Examining the critical barriers to NZEBs' implementation in the Ghanaian construction industry

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We [the authors] thank the Editor and the Reviewer(s) for their time and efforts in reviewing our manuscript. We appreciate your constructive comments, suggestions, and queries that have greatly assisted us in improving the quality of the manuscript. Please, each comment/suggestion/question has been addressed and the revised manuscript submitted for your consideration. We believe that we have addressed the comments raised to the satisfaction of the reviewer(s). All changes made during the revision have been "tracked" within the revised manuscript using coloured font, and responses to each comment/suggestion are provided in the tables below.

	Associate Editor(s)' Comments:	Authors' Changes and Responses	Page(s)
1	The revised manuscript appears to have addressed most of the comments and suggestions the Associate Editor and Reviewers provided. The comments below outline the areas that still require attention: discuss the adoption of Net Zero Energy Buildings (NZEB) within the Ghanaian construction industry as a separate topic to clarify how sustainable practices are being integrated and the specific challenges and benefits experienced within this context.	The authors are grateful for the comment. Section 2.2 has been inserted to discuss the adoption of net zero energy buildings in Ghanaian construction by looking at sustainable practices and efforts by the nation towards the concept.	3
2	Outline the methodology used for distributing the questionnaires. In Section 3.4, include details such as the sampling method, distribution channels, and response rates.	The authors are grateful for the comment. The sampling techniques, response rate, and distribution channel have been highlighted in the revised version of the manuscript.	5-6
3	discuss the implications of your findings in detail. Highlight how your results impact the industry, policy-making, and future research directions.	The implications of the study has been expanded and brought before the conclusion as suggested by the august reviewer (2).	13-14
4	Provide a table that outlines the demographic information, such as age, gender, position, years of experience, and education level, of your respondents to add transparency and	The authors are grateful for the comment. The demographic information of the respondents have	Supplementary file 2

	depth to your analysis and to help understand the context of the study findings.	been inserted as suggested by the august reviewer.	
5	Explicitly clarify all the thresholds and justifications used in FSE Analysis. Reviewer 2 requested the thresholds/utilized interpretations.	The authors are grateful for the comment. The thresholds and justifications used in the FSE analysis have been inserted under section 4.5	8
	Reviewer 1 Comments:	**Authors' Changes and Responses**	
1.	Why is it difficult to provide a small table for the demographic information provided?	The authors are grateful for the comment. The demographic information of the respondents have been inserted as suggested by the august reviewer.	Supplementary file 2
	Reviewer 2 Comments:	**Authors' Changes and Responses**	
1	Originality: Does the paper contain new and significant information adequate to justify publication? Will the paper be of interest to an international readership? Will the paper be useful to the respective profession and/or discipline?: No issue	The authors are grateful for the comment.	N/A
2	Relationship to Literature: Does the paper demonstrate an adequate understanding of the relevant literature in the field, the ability to review the literature and cite an appropriate range of literature sources? Is any significant work ignored?: Discuss Net Zero Energy Buildings adoption in the Ghanaian construction industry as a separate topic	Section 2.2 has been inserted to discuss the adoption of net zero energy buildings in Ghanaian construction by looking at sustainable practices and efforts by the nation towards the concept.	3
3	Methodology: Is the paper's argument built on an appropriate base of theory, concepts, or other ideas? Has the research or equivalent intellectual work on which the paper is based been well designed? Are the methods employed robust, rigorous and appropriate?: • Explain how the questionnaires were distributed in section 3.4	The questionnaire distribution has been discussed in section 3.4. Thanks to the august reviewer.	6
4	Results: Are results presented clearly, correct technically and analysed appropriately? Do the conclusions adequately tie together the other elements of the paper? Do the charts, tables and figures add value and enhance the interpretation of the results?: No issue	The authors are grateful to the august reviewer.	N/A
5	Implications for research, practice and/or society: Does the paper identify clearly any implications for research, practice and/or society? Does the paper bridge the gap	The authors are grateful for the comment.	13-14

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	between theory and practice? How can the research be used in practice (economic and commercial impact), in teaching, to influence public policy, in research (contributing to the body of knowledge)? What is the impact upon society (influencing public attitudes, affecting quality of life)? Are these implications consistent with the findings and conclusions of the paper?: • The author must discuss the implications of the findings before the conclusion	The implication of the study findings has been discussed before the conclusion as suggested by the reviewer.	
6	Quality of Communication: Does the paper clearly express its case, measured against the technical language of the field and the expected knowledge of the journal's readership? Has attention been paid to the clarity of expression and readability, such as sentence structure, jargon use, acronyms, etc.: No Issue	The authors are grateful to the august reviewer.	N/A

Examining the critical barriers to NZEBs implementation in the Ghanaian construction industry

Abstract

Purpose: Net zero energy buildings (NZEBs) are essential for reducing the environmental consequences of the construction industry. However, its uptake within the industry has been limited, and the inherent barriers remain not fully explored especially in developing countries. This paper examines the critical barriers that hinder the implementation of NZEBs in the construction sector of developing economies like Ghana.

Design/methodology/approach: Quantitative data were collected from 80 construction professionals in the Ghanaian construction industry (GCI) using online survey questionnaires. The dataset underwent analysis following a four-level analytical protocol comprising reliability test analysis, mean score ranking, exploratory factor analysis, and fuzzy synthetic evaluation (FSE).

Findings: Market readiness barriers were considered the most crucial barriers to the implementation of NZEBs in the GCI with an index of 4.023. This was followed by awareness and policy barriers with an index of 4.007. Lastly, resistance to change, then cost and capacity barriers were ranked third and fourth, based on their indices of 3.763 and 3.615 respectively.

Originality/value: The results of this research shed light on a relatively unexplored area within the construction sector, particularly in a developing country like Ghana. The findings of this study will provide valuable information to support policy reviews and formulation and buttress the drive toward sustainability and achieving NZEBs.

Keywords: Barriers, carbon emission, construction, fuzzy synthetic evaluation, Ghana, NZEBs.

1. Introduction

Energy demand has been rising in recent decades since energy is a crucial component of global social, economic, and technical advancement (Pan *et al.*, 2018). However, there is a connection between climate change, greenhouse gas (GHG) emissions, and energy usage (Cristino *et al.*, 2021). Typically, residential and commercial end users make up the majority of the energy spent in the construction industry, which accounts for 20.1% of all supplied energy consumed globally. A large portion of this energy consumption is directly related to construction and electricity demand (U.S. Energy Information Administration, 2016). One of the biggest environmental problems of the twenty-first century is climate change (Solnørdal and Foss, 2018). The global climate and its effects on business management, politics, the economy, and society's way of life have been causing major challenges (Pierrehumbert, 2019; Solnørdal and Foss, 2018). Consequently, a variety of policies have been enacted and put into practice to actively encourage improved building energy efficiency, such as the NZEBs idea, which presents a workable plan for reducing carbon dioxide (CO_2) emissions (Abdellah and Masrom, 2018). To ensure a future that is robust, energy-efficient, and has net zero carbon emissions, it is necessary to improve and transform the energy and carbon performance of the building and construction sector to meet the pressing global climate change challenge (Ohene *et al.*, 2022). However, the 2022 Global Status Report for Buildings and Construction makes it clear that the industry is not prepared to handle this issue (Hamilton *et al.*, 2022). To prevent the disastrous effects of climate change, we must take "concrete actions" right away (Hamilton *et al.*, 2022).

One cutting-edge strategy for lowering greenhouse gas emissions and advancing sustainable development is the concept of "Net-Zero Energy Buildings" (NZEBs) (Wells *et al*., 2018). Embracing NZEB principles not only mitigates environmental impacts but also offers economic benefits such as reduced energy costs and enhanced resilience to volatile energy prices. Despite these advantages and the increasing global focus on achieving NZEBs, the adoption of NZEBs in developing countries faces numerous challenges encompassing various dimensions, including technical, economic, regulatory, and institutional factors (Nduka *et al*., 2019). While there are examples of net-zero energy buildings across the world, North America and Europe have more of them. These areas are receiving more attention, which may be related to investment opportunities, more advanced research, and the availability of technology (Ohene *et al*., 2022). These regions are characterised by enabling legislature, regulations, and economic support, yet several barriers still militate against the widespread uptake of NZEBs. Over the past years, these barriers have been studied across various jurisdictions (Pan and Pan, 2021). However, such studies have been highly localised and specific to these regions and hence, cannot be generalised for both developed and developing regions considering the disparity in development and technological advancements of these regions. To that effect, limited attempts have been made to specifically examine barriers to NZEBs peculiar to developing economies like Ghana to enable the mapping of effective mitigation strategies. Moreover, there is a lack of surveys of state-of-the-art perspectives on the subject. This study bridges the gap by identifying and analysing the key barriers to NZEB implementation within the Ghanaian construction industry (GCI). By understanding the root causes of these challenges, the study seeks to provide insights that can inform policy interventions, industry strategies, and capacity-building initiatives to facilitate the transition towards sustainable building practices in Ghana.

