

# RISK ANALYSIS OF BUILDING ENERGY PERFORMANCE GAP: CONSIDERING PROJECT COMPLEXITY

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Compelling evidence reveals a substantial energy performance gap (BEPG) in low- and zero-energy buildings. While risks contributing to BEPG stem from various complexities of projects, existing literature lacks comprehensive risk analysis of BEPG considering project complexities. This study addresses this gap by comprehensively identifying project complexities and energy performance risks and analysing their relationship through a literature review and interviews. Findings highlight technology synergies, time and cost constraints, internal and external uncertainties, and client and supply chain immaturity as significant complexity factors affecting energy performance risks and leading to BEPG. The varying impacts of complexities underscore the need to integrate project complexity into BEPG risk analysis for tailored risk management strategies in building projects. This study not only contributes to the BEPG literature by introducing a risk analysis perspective into building energy performance management, but also benefits project stakeholders by enhancing understanding of BEPG-related risk factors and providing references for proactively assessing and mitigating risks, thereby increasing the likelihood of achieving energy performance targets and reducing BEPG.

Keywords: energy performance gap; risk analysis; zero-energy buildings; project complexity

## INTRODUCTION

The building stock contributes to about 40% of the global energy-related carbon emissions, hence achieving net-zero energy targets in buildings is crucial for mitigating global carbon emissions (World Green Building Council, 2023). However, compelling evidence reveals a substantial difference between the predicted and actual energy consumption in buildings, commonly known as the building energy performance gap (BEPG), averaging around 30% (van Dronkelaar *et al.*, 2019). To address this, many scholars have studied factors contributing to the BEPG and corresponding mitigating strategies. These studies have predominantly focused on identifying and addressing individual factors, with limited consideration of the interrelationships among them. However, the need to include intricate relationships between these factors in the analysis and management of BEPG has been highlighted, as a factor that may pose a significant threat to building energy performance through

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its cause-and-effect relationships with other factors (Xu and Zou, 2020). Furthermore, there is sufficient implicit evidence in the literature that most of the contributing factors of BEPG origin from the complexity of low- and zero-energy building (ZEB) projects, such as conflicts between project objectives, the complexity of building energy systems and controls, the uncertainty of building usage and occupant behaviours etc. (Thompson *et al.*, 2022). Due to different project characteristics, these projects present different types and degrees of complexity, resulting in diverse risk scenarios and occurrence probabilities (Qazi *et al.*, 2016). Therefore, capturing project complexity in the analysis and management of BEPG is important to reflect unique project characteristics and develop bespoke mitigation strategies.

As energy performance is becoming a regulatory requirement for building projects, a scientific and systematic risk analysis is of great significance in identifying, assessing, and mitigating factors affecting energy performance (hereinafter referred to as energy performance risks (EPRs)). The risk analysis approach not only provides a holistic perspective to consider a wide range of risk-related factors (e.g., project complexity and uncertainty), but also enables the systematic identification and analysis of those factors with the consideration of their causal relationship (Tepeli *et al.*, 2021). Existing literature has analysed risks in different construction projects, with the majority focusing on project completion and delivery, including risks associated with cost, delay, quality, and safety dimensions (Erol *et al.*, 2020). Currently, there is a lack of research systematically and comprehensively analysing risk factors affecting energy performance targets in ZEB projects, aiming to reduce the BEPG. This study attempts to fill this research gap by comprehensively identifying project complexities and EPRs contributing to BEPG and analysing the relationship between them, based on literature review and interview surveys.

## LITERATURE REVIEW

### Energy Performance Risks in Buildings

Studies on BEPG have identified various risk factors that contribute to BEPG, which can be classified into design risk, construction risk, handover and commissioning risk, operational risk, and lifecycle risk. In the design stage, inappropriate assumptions and modelling are the factors most frequently cited in the literature, contributing to inaccuracies in energy performance predictions (de Wilde, 2014). Design defects can also compromise energy performance.

Examples include energy systems with poor robustness, insufficient integration between different energy systems, and inconsistencies or mismatches in the capacities of energy systems resulting in under- or over-sizing (Borgstein *et al.*, 2018).

Moreover, inadequacy of building design has repercussions for the construction and operation of energy-efficient systems. Design that lacks adequate risk assessment and uncertainty analysis may fail to detect and address potential vulnerabilities and uncertainties, resulting in unintended consequences and varied operation performance (Zou *et al.*, 2019). Technology and design with low visibility and usability can negatively affect occupant's understanding and the effective use of energy-efficient systems (Watson, 2015). The lack of details in design increases the possibility of deviating from the design intent as contractors and FM teams must define unspecified details (Tuohy and Murphy, 2015).

