategies to enhance economic and environmental sustainability.	Guides in forming energy-efficient strategies and policies for sustainable and affordable passive houses in the UK.

4. Conclusions

Upon conducting a comprehensive analysis of the above 13 studies, I have identified several significant discoveries that should be taken into consideration during the subsequent stage of the PhD project:

5. The literature review emphasizes the need for a larger and more diverse sample to enhance the generalizability of the findings and the importance of incorporating diversified data sources to obtain a more holistic understanding of energy performance.

6. Future research must delve deeper into comprehensive strategies, encompassing economic evaluations and environmental impacts, thereby aligning with broader sustainability goals.

7. The literature review clearly signals the necessity for a paradigm shift in evaluating the energy efficacy of passive houses in the UK, emphasizing an integrated approach that also considers embodied and transport energy demands. This approach advocates for more precise per capita assessments, promising a pathway to genuinely net-zero energy buildings in the UK.

8. The literature review underscores the urgent need to focus on the usage stage of UK residential structures to mitigate environmental impacts, spotlighting potential benefits through optimizing construction materials and promoting recycling initiatives. An expansion to encompass behavioural analyses and sustainable materials exploration could facilitate actionable strategies towards realizing net-zero energy buildings in the UK.

9. To further advance towards a sustainable construction landscape, future research should foster multidisciplinary collaborations and delve into broader contextual factors influencing embodied carbon, thereby guiding actionable, holistic strategies for carbon-optimal designs in passive houses.

10. The literature review underscores the necessity of developing unified, reliable embodied carbon databases to enhance the accuracy of carbon footprint analyses in the UK's residential buildings, urging future research to foster globally adaptable and sustainable practices in the construction industry.

11. To foster a swift transition to carbon neutrality in the UK's residential sector, further studies should evaluate the economic viability and societal impacts of adopting Passivhaus principles on a large scale, focusing on community engagement and comprehensive life cycle assessments of sustainable building materials, thereby guiding informed policy and fostering international collaboration.

12. To attain the 2050 carbon reduction goals in the UK's affordable housing sector, a synergized effort focusing on stringent regulations, knowledge-sharing, and consumer awareness is critical. Addressing financial hurdles and revamping current methodologies for improved accuracy in embodied energy calculations are vital steps towards fostering a sustainable, energy-efficient housing landscape.

13. To facilitate a transition to sustainable construction in the UK, urgent developments in post-construction data sharing, nuanced government guidelines, and comprehensive benchmarking systems are crucial. The industry should embrace collaboration and innovation, alongside fostering transparency and skill development, steering towards global sustainability goals effectively and efficiently.

14. To expedite the UK's transition to nZEB standards, future research should prioritize exploring sustainable material alternatives and socio-economic factors impacting local productions, focusing on enhancing the economic and logistical feasibility of domestic manufacturing.

15. To further the UK's transition to net-zero energy buildings, future studies should focus on a localized approach, exploring diverse UK-centric case studies and expanding analysis to encompass the entire building life cycle, thus providing a more holistic view and actionable insights tailored to the UK's unique climatic and regulatory context.

16. Emphasis should be on examining the rapidly evolving renewable energy landscape and exploring innovative financial strategies, including green financing and governmental incentives, to mitigate the impending housing affordability crisis while promoting responsible energy consumption and sustainability.

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