2. Literature Review

2.1 Overview of Net Zero Energy Buildings (NZEBs)

According to Wells *et al*. (2018), the NZEB concept encompasses buildings characterised by features such as achieving parity between energy generation and usage, substantial reductions in energy demands, and costs of energy equivalent to zero or net-zero greenhouse gas emissions. It can also denote a building that produces ample renewable energy on-site to meet its energy needs (Peterson *et al*., 2015). The concept of NZEBs extends beyond individual buildings, as evidenced by (Wardhani and Susan, 2022), who emphasise the use of cheap, non-polluting, and renewable energy sources to achieve net zero energy (NZE) in buildings. This suggests that achieving NZE goes hand in hand with considering broader contexts or systems rather than isolated buildings. The reference to "cheap, non-polluting, and renewable energy sources" is evidence that achieving NZE in buildings involves the utilization of energy sources that are not only environmentally friendly but also cost-effective which aligns with the sustainable and eco-friendly nature of NZEBs.

Lu *et al*. (2015) posited that buildings can attain net-zero energy through various means, encompassing integrated building design, retrofits, and energy conservation. For instance, replacing radiators with underfloor heating can reduce energy consumption, as less heating of water is required to achieve thermal comfort (Ahmed *et al*., 2022). The generation and utilisation of renewable energy sources such as wind, solar, geothermal, and bioenergy are also pivotal in realising the goals of NZEBs (Ahmed *et al*., 2022). Garmsiri and Rosen (2018) also highlighted the integration of transportation energy and waste management in achieving NZE in solar buildings. In essence, the collective findings from various researchers underscore the importance of holistic strategies, renewable energy integration, and innovative design approaches and tools to realise the sustainable vision of NZEBs.

NZEBs are characterised by significantly reduced energy requirements, with the remaining energy needs being met by renewable technologies either on-site or off-site (Nduka *et al*., 2019; Torcellini *et al*., 2006). This approach offers several notable benefits; including financial efficiency, optimal utilisation of limited resources for development, environmental sustainability, and energy security (Nduka *et al*., 2019; Torcellini *et al*., 2006). Consequently, the effective evaluation of NZEB policies and adoption strategies in developing nations holds the potential to provide clean energy, address shortfalls in the national grid, and generate new sources of income through the sale of carbon credits. It is evident from the aforementioned benefits that the adoption of net-zero practices is advantageous both for the economy and the sustainable use of the environment (Nduka *et al*., 2019).

Adhikari *et al*. (2012) highlight the economic prospects of NZEBs, indicating that the economic payback period for NZEB construction with feed-in tariffs on Photovoltaic (PV) systems is less than 14 years. Furthermore, the transfer of surplus PV energy to the grid yields an annual energy rating of 70 kWh/m2a. Additionally, the implementation of energy efficiency measures in existing buildings results in annual energy savings of approximately 658.8 MWh, equivalent to 27% of building consumption, and avoids the emission of 545.6 tons of CO_2 (Nduka *et al*., 2019; Adhikari *et al*., 2012).

2.2 Net Zero Energy Buildings in the Ghanaian Construction Industry

Aning (2023) disclosed that carbon emissions in Ghana are worsening rather than improving. As a signatory to the Paris Agreement, Ghana submitted its nationally determined contributions (NDCs), outlining its strategies for reducing greenhouse gas (GHG) emissions. In November 2021, Ghana provided updated NDCs for 2020 to 2030, reiterating its commitment to combating climate change and aiming for a 15% reduction in GHG emissions by 2030. This target requires contributions from various sectors, including the construction industry (Aning, 2023). Despite the industry's potential role, previous studies have shown that the concept of NZEB is still in its early stages and its adoption is uncertain (Ohene et al., 2022). Ghana's renewable energy potential, particularly in wind and solar power (Akom et al., 2020), provides a pathway to achieving NZEBs. Optimal integration of these energy sources is crucial for designing and operating residential NZEBs (Basher et al., 2021). However, transitioning to NZEBs in Ghana involves addressing challenges such as awareness, financial barriers, and insufficient governmental frameworks for enhancing energy efficiency in industries (Akom et al., 2020).

2.3 Barriers Impeding the Implementation of Net Zero Energy Buildings (NZEBs)

While many studies have investigated and proved that many benefits can be achieved through the implementation of NZEBs, there still exist several barriers to NZEBs that need to be addressed to ensure that this concept is implemented thoroughly. Cao *et al*. (2016) pointed out that the imbalance of NZEB developments is due to economic causes such as high initial investment and long payback periods, which pose the main barriers to NZEBs in developing regions. According to Abdellah and Masrom (2018), cost barriers, technical and technological barriers, and government policy barriers are the main barrier areas to implementing NZEBs in Malaysia. It was postulated that implementing NZEBs often requires a higher initial investment compared to traditional buildings due to the integration of energy-efficient technologies and renewable energy systems. Also, while NZEBs offer significant energy cost savings over their lifetime, the higher upfront costs can deter developers and investors who prioritise short-term financial considerations. Singh *et al*. (2021) found that the wider adoption of net-zero-energy homes is constrained by the prevailing reluctance of home builders to build such homes. McCoy *et al*. (2015) added that home builders are sceptical of potential homeowners' acceptance of net-zero-energy homes due to the higher initial prices of such homes. Concerning this, Makvandia and Safiuddin (2021) added that the initial construction costs increase significantly due to the lack of technological knowledge and industry experts who possess the technical skills and experience to maximise the benefits of passive design and install energy-producing components in homes.

Implementing NZEBs involves integrating multiple energy-efficient technologies such as solar panels, energy-efficient HVAC systems, and advanced building insulation (Feng *et al*., 2019; Abdellah and Masrom, 2018). Coordinating these systems and ensuring they work synergistically can be technically challenging, especially in developing countries. The availability of energy-efficient building materials and technologies may also be limited, particularly in certain regions or markets, which can pose challenges for implementation. Moreover, the absence of supportive policies and regulations, such as building codes mandating energy efficiency standards or incentives for NZEBs, can discourage developers from investing in these projects (Abdellah and Masrom, 2018).

Feng *et al*. (2019) discovered that the high initial cost of NZEBs and a shortage of personnel for NZEB design, building, operation, and management are the main barriers preventing their implementation. There is often a shortage of personnel with the necessary expertise in NZEB design, construction, operation, and management. This includes architects, engineers, construction workers, and building managers who are trained in energy-efficient building practices and technologies. Furthermore, existing educational and training programs may not adequately prepare professionals for the specific requirements of NZEB projects, leading to a shortage of qualified personnel in the workforce. It was added that the demand for skilled personnel in the construction and building management sectors can outstrip the available supply, exacerbating the shortage of personnel for NZEB projects (Souiad *et al*., 2022; Feng *et al*., 2019).

Godin *et al*. (2021) also categorised the barriers to NZEB implementation into four themes, which include market, state, cultural, and technical barriers. Market-related barriers, such as the cost of NZE homes, the demand for NZE homes, and the financing schemes available to homebuyers, were considered the most significant barriers to the adoption of NZEB. They added that market changes alone cannot guarantee the widespread adoption of NZEBs. However, Singh *et al*. (2021) asserted that the current approaches to housing design appear to be ignoring the more sustainable options suggesting that market forces continue to be a barrier to the widespread adoption of NZE housing by residential and multi-residential builders.

State-related barriers, such as the government's interest and involvement in energy efficiency and NZEB were also considered critical to the implementation of NZEBs. In relation to the cultural-related barriers, Godin *et al*. (2021) asserted that awareness of NZE homes' benefits and resistance to change are both complex issues affecting the adoption of NZEBs. Consequently, technical-related barriers such as a lack of qualified labour and local expertise impede the adoption of NZEBs (Godin *et al*., 2021).

According to Nduka *et al*. (2019), there is a lack of awareness regarding practices related to NZEBs among stakeholders. It was noted that most homeowners are unaware of the energy and carbon footprint of their current or prospective homes, as well as how to reduce it. Additionally, in many developing nations, there is still a perception that the concept of NZEBs is foreign and not yet suitable for integration into their building systems. Therefore, raising awareness about NZEBs would be beneficial in educating people about the concept and encouraging behavioural change. Several other barriers were identified from the literature which have been shown in Table S1.

3. Research Methodology

The adopted research methodology processes involved in this study have been discussed below;

3.1 Research design

This study employed a quantitative methodology to capture a diverse range of respondent opinions. This approach is essential for the generalisation of research findings to a larger population and utilises structured questionnaire surveys (Pittri *et al*., 2024; Agyekum *et al.,* 2023a). The survey strategy, based on the quantitative approach, involved the use of questionnaires. Structured data collection and statistical analysis were employed to mitigate researcher bias, ensuring objectivity. This enhances the reproducibility of studies and the verification of results, thereby contributing to the reliability and validity of research findings (Kumah *et al*., 2022).