Regarding construction, one cause of BEPG is construction defects which results in poor quality of buildings. It is found that poor installation and substandard

components and materials lead to poor quality of building envelope and excessive heat losses (Jain *et al.*, 2020). Another contributing factor to BEPG is construction changes. Specifically, deviations from the original design intent may result from client changing requests without regard to their impact on energy efficiency, or on-site changes and substitute of materials and equipment due to workarounds and value engineering of contractor and sub-contractors (Papachristos *et al.*, 2020).

Ineffective commissioning and handover have been pointed out as major risks of BEPG. Liang *et al.*, (2019) found that only 28% of the 117 buildings surveyed had undergone a commissioning process to verify the proper installation and normal operation of energy-saving technologies. Even if commissioning is performed, it may be basic and isolated without seasonality and commissioning of entire systems. There may also be a lack of fine-tuning during commissioning, so issues go unsolved, and the correctness of the system operation is not guaranteed. (Bunn *et al.*, 2023). Besides, ineffective handover results in users and managers misunderstanding design and performance features, and operating them inefficiently (Gupta and Gregg, 2016). Examples include inaccurate or incomplete operation and maintenance manuals building logbooks, and insufficient training for FM teams.

In the operation stage, changes in operational conditions appeared frequently in ZEBs, posing challenges for building management and control. This arises partly from inaccurate predictions of building use and occupant behaviour made during building design and occupants' tendency to misunderstand and misuse building systems for comfort (Thompson *et al.*, 2022). Inadequacy of performance evaluation also contributes to the BEPG in various ways. Malfunctioning metering systems and the absence of energy audits and POEs hinder accurate energy performance reflection and identification of energy performance issues (Zaid *et al.*, 2017). Additionally, good management practices are vital for improving energy performance. The lack of systematic monitoring and improvement process inhibits the identification of energy savings opportunities and key areas for improvement (Mikhail *et al.*, 2023). Other poor management practices, such as poor maintenance and insufficient training and awareness among building operators, facility managers, and occupants, may lead to premature failure and overriding of energy-efficient technologies and systems (McElroy and Rosenow, 2019).

Regarding poor control strategies, many buildings have been highlighted that the implemented control strategies deviate from the original design specifications, in terms of control sequences, setpoints, or operation models (Wang *et al.*, 2020). Control strategies should also be optimised to reflect actual building conditions, yet in some cases control parameters are poorly calibrated and control setpoints are inappropriate, resulting in energy waste and occupant discomfort (Wu *et al.*, 2023). Furthermore, technical failures frequently occur due to the interaction of technical and managerial factors, such as unknown vulnerabilities of technologies and slow diagnosis and repair of faults (Gupta and Gregg, 2016).

Some risks can also happen throughout the project lifecycle and indirectly contribute to BEPG. For example, lack of alignment and commitment among heterogeneous stakeholders can lead to inconsistent decision-making throughout the project lifecycle, including disagreements over energy performance targets and criteria (Alencastro *et al.*, 2018). This can hinder collaboration, communication, and the establishment of clear accountability, giving rise to EPRs during the project lifecycle. Additionally, failures in the procurement process, clarity, and contractual language can complicate

projects and increase the BEPG (Thompson *et al.*, 2022). For instance, failure to establish maintenance contracts for all building systems can result in poor maintenance and management, leading to frequent technical failures and delayed repairs (Gupta *et al.*, 2017). Stakeholders lack the necessary knowledge and experience in energy-efficient design, construction and operation can result in various EPRs, including sub-optimal decision-making in design, improper installation of technologies, and poor management and control (Xu and Zou, 2020).