3.2 Questionnaire design

After conducting a comparative examination of relevant literature, 20 potential variables as barriers to NZEBs were identified and formulated for the collection of quantitative data.

The questionnaire utilised in this study comprised two distinct sections. Each section contained closed-ended questions, aiming to elicit data from respondents on specific issues. The initial section focused on collecting demographic information, while the second section aimed to gather information on barriers to the delivery of NZEBs among respondents in the GCI. In the second part of the questionnaire, respondents were instructed to indicate their agreement level on a Likert scale ranging from 1 to 5 (where 1 = not at all critical, 2 = slightly critical, 3 = moderately critical, 4 = very critical, and 5 = extremely critical) regarding the barriers to NZEB delivery in the GCI. Before the main field study, it was important to ensure that a pilot study was carried out during the development of the measure. This aimed to identify unclear items or those potentially unsuitable or lacking discriminatory ability among respondents (Agyekum *et al*., 2023b; Baah *et al*., 2023). The piloting involved nine (9) construction professionals who are experts in NZEBs. Five (5) of these professionals were in academia, and four (4) were field experts who have been involved in NZEB construction. The pilot study involved a face-to-face interview session with respondents, ensuring the research instrument's suitability. Questionnaire content and variables were adjusted based on pilot study feedback.

3.3 Sampling Method

Considering the limited familiarity with the NZEB concept among construction professionals in Ghana, purposive and snowball sampling techniques were adopted to ensure the involvement of knowledgeable participants (Pittri *et al*., 2023a). Purposive sampling allows researchers to identify and select respondents with adequate knowledge, accessibility, and willingness to participate effectively (Tongco, 2007). In this study, the following two criteria were used to select the participants; (a) the respondent should have extensive working experience and/or research experience in the construction industry, with a good grasp of the GCI and its associated challenges, and (b) the respondent should have in-depth knowledge of sustainable construction practices, particularly NZEBs, and be familiar with the barriers to their implementation in the

Ghanaian context. Initially, 54 construction professionals with NZEB expertise were identified through purposive sampling. The snowball technique was then employed to locate additional respondents based on recommendations from the initial participants.

3.4 Data collection

After the piloting study, the final set of questionnaires were distributed to the targeted respondents via email using Google Forms, chosen for its ability to guarantee respondent anonymity compared to other methods like face-to-face interviews. Out of the 93 questionnaires distributed, 80 responses were received, indicating an 86% response rate. Thus, the sample size was considered sufficient for data analysis, as it exceeded the typical response rate of 20-30% in the construction industry (Oyewobi *et al*., 2015).

3.5 Data analysis

The data analysis followed a four-level protocol, which involved pretesting the data set, mean score ranking, exploratory factor analysis (EFA), and fuzzy synthetic evaluation (FSE). The Statistical Packages for Social Scientists (SPSS) 27.0 was used to perform the analyses.

Reliability analysis using Cronbach's Alpha was conducted to assess the internal consistency of the dataset. The obtained coefficient of 0.948 confirmed the data's good reliability and internal validity, as it also exceeded the recommended threshold of 0.700 (Field, 2005). Mean score ranking was then performed to evaluate the relative significance of the barriers in terms of their probability and severity.

Exploratory factor analysis was conducted to categorise the critical barriers (CRBs) into principal factors (PCRBs). The suitability of the dataset for factor analysis was confirmed through the Kaiser-Meyer-Olkin (KMO) test (0.776) and Bartlett's test of sphericity ($p < 0.000$) (Field, 2005; Osei-kyei *et al*., 2017). Lastly, FSE was employed to assess the overall criticality or risk level of NZEBs in the GCI. The FSE process involved calculating the weightings for each variable, determining the principal factors, computing the membership functions for each variable and principal factors, and quantifying the impact of the principal factors using the criticality indices (Ameyaw and Chan, 2015; Osei-Kyei *et al*., 2017; Xu *et al*., 2010).

4. Results and Discussion

4.1 Demographic Information of Respondents

The demographic composition of the survey's participants (see Table S2) indicates that, out of the 80 collected questionnaires, 38 (47.5%) identified as architects, 24 (30%) as project/construction managers, 12 (15%) as civil/structural engineers, and 6 (7.5%) as services engineers, suggesting a predominance of architects among the respondents. Moreover, participants were asked to specify their tenure in their current profession. Twenty (25%) reported being in their current roles for 0 to 5 years, while 38 (47.5%) indicated a tenure of 6 to 10 years. Additionally, 12 (15%) had held their positions for 11 to 15 years, and 10 (12.5%) had been in their current roles for over 15 years. Regarding professional affiliations, 38 (47.5%) were members of the Ghana Institute of Architects (GIA), 18 (22.5%) belonged to the Ghana Institute of Engineers (GhIE), 10 (12.5%) were part of the Association of Building and Civil Engineering Contractors of Ghana (ABCECG), and 14 (17.5%) were design professionals associated with the Institute of Engineering and Technology Ghana (IET Ghana).

4.2 Reliability Analysis

The Cronbach Alpha coefficient obtained was 0.948, indicating a high level of internal consistency. This exceeds the threshold value of 0.700 (Field, 2005).

4.3 Mean Score Analysis

Mean score ranking was conducted to evaluate the relative significance of the barriers regarding their criticality. The mean scores of the barriers to implementing NZEB in the GCI for this research were computed to obtain their average assessment on the 5-point Likert scale used, where "1 = Not Critical and 5 = Extremely Critical"**.** Based on the grades of the 5-point Likert scale used in the study, a mean score of 3 or more indicates that the variable is significant (Osei-Kyei *et al*., 2017; Wuni *et al*., 2020). The results of the mean scores analyses are shown in Table 1.

(INSERT TABLE 1 HERE)

4.4 Categorizing the Critical Barriers to NZEBs

A factor analysis was conducted using the average ranking of the 20 barriers to implementing NZEB in the construction industry of Ghana. However, when it comes to factor analysis technique for factor groupings, it is often necessary to have a recommended variable-to-sample size ratio of 1:5 (Lingard and Rowlinson, 2006). Again, it is also possible to assess the suitability of this analysis technique for a given set of data by conducting preliminary statistical tests such as correlation and anti-image matrix, KMO, Bartlett's test of sphericity, and reliability test (Ahadzie *et al*., 2008). Therefore, if the statistical tests yield favourable results, even if they do not conform to the recommended size ratio, the factor analysis technique can be carried out with confidence and reliability (Osei-Kye *et al*., 2014; Li *et al*., 2005a). In this regard, initial tests were conducted to determine the suitability of the factor analysis technique in this study. First, the data's internal consistency was assessed using Cronbach's α model, which provides values between 0 and 1. As indicated by Field (2005), Cronbach's α value above 0.70 is considered acceptable, indicating a strong internal consistency and reliability of the data set. A remarkable value of 0.948 is attained for the data set, indicating a strong level of consistency and reliability in the research instrument. A test for sampling adequacy, known as the Kaiser-Meyer-Olkin (KMO) Test, was performed on the dataset. The analyses yielded a statistic of 0.776, surpassing the 0.6 threshold utilized in previous studies (Osei-Kyei *et al.* 2017). This indicates that the dataset is well-suited for structure detection. A Bartlett's test of sphericity was performed to assess the relationship and suitability of the factors for structure detection. The analyses produced a Chi-square value of approximately 1983.665. With a p-value less than 0.000, it is evident that the correlation matrix is not an identity matrix. Therefore, the dataset is well-suited for factor analysis. While there are various methods to assess the appropriateness of a dataset for factor analysis, the positive outcomes of the statistical indicators mentioned above are generally seen as sufficient evidence to support the dataset's suitability. Consequently, an exploratory factor analysis was performed using Principal Component Analysis for factor extraction and Varimax with Kaiser Normalization for factor rotation. Varimax rotation was selected for its ability to simplify interpretation, as it represents the principal component factor with a small number of variables (Abdi, 2003). The results of the exploratory factor analysis are displayed in Table 2.

(INSERT TABLE 2 HERE)

4.5. Evaluating the criticality of the barriers to NZEBs in the Ghanaian construction industry using FSE modelling

Several studies have utilized FSE in the construction engineering and management research domain to assess project management concerns. In a study conducted by Osei-Kyei *et al.* (2017), the authors utilized FSE to assess the critical success factors (CSFs) in the operational management of PPP projects. Similarly, Ameyaw and Chan (2015) employed FSE to evaluate the risk factors associated with public-private partnership (PPP) water projects in developing countries. Additionally, Wuni *et al.* (2020) utilized FSE to assess the success factors for MiC projects. Hence, the ongoing research utilizes the FSE technique to assess the obstacles to achieving NZEBs in the construction industry of Ghana. FSE is a powerful tool for multi-criteria decision-making problems, particularly when dealing with complex systems involving uncertainties and subjective judgements (Ameyaw and Chan, 2015; Liu *et al.*, 2013; Xu *et al.*, 2010). The FSE approach offers several advantages over other similar statistical tools, making it more suitable for this study. FSE can handle inherent fuzziness and uncertainty associated with subjective evaluations provided by experts (Xu *et al.*, 2010). In the context of assessing barriers to NZEBs, the perceptions and opinions of construction professionals may be influenced by their individual experiences, knowledge, and biases. FSE addressed these challenges by using membership functions to quantify the degree of belonging of each barrier to a particular critical level, thereby capturing the fuzziness in the evaluation process (Ameyaw and Chan, 2015). The FSE was implemented using a comprehensive methodology that consisted of three levels. The initial step involves calculating the weightings for each variable and determining the principal factors or components. Next, the membership function is computed for each variable and the principal factors. Finally, the impact of the Principal Factors is quantified using the criticality indices.

The criticality index obtained for each Principal critical barrier or factor (PCRBs) of NZEBs is interpreted based on a predefined scale. In this study, a five-point scale was adopted, where 1 represents "not at all critical" and 5 represents "extremely critical". The criticality threshold was set at 3, which corresponds to the linguistic term "critical" on the five-point scale. This threshold has been widely used in previous studies employing FSE (Ameyaw and Chan, 2015; Liu *et al.*, 2013; Xu *et al.*, 2010). PCRBs with a criticality index greater than or equal to 3 are considered critical and require prioritized attention and mitigation measures.

4.5.1 Determining the appropriate weightings for critical barriers (CRBs) and principal critical barriers (PCRBs)

The weightings for 20 CRBs and 4 PCRBs are established based on the mean score values obtained from the questionnaire survey. Given the mean values, the weightings are computed using the following equation (Yeung *et al.*, 2007):

$$Wi = \frac{Mi}{\sum Mii}$$

Where Wi is the weightings of the CRBs and PCRBs; Mi is the mean score value of CRBs/PCRBs, Mii is the summation of the mean score value of all the CRBs/PCRBs

(INSERT TABLE 3 HERE)

4.5.2 Determining the membership function of each CRB and PCRB

To determine the membership of each PCRB, the membership function of each CRB must be established first. This establishes the foundation for calculating the membership of each PCRB. The membership function of CRB is determined through expert evaluation, where grades are assigned to indicate the level of criticality (ranging from 1 - Not critical to 5 - extremely critical). As an illustration, the survey findings showed that a small percentage of experts considered "Lack of expertise for constructing NZEBs (CRB11)" to be not critical, while a larger percentage rated it as fairly critical, critical, very critical, or extremely critical. Regarding this matter, the membership function for this specific factor can be expressed by the following equation:

$$MF_{(CRB11)} = \frac{0.03}{NC(1)} + \frac{0.13}{FC(2)} + \frac{0.13}{C(3)} + \frac{0.36}{VC(4)} + \frac{0.36}{EC(5)}$$

This is also written as (0.03, 0.13, 0.13, 0.36, 0.36). Using the same approach, the membership functions of the remaining CRBs are computed and this is shown in Table 4. The membership function of the CRBs is further used to compute the membership functions of each PCRB. The PCRBs are determined using the equation;

$$D = W_i \circ R$$

Where D represents the final evaluation matrix; W_i is the weightings for all the CRBs under each PCRBs; R is the fuzzy evaluation matrix for each PCRBs; and $\circ$ is a fuzzy composition operator.

Using PCRB1 (Factor grouping 1) as an example, the weightings for all the CRBs under this factor are expressed as:

$$W_i = (0.162, 0.167, 0.169, 0.169, 0.172, 0.162) \text{ and } R = \begin{vmatrix} 0.03 & 0.13 & 0.13 & 0.36 & 0.36 \\ 0.04 & 0.03 & 0.30 & 0.41 & 0.17 \\ 0.04 & 0.03 & 0.19 & 0.36 & 0.39 \\ 0.06 & 0.05 & 0.14 & 0.23 & 0.53 \\ 0.08 & 0.01 & 0.10 & 0.31 & 0.50 \\ 0.06 & 0.11 & 0.13 & 0.26 & 0.44 \end{vmatrix}$$

Therefore, the membership function of PCRB1 (Factor grouping 1) is calculated as:

$$D_{PCRB1} = (0.162, 0.167, 0.169, 0.169, 0.172, 0.162) \times R = \begin{vmatrix} 0.03 & 0.13 & 0.13 & 0.36 & 0.36 \\ 0.04 & 0.03 & 0.30 & 0.41 & 0.17 \\ 0.04 & 0.03 & 0.19 & 0.36 & 0.39 \\ 0.06 & 0.05 & 0.14 & 0.23 & 0.53 \\ 0.08 & 0.01 & 0.10 & 0.31 & 0.50 \\ 0.06 & 0.11 & 0.13 & 0.26 & 0.44 \end{vmatrix}$$

$D_{PCRB1} = (0.05, 0.06, 0.15, 0.30, 0.44)$ as shown in table 4.

Using the same approach, the membership functions of PCRB2, PCRB3 and PCRB4 were derived and shown in Table 4. After determining the membership of each PCRB, the criticality (index) for each PCRB (factor grouping) is calculated.

(INSERT TABLE 4 HERE)

4.5.3 Quantifying the criticality of the PCRBs (Factor groupings)

After determining the membership function of each PCRB, the criticality index for each factor grouping (PCRB) is calculated using the equation below:

$$\boldsymbol{Criticality\ index\ (CI) for\ each\ PCRB} = \sum_{i=1}^{5} D \times E$$

Where D denotes the final evaluation matrix of a given PCRB and E denotes the grade alternatives of the 5-point rating scale.

From Table 4, the following outcomes can be derived:

$D_{PCRB1} = (0.05, 0.06, 0.15, 0.30, 0.44)$

$D_{PCRB2} = (0.07, 0.09, 0.20, 0.33, 0.29)$

$D_{PCRB3} = (0.07, 0.05, 0.13, 0.30, 0.4)$

$D_{PCRB3} = (0.10, 0.10, 0.10, 0.34, 36)$

Therefore, the criticality indices of the PCRBs are computed as follows:

$PCRB_{CI} = D_{PCRB1} \times E = (0.05, 0.06, 0.15, 0.30, 0.44) \times (1, 2, 3, 4, 5) = 4.023$

$PCRB_{CI} = D_{PCRB2} \times E = (0.07, 0.09, 0.20, 0.33, 0.29) \times (1, 2, 3, 4, 5) = 3.615$

$PCRB_{CI} = D_{PCRB3} \times E = (0.07, 0.05, 0.13, 0.30, 0.40) \times (1, 2, 3, 4, 5) = 4.007$

$PCRB_{CI} = D_{PCRB4} \times E = (0.10, 0.10, 0.10, 0.34, 36) \times (1, 2, 3, 4, 5) = 3.763$

4.6. Results of the Data Analysis

4.6.1 Mean Score Ranking of the Barriers to NZEBs in the Ghanaian Construction Industry

The mean score analysis reveals several key barriers perceived by construction professionals as impeding the implementation of NZEBs in Ghana. "Lack of awareness of passive design and benefits" was ranked first, with a mean score of 4.30. This aligns with findings from Reddy (2016), indicating a lack of knowledge and understanding of passive design principles and how they contribute to NZEB goals in the local context. Educational campaigns focusing specifically on passive design strategies suitable for the Ghanaian climate could help address this barrier. "Lack of knowledge and awareness of NZEB benefits" ranked second with a mean score of 4.17. This validates research by Godin *et al*. (2021) showing that awareness of benefits is a complex issue affecting NZEB adoption. Targeted training programs highlighting the advantages of NZEBs for professionals could enhance knowledge and motivate adoption.

The third highest-ranked barrier is the "Lack of experts capable of doing quality assurance for NZEBs." Poor assurance during design and construction risks performance gaps and unmet efficiency goals in the operational building (Ilmonen, 2015). Specialist training and certification schemes are needed in Ghana, equipping professionals to reliably evaluate and validate NZEB projects. Overall, the top barriers relate strongly to knowledge gaps, highlighting the critical need for educational initiatives, capacity-building programs, and awareness campaigns tailored specifically for Ghanaian construction stakeholders. By improving understanding and expertise related to NZEBs, these strategies can systematically address the key obstacles identified from the survey analysis.

4.6.2 Factor grouping of the critical barriers to NZEBs in the Ghanaian construction industry

The factor analysis (FA) identified four structural components of the barriers to NZEBs in the GCI, as displayed in Table 3. Factor analysis is a valuable tool for condensing a lengthy list of factors into a more organized and concise framework of components. It simplifies the cognitive challenges of managing and prioritizing the extensive list of obstacles to NZEB (Ameyaw and Chan, 2015) and offers assistance in making strategic resource allocations. A 4-factor solution was generated by the factor analysis, which includes PCRB1 - Market readiness barriers, PCRB2 - Cost and Capacity barriers, PCRB3 - Awareness and policy, and PCRB4 - Resistance to change.