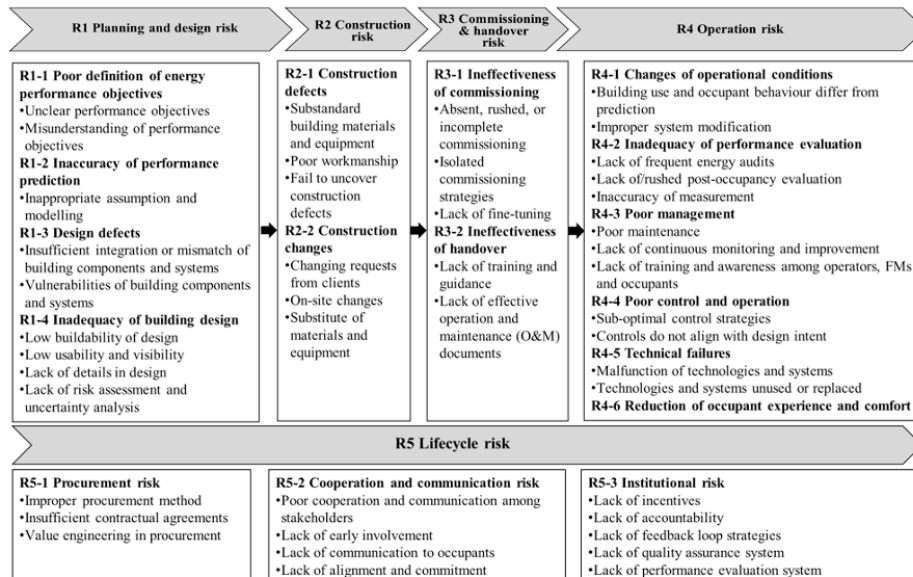


Figure 1: Contributing factors of building energy performance gap

### Project Complexity and Energy Performance Risk

Project risk management scholars view complexity as a crucial source of project risks as increasing complexity makes projects hard to anticipate and control (Tepeli *et al.*, 2021). This emphasizes the importance of theorising and integrating project complexity in risk analysis. Although some studies on BEPG have mentioned the influence of different project complexity factors on building energy performance, there is no clear and systematic demonstration of the relationship between project complexity and EPR.

According to Bosch-Rekvelde *et al.*, (2011), the complexity of projects can be conceptualised into three dimensions, namely technical, organisational, and environmental complexity. Technical complexity (T) is mainly associated with the content of the project, including size, variety, breadth of scope, the level of interdependence of people or tasks, or the pace of the work. Organisational complexity (O) includes the softer aspects of the project, such as people and resources within the project team. Environmental complexity (E) includes the influence of internal and external environments, such as stakeholders and economic, social, and natural environment.

The technical complexity of ZEBs has been intensely discussed in the literature from different aspects. For instance, larger sizes of ZEBs often entail more complex systems, posing challenges for monitoring and control, and potentially leading to energy wastage from occupants and technologies not being used (Borgstein *et al.*, 2018). The number and variety of tasks influence the amount of information required for different disciplines and defect generation rates (Papachristos *et al.*, 2020).

Additionally, the involvement of numerous stakeholders and subcontracted package components can increase fragmentation in the delivery process, making supervision and monitoring challenging, as well as complicating data collection and exchange (Shrubsole *et al.*, 2019). The variety of building functions and services can directly impact occupancy and occupant behaviour, complicating prediction and control (Jain *et al.*, 2021). Furthermore, zero-carbon technologies have seen considerable efficiency improvements, while innovative technologies are often not well implemented and performed in buildings due to technology incompatibility, lack of knowledge and information, and economic barriers etc (Carlander and Thollander, 2023).

In terms of organisational complexity, the time of delivery can significantly affect the building processes. Frank *et al.*, (2015) indicated that the time of delivery may not give clients the opportunity to choose from alternative materials, equipment, and/or technology and does not aid maintainability. And budgetary limitations, value engineering or operational costs hinder proper building processes and components (Thompson *et al.*, 2022).

ZEB projects also have various environmental complexities. The energy performance is influenced by various internal and external uncertainties, such as climate conditions, building usage, occupancy, and user behaviour, which are difficult to predict in design (Van Dronkelaar *et al.*, 2016). The interaction between occupants and energy systems is intricate. Available control over building appliances and systems can influence occupants' behaviour, potentially affecting energy use positively or negatively (Weerasinghe *et al.*, 2023). Besides, many stakeholders and their diverse perspectives on energy performance targets can complex the implementation of project tasks. Personnel changes of the FM team may cause the loss of institutional knowledge, and decreased energy efficiency if new personnel are not adequately trained or experienced in energy-efficient systems (Gupta and Gregg, 2016). Additionally, changes in project scope can result in significant deviations from what was originally specified. These alterations may affect the quality of building construction yet are rarely fed back into the energy model (Menezes *et al.*, 2012).