4.7 Discussions of the research findings

According to the findings in Table 5, the evaluation model has identified the factor grouping that poses significant barriers to NZEBs in the GCI. Market readiness barriers are ranked first with an index of 4.023, which is considered very critical. This is followed by awareness and policy barriers, with an index of 4.007. Lastly, resistance to change and cost and capacity barriers have indices of 3.763 and 3.615, respectively. The purpose of the indices and ranking is to provide practitioners with important information about the critical issues that require attention in the adoption of NZEBs in the GCI.

(INSERT TABLE 5 HERE)

4.7.1 PCRB1 – Market Readiness Barriers

This factor grouping explained 53.073% of the total variance in the factor analysis, suggesting that market-related barriers significantly hinder the adoption of NZEBs. The PCRB1 grouping emphasizes that the main obstacles hindering NZEB adoption are currently related to the market which is in line with prior research conducted by Godin *et al*. (2021), who discovered that market barriers pose the greatest challenge to the implementation of NZEBs. The market readiness barriers consist of six critical barriers (CRBs), which include the absence of local expertise for NZEB construction, limited demand for NZEBs, inadequate financing schemes for homebuyers, insufficient awareness among design professionals, a shortage of quality assurance experts, and a lack of market competition. The most significant obstacle in the market was the limited availability of local expertise, which received the highest ranking with a mean score of 3.91 and a weighting of 0.162. This highlights the current shortage of professionals with specialized knowledge and skills to design and construct NZEBs as a significant obstacle. For the successful delivery of NZEBs, it is crucial to have a team of experienced local professionals who are well-versed in advanced technologies and integrated design. However, there is still a significant lack of expertise that continues to be a major obstacle in the market. There is a pressing need for the development of training programs and certification courses to quickly enhance local capacity (Pittri *et al*. 2023b). Similarly, the current market environment presents a significant barrier due to the lack of demand for NZEBs. The survey results indicate that there is still a lack of enthusiasm among homebuyers and developers, with a mean score of 4.03 and a weighting of 0.167. Possible factors that may have an impact include the significant initial expenses associated with NZEBs and the lack of awareness in the market regarding their advantages. Increasing consumer awareness, along with providing financial incentives, could potentially stimulate market demand. The lack of financial support for homebuyers interested in NZEBs is a significant market obstacle. These projects can become financially viable for buyers by ensuring access to affordable loans and mortgages. With a mean score of 4.08 and a weighting of 0.169, the feasibility of these projects is evident. Governments can implement specialized funding programs and collaborate with banks/financial institutions to tackle this issue.

4.7.2 PCRB2 – Cost and Capacity Barriers

This factor grouping explained 12.185% of the total variance in the factor analysis, and it is considered critical with a risk level of 3.615. Six significant barriers need to be addressed, which pertain to project costs and the capabilities of the human resources involved. The most significant risk factor in this category is the increased cost of NZEBs, with a weighting of 0.162 and a mean of 3.92. The significant financial investment needed is a common obstacle that restricts the adoption of NZEBs (Makvandia and Safiuddin, 2021; McCoy *et al*., 2015). The costs of implementing advanced technologies and systems to enhance energy efficiency and on-site renewable energy production can be higher upfront compared to conventional buildings. This presents financial challenges and concerns about affordability for numerous clients and developers. Strategies that involve thorough cost-benefit analysis and the use of financial incentives will play a crucial role in overcoming the cost barriers associated with NZEBs. The shortage of skilled workers for NZEB construction was ranked as the second most significant factor, with a weighting of 0.128. The specialized nature of NZEB design and technologies necessitates having construction teams with the necessary skills and competencies, which are still lacking in many markets (Reddy, 2016; Godin *et al*, 2021). Providing specialized training programs focused on NZEBs will help industry professionals enhance their skills and bridge the gap in experience and knowledge. Two other significant barriers within this grouping are the insufficient personnel capacity for operating and managing NZEBs, as well as the inadequate personnel capacity for designing and constructing NZEBs. Their weightings were 0.129 and 0.130 respectively, highlighting their significance. The expertise required for NZEB project delivery is currently limited, which poses risks for implementation (Feng *et al*., 2019). To address this, a comprehensive approach to capacity building that covers design, construction, and O&M phases will help mitigate long-term personnel-related risks. In summary, the cost and capacity grouping emphasises the significant resource requirements in delivering NZEB projects, which can hinder their adoption. The risks highlight the significance of financial enabling mechanisms and ongoing investments in localized human capital development.

4.7.3 PCRB3 – Awareness and Policy Barriers

This grouping accounted for 8.567% of the total variance and had a risk level of 4.007, indicating a high level of criticality. There are five significant barriers that need to be addressed, which pertain to awareness, policy, and political commitment. One of the main obstacles in this category is a lack of knowledge and awareness of the benefits of NZEB, with a weighting of 0.207 and a mean of 4.17. This aligns with the findings of Godin *et al*. (2021), which support the notion that understanding the advantages of NZEBs is an intricate factor influencing the widespread adoption of NZEBs. Despite the clear benefits, there is a lack of understanding among many construction stakeholders when it comes to NZEBs, which is hindering their adoption (Darko *et al*., 2017). Focused educational and promotional initiatives that highlight the benefits of NZEB will help increase awareness. The government's lack of interest in energy efficiency construction was the second highest weighted risk variable at 0.201. Lack of emphasis on state prioritization and involvement is consistently identified as a barrier to NZEBs (Godin *et al*, 2021; Singh *et al*., 2021). Governments play a crucial role in promoting supportive regulations, providing incentives, and setting an example in public buildings. The absence of definitive signals and dedication from policymakers continues to fuel hesitancy among builders and consumers. Another significant obstacle is the clash with public policy regulation and the absence of political determination for NZEB construction, with a weight of 0.201. The reliance on regulatory frameworks and political support exposes NZEB projects to potential uncertainties (Ameyaw and Chan, 2015). Uncertain or volatile policy environments create risks that discourage private investments. It is thus imperative for governments to establish and enforce regulations that promote energy efficiency and the achievement of net zero carbon goals. This requires unwavering political determination and commitment. Overall, the focus is on the importance of spreading knowledge and providing support mechanisms to enable NZEBs. A comprehensive approach that includes public education, efficient policies, and strong leadership will be instrumental in driving progress.

4.7.4 PCRB4 – Resistance to change

This factor grouping explained 7.573% of the total variance and had a criticality index of 3.763, suggesting a high level of criticality. It only consists of one primary obstacle - resistance to change. Resistance to change was the only factor considered in this group, with a weighting of 1.000 and a mean value of 3.82. This supports previous research that emphasizes the challenge of resistance to change as a significant obstacle to achieving sustainability in construction, including for NZEBs (Häkkinen and Belloni, 2011; Darko *et al*., 2017). The shift toward NZEBs represents a significant transition that necessitates shifts in mindsets, practices, technologies, and policies. However, there is a prevailing resistance among the public and industry stakeholders. Developers tend to stick to traditional building approaches; policymakers are hesitant to implement progressive regulations; and consumers have firmly held onto their homebuying perspectives. Overcoming resistance will require a collaborative approach, with the use of incentives, public awareness campaigns, and early involvement of stakeholders. Despite being an independent factor, the reluctance to embrace change presents intricate social and behavioural obstacles that greatly hinder the adoption of NZEB. It is crucial to implement strategies that focus on changing attitudes among all groups involved, in addition to technical solutions. According to Häkkinen and Belloni (2011), there is strong resistance to embracing sustainable transitions like NZEBs, mainly because of the perceived risks associated with adopting new technologies and building methods. A combination of strategies and efforts to promote receptiveness will be crucial.

5. Implications of the study

In terms of practice, the findings offer valuable insights for policymakers, construction professionals, and industry stakeholders. The identification of the critical barriers related to marker readiness, awareness, policy, resistance to change, cost and capacity underscores the need for concrete efforts to address these challenges. Policymakers can use these findings to develop targeted policies and incentives that encourage the adoption of NZEBs in the GCI. From the societal perspective, the adoption of NZEBs has the potential to significantly contribute to the sustainable development goals of Ghana and other developing countries. By reducing the energy consumption and carbon footprint of buildings, NZEBs can help mitigate the impacts of climate change and improve the overall quality of life for citizens. The study emphasises that the industry needs to develop strategies for thorough cost-benefit analysis and explore innovative financing models to make NZEBs more financially viable.

The study highlights the current deficiency in professionals possessing specialised knowledge and expertise in designing and constructing NZEBs. Policymakers should focus on developing educational campaigns and promotional initiatives to increase awareness among construction stakeholders and the general public. To effectively implement NZEB projects, it is essential to assemble a proficient team of local practitioners well-acquainted with cutting-edge technologies and integrated design principles. There is an urgent necessity for the establishment of training initiatives and certification programs to swiftly enhance local capabilities. Augmenting consumer awareness and offering financial incentives could potentially boost the demand for NZEBs in the market. Achieving this objective may involve educating professionals on NZEB practices and integrating NZEB concepts into the educational curriculum for construction professionals, among other strategies.

Researchers can build upon these findings to develop targeted solutions and strategies for overcoming these barriers. The study also highlights the need for more context-specific research in developing countries to better understand the unique challenges they face in transitioning to sustainable construction practices.

6. Conclusion

This study revealed the cluster of factors posing significant challenges to achieving NZEBs in the GCI. Leading the list were barriers related to market readiness, succeeded by obstacles pertaining to awareness and policy. Following these were resistance to change and barriers related to cost and capacity, ranked third and fourth, respectively. The key limitation was the study's relatively small sample of respondents, a result of the challenges associated with data collection within the construction sector. Although the study acknowledges this constraint, it is essential to recognise that it does not compromise the credibility and accuracy of the findings presented. Instead, it offers insight for bolstering and broadening future research initiatives in this domain. Subsequent studies can thus expand the breadth of investigation using a qualitative approach to how the respondents consider the variables as barriers to NZEBs implementation. Also, future research should focus on fostering collaboration between various disciplines such as architecture, engineering, environmental science, and social sciences to develop holistic solutions for sustainable construction

List of references

Abdellah, R. H., and Masrom, M. A. N. (2018), "Exploring the barriers of net zero energy buildings (NZEBS) implementation in Malaysia: Perception of Malaysian construction practitioners", *International Journal of Integrated Engineering, 10*(9).

Abdi, H. (2003), "Factor rotations in factor analyses", in Lewis-Beck, M., Bryman, A. and Futing, T. (Eds), Encyclopedia for Research Methods for the Social Sciences, Sage, Thousand Oaks, CA, pp. 792-795

Adhikari, R. S., Aste, N., Del Pero, C., and Manfren, M. (2012), "Net zero energy buildings: expense or investment?", *Energy Procedia*, *14*, 1331-1336.

Agyekum, A.K., Fugar, F.D.K., Agyekum, K., Akomea-Frimpong, I. and Pittri, H. (2023a), "Barriers to stakeholder engagement in sustainable procurement of public works",", *Engineering, Construction and Architectural Management*, *30*(9), pp.3840-3857.

Agyekum, K., Dompey, A. M. A., Pittri, H., and Botchway, E. A. (2023b), "Design for maintainability (DfM) implementation among design professionals: empirical evidence from a developing country context", *International Journal of Building Pathology and Adaptation*.

Ahadzie, D.K., Proverbs, D.G. and Olomolaiye, P.O. (2008), "Critical success criteria for mass house building projects in developing countries", International Journal of Project Management, Vol. 26 No. 6, pp. 675-687.

Ahmed, A., Ge, T., Peng, J., Yan, W.C., Tee, B.T. and You, S. (2022), "Assessment of the renewable energy generation towards net-zero energy buildings: A review", *Energy and Buildings*, *256*, p.111755.

Akom, K., Shongwe, T., Joseph, M.K. and Padmanaban, S. (2020), "Energy framework and policy direction guidelines: Ghana 2017–2050 perspectives", *IEEE Access*, *8*, pp.152851-152869. https://doi.org/10.1109/ACCESS.2020.3018314

Ameyaw EE, Chan APC. (2015), "Evaluation and ranking of risk factors in public-private partnership water supply projects in developing countries using fuzzy synthetic evaluation approach", *Expert Syst Appl.* 42(12):5102–5116.

Aning A. (2023). The 'Net Zero' agenda: The challenges and possibilities in Ghana. https://www.ghanaweb.com/GhanaHomePage/business/The-Net-Zero-agenda-The-challenges-and-possibilities-in-Ghana-1723814 [Accessed on 7 June 2023]

Baah, B., Acheampong, A., Osei-Asibey, D. and Afful, A.E. (2023), "Assessing the role of respectable engagement in improving construction employee's safety perception", *Smart and sustainable built environment*, *12*(5), pp.937-962.

Basher, M. K., Alam, M. N. E. and Alameh, K. (2021), "Design, development, and characterization of low distortion advanced semitransparent photovoltaic glass for buildings applications", *Energies*, Vol. 14 No. 13, pp.3929. https://doi.org/10.3390/en14133929

Botchway, E.A., Agyekum, K., Amudjie, J. and Pittri, H. (2023), "Occupants perceived importance and satisfaction with fire safety considerations of high-rise students' housing facilities", *Journal of Facilities Management*, Vol. ahead-of-print No. ahead-of-print. https://doi.org/10.1108/JFM-12-2022-0131

Brown, T.A. (2015), "Confirmatory Factor Analysis for Applied Research, Guilford Publications, New York.

Cao, X., Dai, X. and Liu, J. (2016), "Building energy-consumption status worldwide and the state-of-the-art technologies for zero-energy buildings during the past decade", *Energy and buildings*, *128*, pp.198-213.

Cristino, T. M., Neto, A. F., Wurtz, F., and Delinchant, B. (2021), "Barriers to the adoption of energy-efficient technologies in the building sector: A survey of Brazil", *Energy and Buildings, 252*, 111452. https://doi.org/10.1016/j.enbuild.2021.111452

Darko, A., Chan, A.P.C., Ameyaw, E.E., He, B.J. and Olanipekun, A.O. (2017), "Examining issues influencing green building technologies adoption: The United States green building experts' perspectives", *Energy and Buildings*, *144*, pp.320-332. Will green building development take off? An exploratory study of barriers to green building in Vietnam. https://doi.org/10.1016/j.enbuild.2017.03.060

Esbensen, T. V. (1980), "*Solar-assisted low-energy dwellings* (No. DOE/CS-T0145)", Burt, Hill, Kosar, Rittlemann, and Associates, Butler, PA (USA); Mortensen and Esbensen, Sonderborg (Denmark).

Feng, W., Zhang, Q., Ji, H., Wang, R., Zhou, N., Ye, Q., Hao, B., Li, Y., Luo, D. and Lau, S.S.Y. (2019), "A review of net zero energy buildings in hot and humid climates: Experience learned from 34 case study buildings" *Renewable and Sustainable Energy Reviews*, *114*, p.109303.

Field, A. (2005), "Discovering Statistics Using SPSS", 2nd ed., Sage, Thousand Oaks, CA

Garmsiri, S. and Rosen, M.A. (2018), "Energy Benefits of Integrating Transportation Energy with A Net Zero Energy Solar Building Using Captured Waste Hydrogen Fromfrom Electrochemical Plants Andand Bio-Gas Fromfrom Various Bio-Gasification Processes."

Godin, K., Sapinski, J.P. and Dupuis, S., (2021), "The transition to net zero energy (NZE) housing: An integrated approach to market, state, and other barriers", *Cleaner and Responsible Consumption*, 3, p.100043. https://doi.org/10.1016/j.clrc.2021.100043

Häkkinen, T. and Belloni, K. (2011), "Barriers and drivers for sustainable building", *Building Research & Information*, *39*(3), pp.239-255.

Hamilton, J., Kennard, D. H., Rapf, O., Kockat, D. J., Zuhaib, D. S., Toth, D. Z., and Milne, C. (2022), "United Nations Environment Programme (2022). 2022 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector", *Efficient and Resilient Buildings and Construction Sector (Nairobi).*

Ilmonen, L. (2015), "Development of a quality assurance tool to minimize performance gap in nZEBs."

Kumah, V.M.A., Agyekum, K., Botchway, E.A., Pittri, H. and Danso, F.O. (2022), "Examining Built Environment Professionals′ Willingness to Pay for Green Buildings in Ghana", *Buildings*, *12*(12), p.2097.

Li, B., Akintoye, A., Edwards, P.J. and Hardcastle, C. (2005), "Critical success factors for PPP/PFI projects in the UK construction industry", Construction Management and Economics, Vol. 23 No. 5, pp. 459-471.

Lingard, H. and Rowlinson, S. (2006). "Letter to the editor", Construction Management and Economics, Vol. 24 No. 11, pp. 1107-1109

Liu, J., Li, Q. and Wang, Y. (2013), "Risk analysis in ultra-deep scientific drilling project—A fuzzy synthetic evaluation approach", *International Journal of Project Management, 31*(3), pp.449-458.

Lu, Y., Wang, S. and Shan, K. (2015), "Design optimization and optimal control of grid-connected and standalone nearly/net zero energy buildings", *Applied Energy*, *155*, pp.463-477.

Makvandia, G. and Safiuddin, M. (2021), "Obstacles to developing net-zero energy (NZE) homes in Greater Toronto Area", *Buildings*, *11*(3), p.95.