## **METHOD**

### **Data Collection**

The extant literature falls short of unveiling the nexus of project complexities and EPRs in generating the BEPG. To address this gap, both primary and secondary data collection were conducted to investigate the relationship between project complexities and EPRs. Semi-structured interviews were chosen to collect primary data, as they offer distinct advantages in academic research by allowing researchers to gather in-depth information aligned with the study's focus and providing flexibility compared to unstructured interviews. Based on the categories of EPRs and project complexities identified from the literature review, the semi-structured interviews were aimed at validating and complementing the complexities of ZEB projects and understanding how they interact with EPRs leading to BEPG. Accordingly, an interview protocol was employed, comprising a predefined set of questions to guide one-on-one interactions with the participants. The questions focused on what makes the ZEB project complex or difficult to manage, and how do different project complexities lead to EPRs and BEPG. To ensure comprehensive and diverse insights, five interviews were conducted with participants from various professional backgrounds (refer to Table 1). Participants were identified and selected based on two criteria. First, the

participants were required to have at least five years of experience in the building sector to ensure they had sufficient knowledge and experience in the field. Second, participants were chosen based on their involvement in delivering low-carbon building projects in the UK to communicate and demonstrate project practices. The interviews lasted between 1 and 1.5 hours and were conducted in an open, consistent, and flexible manner using the pre-designed interview protocol. All responses were then recorded and transcribed by the researcher.

Table 1: Key information of semi-structured interviews

Participant code	Professional background	Years of experience	Interview duration
P1	Architect	> 10	1h
P2	Government Client	> 10	1h
P3	Project Management Professional	> 10	1.5h
P4	Sustainability consultant	> 10	1h
P5	Contractor	5-10	1h

Thematic analysis was employed in this study to code the interview transcripts systematically, as it enables the identifying, analysis, and reporting of patterns or themes within qualitative data. Initially, the principal researcher meticulously read all transcripts to code excerpts relevant to BEPG. These codes captured influencing factors directly or indirectly affect BEPG, as mentioned by the participants, and were cross-checked by the research team to achieve consensus. Subsequently, all codes were organised into themes, focusing on patterns or connections between them. The themes were then reviewed and named based on the categories of EPRs and project complexities derived from the literature review. Within and among each theme, the data were analysed to explore causal relationships between EPRs and project complexities. Indications of causality, such as sequences of events or conditional statements, were identified and examined. Finally, the study presented the analysis results and explanations.

## FINDINGS AND DISCUSSION

The results of the literature and interviews confirm that different project complexities have various effects on EPRs, as shown in Figure 2. This demonstrates the importance of complexity in building energy performance management and the need to integrate complexity into the development of proactive risk management strategies during the front-end development phases of ZEBs (Erol *et al.*, 2020). It is also worth noting that complexity does not always affect EPRs negatively in ZEB projects; conversely, it could lead to opportunities when combined with the appropriate management strategies.

In terms of technical complexity, both literature and interview results emphasize that the technical complexity of ZCBs lies in the exploitation of technology synergies. Achieving zero-energy requires utilising different technologies, including passive design technologies, energy-efficient technologies, and renewable energy technologies, to enhance building components and systems. These technologies need to be coordinated and optimised under specific project conditions to achieve multiple, sometimes conflicting objectives, such as energy performance, cost, and indoor environmental quality (Sun *et al.*, 2020). This can be achieved through integrated design among interdisciplinary teams. One participant noted, "most of these technologies we can use are already there and are already successful."

Complexity factors	Source	R1-1	R1-2	R1-3	R1-4	R2-1	R2-2	R3-1	R3-2	R4-1	R4-2	R4-3	R4-4	R4-5	R4-6	R5-1	R5-2	R5-3	R5-4
T1 Complexity of technology and system	B	+	+	+	+		+			+	+	+	+	+					
T2 Number of performance criteria	B			+															
T3 Number and variety of tasks	L			+		+												+	
T4 Dependencies between tasks	B					+	+												
T5 Number of building functions and services	L	+								+	+	+	+						
T6 Number of building physical constraints	L		+			+													
T7 Newness of technology	B	+	+			+				+	+	+	+	+					+
O1 Level of cost and time constraints	B	+	+	+	+	+	+	+	+				+	+				+	+
O2 Interface between project disciplines	B			-	-														
O3 Prior experience with parties involved	L																		
E1 Number of stakeholders	L																		
E2 Variety of stakeholders' perspective on energy performance objective	B	+																	
E3 Overlap of stage partners' activities	B																		
E4 Changes in stakeholders	L				+														
E5 Uncertainty of building use and occupancy	B		+							+		+	+						
E6 Uncertainty of occupant behaviour	B		+	+						+		+	+						
E7 Uncertainty of climate conditions	B		+	+						+		+	+						
E8 Number of interactions between occupant and system	L		+			-				+		+	+						
E9 Occupant changeover rate	L		+							+	+	+	+						
E10 Supply chain maturity	E						+		+										
E11 Client maturity	B	+						+											
E12 Strictness of standards and regulations	B		+																