McCoy, A.P., Koebel, C.T., Sanderford, A.R., Franck, C.T. and Keefe, M.J. (2015), "Adoption of high-performance housing technologies among US homebuilding firms, 2000 through 2010", *Cityscape*, *17*(2), pp.167-188.

Nduka, D.O., Ede, A.N., Oyeyemi, K.D. and Olofinnade, O.M. (2019), November. "Awareness, benefits and drawbacks of net zero energy building practices: construction industry professional's perceptions", In *IOP Conference Series: Materials Science and Engineering* (Vol. 640, No. 1, p. 012026). IOP Publishing. https://doi.org/10.1088/1757-899X/640/1/012026

Ohene, E., Hsu, S.C. and Chan, A.P. (2022), "Feasibility and retrofit guidelines towards net-zero energy buildings in tropical climates: a case of Ghana", *Energy and Buildings*, *269*, p.112252.

Osei-Kyei, R., Chan, A.P.C. and Ameyaw, E.E. (2017), "A fuzzy synthetic evaluation analysis of operational management critical success factors for public-private partnership infrastructure projects", *Benchmarking: An International Journal,* Vol. 24 No. 7, pp. 2092-2112

Oyewobi, L.O., Windapo, A.O. and Rotimi, J.O.B., (2015), "Measuring strategic performance in construction companies: a proposed integrated model", *Journal of Facilities Management*, *13*(2), pp.109-132.

Pan L., Xu Q., Nie Y., and Qiu T. (2018), "Analysis of climate adaptive energy-saving technology approaches to residential building envelope in Shanghai", *J. Build. Eng. (19)* 266–272. https://doi.org/10.1016/j.jobe.2018.04.025.

Pan, W., and Pan, M. (2021), "Drivers, barriers and strategies for zero carbon buildings in high-rise high-density cities", *Energy and Buildings*, 242, 110970. https://doi.org/10.1016/j.enbuild.2021.110970

Peterson, K. (2015), "A common definition for zero energy buildings", Prepared for the US Department of Energy by The National Institute of Building Sciences, US Department of. *Energy*.

Pierrehumbert R. (2019), "There is no Plan B for dealing with the climate crisis, *Bull. Atom", Sci.* 75 (5) 215–221. https://doi.org/10.1080/00963402.2019.1654255.

Pittri, H., Agyekum, K., Ayebeng Botchway, E., Opoku, A., and Bimpli, I. (2023a), "Design for deconstruction (DfD) implementation among design professionals: Empirical evidence from Ghana", *International Journal of Construction Management*, 1-11.

Pittri, H., Agyekum, K., Botchway, E. A., Alencastro, J., Oladinrin, O. T., and Dompey, A. M. A. (2023b), "Drivers for design for deconstruction (DfD) implementation among design professionals", *Smart and Sustainable Built Environment*.

Pittri, H., Godawatte, A.G.R., Agyekum, K., Botchway, E.A., Dompey, A.M.A., Oduro, S. and Asamoah, E. (2024), "Examining the barriers to implementing design for deconstruction in the construction industry of a developing country", *Construction Innovation*.

Reddy, S. (2016), "Net zero energy building movement in India-An overview", *International Journal of Research in Science, Engineering and Technology*, *2*, pp.360-63.

Singh, B., Sharma, S.K. and Syal, P. (2021), "Net Zero Energy Building (NZEB) Design", *Journal of The Institution of Engineers (India): Series A*, *102*, pp.237-247.

Solnørdal M.T., and Foss L. (2018), "Closing the Energy Efficiency Gap—A Systematic review of empirical articles on drivers to energy efficiency in manufacturing firms", *Energies* (11)518. https://doi.org/10.3390/en11030518.

Souaid, C., van der Heijden, H., and Elsinga, M. (2022), "Perceived Barriers to Nearly Zero-Energy Housing: Empirical Evidence from Kilkenny, Ireland", *Energies*, 15(17), 6421.

Tongco, M.D.C. (2007), "Purposive sampling as a tool for informant selection", *Ethnobotany Research and Applications,* Vol. 5, pp. 147-158, available at: https://scholarspace.manoa.hawaii.edu/communities/f85cb358-9603-4ea0-8925-9e48d3cf18be. (accessed 29 January 2024).

Torcellini, P., Pless, S., Deru, M., and Crawley, D. (2006), "Zero energy buildings: a critical look at the definition (No. NREL/CP-550-39833)", *National Renewable Energy Lab. (NREL),* Golden, CO (United States).

U.S. Energy Information Administration (EIA) (2016), "*International Energy Outlook 2016 with projection to 2040.*"

Wardhani, D.K. and Susan, S. (2022), "Criteria Formulation for a Web-based Assessment Tool for the Net-Zero Healthy Building", In *International Webinar on Digital Architecture 2021 (IWEDA 2021)* (pp. 66-74). Atlantis Press.

Wei, J., Li, J., Zhao, J. and Wang, X. (2023), ". Hot Topics and Trends in Zero-Energy Building Research—A Bibliometric Analysis Based on CiteSpace", *Buildings*, 13(2), p.479. https://doi.org/10.3390/buildings13020479

Wells, L., Rismanchi, B. and Aye, L., (2018), "A review of Net Zero Energy Buildings with reflections on the Australian context", *Energy and buildings*, 158, pp.616-628. https://doi.org/10.1016/j.enbuild.2017.10.055

Wuni IY, and Shen GQ. (2020), "Critical success factors for management of the early stages of prefabricated prefinished volumetric construction project life cycle", *Eng Constr Archit Manage.* 1–15.

Xu, Y., Chan, A.P. and Yeung, J.F. (2010), “Developing a fuzzy risk allocation model for PPP projects in China”, *Journal of construction engineering and management*, *136*(8), pp.894-903.

Yeung, J.F., Chan, A.P.C., Chan, D.W. and Li, L.K. (2007), “Development of a partnering performance index (PPI) for construction projects in Hong Kong: a Delphi study”, Construction Management and Economics, Vol. 25 No. 12, pp. 1219-1237.

Table 1. Mean Score Ranking of the Barriers to NZEB

SN	Barriers	Mean	St. Deviation	Rank
CRB1	Lack of awareness of passive design and benefits	4.30	0.976	**1st**
CRB2	Lack of knowledge and awareness of NZEB benefits	4.17	1.104	**2nd**
CRB3	Lack of experts capable of doing quality assurance for NZEBs	4.15	1.167	**3rd**
CRB4	Lack of awareness and familiarity among design professionals	4.09	1.212	**4th**
CRB5	Lack of financing schemes available to homebuyers	4.08	1.012	**5th**
CRB6	Regulation and lack of political will for NZE construction	4.05	1.115	**6th**
CRB7	Low government interest in energy efficiency construction	4.05	1.115	**7th**
CRB8	Lack of demand for NZEBs,	4.03	1.037	**8th**
CRB9	High initial investment cost	3.96	1.195	**9th**
CRB10	Lack of suitable variety and competitive market for high-performance NZEBs	3.92	1.257	**10th**
CRB11	Lack of local expertise for constructing NZEBs	3.91	1.133	**11th**
CRB12	Lack of qualified labour for constructing NZEBs	3.88	1.247	**12th**
CRB13	Lack of personnel capacity for NZEB operation and management.	3.85	1.085	**13th**
CRB14	Lack of personnel capacity for NZEB design and construction	3.85	1.153	**14th**
CRB15	Higher cost of NZEBs	3.83	1.131	**15th**
CRB16	Resistance to change	3.82	1.288	**16th**
CRB17	Long payback periods for NZEBs	3.59	1.176	**17th**
CRB18	Conflict with public policy regulation and policy clarity	3.58	1.426	**18th**
CRB19	Lack of evaluation and valuation processes	3.56	1.217	**19th**
CRB20	Low return on investment for NZEBs	3.29	1.200	**20th**

Table 2. Factor Extraction and their Loading

SN.	Factor groupings	Factor Loadings	Eigenvalue	% of variance explained	Cumulative % variance explained
PCRB1	**Market Readiness Barriers**		**14.815**	**53.073**	**53.073**
CRB11	Lack of local expertise for constructing NZEB	0.800			
CRB8	Lack of demand for NZEBs	0.616			
CRB5	Lack of financial schemes available to homebuyers	0.794			
CRB4	Lack of awareness and familiarity among design professionals	1.014			
CRB3	Lack of experts capable of doing quality assurance for NZEB	1.014			
CRB10	Lack of suitable variety and competitive market for high-performance	0.851			
PCRB2	**Cost and Capacity Barriers**		**3.401**	**12.185**	**65.258**
CRB15	Higher cost of NZEBs	0.979			
CRB12	Lack of qualified labour for construction NZEBs	0.836			
CRB14	Lack of personnel capacity for NZEB design and construction	0.808			
CRB13	Lack of personnel capacity for	0.656			

	NZEB operation and management				
CRB17	The long payback period for NZEBs	0.958			
CRB20	Low return on investment for NZEBs	0.770			
CRB9	High Initial investment cost	0.977			
CRB19	Lack of evaluation and valuation processes	1.017			
PCRB3	**Awareness and Policy Barriers**		**2.391**	**8.567**	**73.825**
CRB2	Lack of knowledge and awareness of NZEB benefits	0.812			
CRB1	Lack of Awareness of passive design and benefits	0.544			
CRB17	Low government interest in energy efficiency construction	0.931			
CRB18	Conflict with public policy regulation and policy clarity	0.639			
CRB6	Regulation and lack of political will for NZEB construction	0.954			
PCRB4	**Resistance to change**		**2.114**	**7.573**	**81.397**
CRB16	Resistance to change	1.000			

Table 3. Weighting functions of each variable and the principal components

SN.	Factors (CRBs) and Factor grouping (PCRBs)	Mean score for factors	Weight for each factor	Total Mean for each factor groupings	Weight for each factor grouping
PCRB1	**Market Readiness Barriers**			24.18	0.310
CRB11	Lack of local expertise for constructing NZEB	3.91	0.162		
CRB8	Lack of demand for NZEBs	4.03	0.167		
CRB5	Lack of financial schemes available to homebuyers	4.08	0.169		
CRB4	Lack of awareness and familiarity among design professionals	4.09	0.169		
CRB3	Lack of experts capable of doing quality assurance for NZEB	4.15	0.172		
CRB10	Lack of suitable variety and competitive market for high-performance	3.92	0.162		
PCRB2	**Cost and Capacity Barriers**			29.81	0.382
CRB15	High cost of NZEBs	3.92	0.162		
CRB12	Lack of qualified labour for construction NZEBs	3.83	0.128		
CRB14	Lack of personnel capacity for NZEB design and construction	3.88	0.130		
CRB13	Lack of personnel capacity for NZEB operation and management	3.85	0.129		
CRB17	The long payback period for NZEBs	3.59	0.120		
CRB20	Low return on investment cost	3.29	0.110		
CRB9	High initial investment cost	3.96	0.133		
CRB19	Lack of evaluation and valuation process	3.56	0.119		
PFAC3	**Awareness and Policy Barriers**			20.15	0.258
CRB2	Lack of knowledge and awareness of NZEB benefits	4.17	0.207		
CRB1	Lack of Awareness of passive design and benefits	4.30	0.213		
CRB17	Low government interest in energy efficiency construction	4.05	0.201		
CRB18	Conflict with public policy regulation and policy clarity	3.58	0.178		
CRB6	Regulation and lack of political will for NZEB construction	4.05	0.201		
PCRS	**Resistance to change**			3.82	0.049
CRB16	Resistance to change	3.82	1.000		

Table 4. Membership Function of the CRBs and PCRBs

SN.	Factors (CRBs) and Factor grouping (PCRBs)	Weight for each factor	Membership function for CRBs	Membership function for PCRBs
PCRB1	**Market Readiness Barriers**			(0.05, 0.06, 0.15, 0.30, 0.44)
CRB11	Lack of local expertise for constructing NZEB	0.162	(0.03, 0.13, 0.13, 0.36, 0.36)	
CRB8	Lack of demand for NZEBs	0.167	(0.04, 0.03, 0.23, 0.30, 0.41)	
CRB5	Lack of financial schemes available to homebuyers	0.169	(0.04, 0.03, 0.19, 0.36, 0.39)	
CRB4	Lack of awareness and familiarity among design professionals	0.169	(0.06, 0.11, 0.13, 0.26, 0.44)	
CRB3	Lack of experts capable of doing quality assurance for NZEB	0.172	(0.08, 0.03, 0.28, 0.29, 0.34)	
CRB10	Lack of suitable variety and competitive market for high-performance	0.162	(0.08, 0.08, 0.16, 0.31, 0.38)	
PCRB2	**Cost and Capacity Barriers**			(0.07, 0.09, 0.20, 0.33, 0.29)
CRB15	High cost of NZEBs	0.162	(0.08, 0.03, 0.28, 0.29, 0.34)	
CRB12	Lack of qualified labour for construction NZEBs	0.128	(0.08, 0.08, 0.16, 0.31, 0.38)	
CRB14	Lack of personnel capacity for NZEB design and construction	0.130	(0.06, 0.09, 0.13, 0.41, 0.31)	
CRB13	Lack of personnel capacity for NZEB operation and management	0.129	(0.04, 0.09, 0.21, 0.35, 0.31)	
CRB17	Long payback period for NZEBs	0.120	(0.08, 0.14, 0.21, 0.33, 0.25)	
CRB20	Low return on investment cost	0.110	(0.11, 0.16, 0.25, 0.31, 0.16)	
CRB9		0.133	(0.08, 0.08, 0.16, 0.26, 0.30)	

CRB19	High initial investment cost	0.119	(0.09, 0.13, 0.18, 0.38, 0.24)	
	Lack of evaluation and valuation process			
PCRB3	**Awareness and Policy Barriers**			(0.07, 0.05, 0.13, 0.30, 0.45)
CRB2	Lack of knowledge and awareness of NZEB benefits	0.207	(0.08, 0.00, 0.15, 0.28, 0.50)	
CRB1	Lack of Awareness of passive design and benefits	0.213	(0.00, 0.10, 0.08, 0.25, 0.58)	
CRB17	Low government interest in energy efficiency construction	0.201	(0.08, 0.01, 0.19, 0.33, 0.40)	
CRB18	Conflict with public policy regulation and policy clarity	0.178	(0.19, 0.06, 0.06, 0.39, 0.30)	
CRB6	Regulation and lack of political will for NZEB construction	0.201	(0.04, 0.08, 0.16, 0.28, 0.45)	
PCRB4	**Resistance to Change**			(0.10, 0.10, 0.10, 0.34, 36)
CRB	Resistance to change	1.000	(0.10, 0.10, 0.10, 0.34, 0.36)	

Table 5. Critical indices of the PCRBs influencing NZEBs in the Ghanaian Construction industry

Code	PCRBs	Index	Description	Rank
PCRB1	Market Readiness Barriers	4.023	**Critical**	**1st**
PCRB2	Cost and Capacity Barriers	3.615	**Critical**	**4th**
PCRB3	Awareness and Policy Barriers	4.007	**Critical**	**2nd**
PCRB4	Resistance to Change	3.763	**Critical**	**3rd**

Table S1 Barriers Impeding the Implementation of Net Zero Energy Buildings (NZEBs)

Barriers	Source
Resistance to change	Godin et al. (2021), Darko et al. (2017)
Lack of knowledge and awareness of NZE homes' benefits	Godin et al. (2021), Darko et al. (2017)
Higher cost of NZEB homes	Godin et al. (2021), Darko et al. (2017), McCoy et al. (2015)
Lack of qualified labour for constructing NZEBs	Godin et al. (2021)
Lack of local expertise for constructing NZEBs	Godin et al. (2021)
High initial investment cost (upfront cost)	Cao et al. (2016); Feng et al. (2019)
Long payback periods for capital investments in NZEBs	Cao et al. (2016)
Lack of demand for NZE homes	Godin et al. (2021)
Lack of financing schemes available to homebuyers	Godin et al. (2021)
Low government interest and involvement in energy efficiency and NZE construction	Godin et al. (2021)
Lack of personnel capacity for NZEB design and construction	Feng et al. (2019)
Lack of personnel capacity for NZEB operation and management	Feng et al. (2019)
Low return on investment for NZEBs	Nduka et al. (2019)
Conflict with public policy regulation and policy clarity	Nduka et al. (2019)
Lack of evaluation and valuation processes for NZEBs	Nduka et al. (2019)
Regulation and lack of political will for NZE construction	Reddy (2016)
Lack of awareness and familiarity among design professionals	Reddy (2016)
Lack of suitable variety and competitive market for high-performance NZEBs	Reddy (2016)
Lack of awareness of passive design and benefits	Reddy (2016)
Lack of experts capable of doing quality assurance for NZEBs	Reddy (2016)

Table S2. Demographic Information of Respondents

Demographic Information	**Frequency**	**Percentage (%)**
Profession		
Architect	38	47.5
Project Manager/Construction Manager	24	30.0
Civil/Structural Engineer	12	15.0
Services Engineer	6	7.5
Respondents' Years of Working in their Current Role		
0-5 years	20	25.0
6-10 years	38	47.5
11-15 years	12	15.0
Over 20 years	10	12.5
Level of Education		
PhD	5	6.3
Master's	42	52.5
Bachelor's	30	37.5
HND	3	3.7
Professional Affiliation		
Ghana Institute of Architects (GIA)	38	47.5
Ghana Institute of Engineers (GhIE)	18	22.5
Association of Building and Civil Engineering Contractors of Ghana (ABCECG)	10	12.5
Institute of Engineering and Technology Ghana (IET Ghana).	14	17.5
TOTAL	**80**	**100**