T = Technical complexity factor, O = Organisational complexity factor, E = Environmental complexity factor  
 L /  = based on literature data, B /  = based on empirical data, B /  = based on both literature and empirical data

Figure 2: The relationship between project complexities and energy performance risks in zero-energy building projects

The new thing is to combine technologies and to find synergies. ... This need integrated planning and design and there is a huge opportunity to optimise energy performance and reduce costs for both investment and operation" (P1). However, a lack of consideration and deployment of integrated design not only results in energy systems with poor robustness but also affect cost-effectiveness and indoor comfort and health (Kampelis *et al.*, 2017).

The main factor of organisational complexity is time and cost constraints, which can rise and exacerbate EPRs during the project lifecycle. The significant impact of time and financial limitation on design phase is highlighted by the participants. "When the design team working on reducing carbon, it doesn't ever help when value engineering comes into it, and things get chopped for finance reasons" (P4) ... "The design of a sustainable solution needs more input, more work, more time. The system of how engineers and architects are paid is not adapted to this new way of working" (P1). In addition, participants indicated that the interface between project disciplines provides opportunities for innovation and optimisation in ZEB design, as it facilitates the interaction and engagement of partners, which aligns with the results of Papachristos *et al.* (2020).

In terms of environmental complexity, the design and operation of building energy systems are significantly affected by uncertain external and internal factors. These uncertain factors can stem from aleatory uncertainty (i.e. inherent randomness from the natural data generation process) or epistemic uncertainty (i.e. vagueness caused by limited data or understanding) (Chen *et al.*, 2022). Aleatory uncertainty is less likely reduceable, while epistemic uncertainty is possible to be reduced through gathering more information or refining models. Supply chain integration has been considered to enhance information collection and sharing, yet the involvement of numerous stakeholders and their diverse perspectives and interests increases supply chain fragmentation, posing challenges to collaboration and communication among parties (Papachristos *et al.*, 2020). These challenges were also cited by the participants.

Notably, the participants highlighted that supply chains are still immature in the delivery of ZCBs resulting in various EPRs. For instance, a government client highlighted that current low-carbon building supply chain lack maturity in both

equipment, materials, and labour viz: "People are not qualified to fix all the panels or air source heat pumps. Companies aren't big enough yet to build the heat pumps or the several solar panels that we need. And we haven't yet got into a world of managing these technologies that all those technologies are continuously measured, verified, and maintained to make sure they perform well. (P2)" In addition, participants also mentioned unsophisticated clients can complex the realisation of ZCBs. Some private companies prioritise profit rather than carbon reduction, only if carbon is monetised and associated with their benefit. Even though some clients aspire for net zero, they may not have sufficient understanding, knowledge, and experience to push innovative solutions and achieve higher levels of performance.

## CONCLUSIONS

Based on the literature review and interview surveys, this study comprehensively identified EPRs and project complexities contributing to the BEPG, revealing intricate relationships between project complexities and EPRs. The results indicate technology synergies, time and cost constraints, internal and external uncertainties, and client and supply chain immaturity as significant complexity factors in ZEB projects, affecting EPRs throughout the project lifecycle and leading to BEPG. Moreover, the varying impacts of technical, organisational, and environmental complexity on EPRs underscore the need to integrate project complexity into BEPG risk analysis to develop appropriate risk management strategies tailored to the unique characteristics of individual ZEB projects, to bridge BEPG.

The study contributes to the BEPG literature by introducing a risk analysis perspective and integrating project complexity into the energy performance management of ZEB projects. The results can benefit project stakeholders by enhancing their understanding of BEPG-related risk factors and providing references for proactively identifying, assessing, and mitigating risks, thereby increasing the likelihood of achieving energy performance targets and reducing BEPG.

Future research in this area is suggested to further explore the relationship between different project complexity factors and their impact on BEPG. Additionally, researchers can apply systematic risk assessment methods to quantitatively assess EPRs in ZEBs by considering project complexities and their relationship with EPRs, thus supporting the development of optimal risk management strategies. Furthermore, there is a need for additional research to develop robust risk management frameworks that effectively address the challenges posed by BEPG and promote the adoption of ZEB practices.

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