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Review of 10 years research on building energy performance gap: Life-cycle and stakeholder perspectives

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ABSTRACT

The reliability, security, and sustainability of energy generation and supply are of global importance and the building sector accounts for up to 32% of total energy consumption, which makes it a key player in the domain. Previous research has identified that the actual energy consumption in buildings could be as much as 2.5 times of the predicted or simulated. This large building energy performance gap (BEPG) between the predicted and actual consumption has caused a significant problem for building energy supply and demand management and therefore have attracted increasing attention from researchers around the world. These researches have resulted in a large number of publications over the last decade. However, research has not reached the phase where the root causes of BEPG could be effectively identified, managed, and eliminated. There remains a lack of systematic and comprehensive review of the current literature to understand the current state of play, and set directions for future research. To fill this gap, in this paper, a thorough survey and review of BEPG research was carried out. The paper collected and analyzed 227 relevant publications and developed a framework for better understanding previous BEPG research. Subsequently, an in-depth analysis of BEPG research was conducted to explore its causes and corresponding strategies (including design concept, "hard" technologies and "soft" measures). Not only the interaction among causes but also the strengths and limitations of corresponding strategies were discussed in detail. Future research is finally recommended based on the limitations of exist strategies, including (1) building energy performance life-cycle thinking; (2) energy performance information integrity; (3) big data collection and analytical method; (4) stakeholders' attributions, decision criteria and behavior; (5) stakeholder interactions; (6) modelling and simulation validation; (7) multidisciplinary approach; and (8) building system flexibility.

1. Introduction

Energy is an essential resource and driving force of a country's social and economic development. With the continuous development of human society, global energy demand and consumption continue to grow, and the energy problem has become increasingly prominent. According to the *International Energy Outlook 2016*, the world's total consumption of marketed energy would expand from 579 Exajoules (EJ) in 2012 to 815 EJ in 2040 [1]. In this context, energy conservation has risen to the strategic level of national development. Building energy, as an important part of an overall energy strategy, has become the focus of attention for most countries over the past three decades. In 2010 the building sector accounted for approximately 32% of total energy use [2], becoming one of the largest end-use sectors worldwide [3]. Considering an expected population of 9.7 billion by the mid-century, along with the growing trend of urbanization and improvement of living standards, people will work, study and live inside buildings for longer time, leading to a stronger growth in energy consumption in buildings which would exceed that in transport and industry sectors [4]. According to the reports of Intergovernmental Panel on Climate Change (IPCC) and International Energy Agency (IEA), global building energy consumption may double to triple by 2050 and represent the largest proportion (by over one-third) of energy consumption in the overall economy [5,6]. Facing the grim energy situation, many countries have proposed energy conservation goals and strategies. For example, in the United States (US), the 2007 Energy Independence and Security Act (EISA) requires certain new federal building construction and major building renovation projects to eliminate fossil emissions by 2030 [7]; the United Kingdom (UK) requires that new buildings should achieve a Building Energy Rating (BER) lower than the prescribed Target Energy

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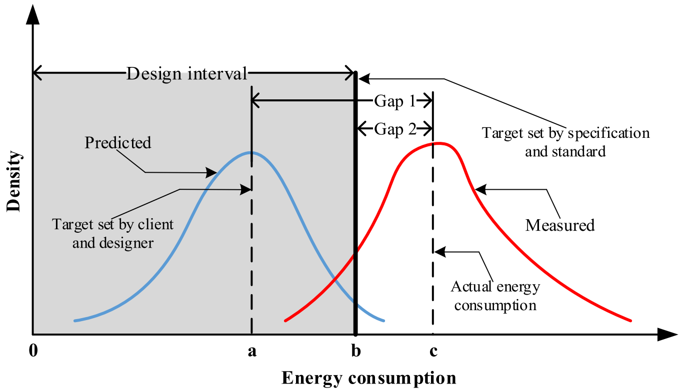

Fig. 1. Types of BEPG.

Rating [8]; China has proposed energy control from three levels, i.e., national (macro), regional (mezzo) and building (micro). Nevertheless, there are a large number of buildings did not meet the energy conservation goals, including those used advanced energy conservation technologies [9,10]. According to the statistics, the actual measured building energy consumption can be as much as 2.5 times higher than the predicted consumption [8,11], which will seriously hinder the realization of the goal of energy conservation. Therefore, it is important to obtain a comprehensive and systematic understanding of the building energy performance gap (BEPG) between the predicted and measured values.

The current literature researches have provided three different definitions and meanings for BEPG, such as the gap between predicted and actual energy performance [12], the gap between simulated and measured energy performance [13], the gap between predicted and measured energy performance [11]. There are two definitions of building energy. The first refers to the energy consumption during production, transportation, construction, operation and end-of-life phases [14]. The second refers to the energy that is imported from the outside in operation stage, including the energy that maintains building environment (e.g., ventilation, lighting, heating, and cooling) and various types of building activities (e.g., working, cooking and entertainment) [11,15]. In this study, building energy is referred to the latter definition.

To control the rapid growth of building energy consumption, many governments had set up building energy efficiency target [7,8]. Therefore, the energy consumption target set by owner and designer should not exceed the ones set by government target specification and standard (Fig. 4). In general, there is no difference between simulated and predicted building energy performance since predicted values are derived from simulated values. At the design stage, a building is designed according to the target set by owner and designer, and the predicted building energy consumption is attained by modeling and simulation. It should be noted that design is a process that may be constantly optimized. If the predicted or simulated energy performance does not achieve the goal set by owner and designer, the design needs to be adjusted. However, the standard of the target set by owner and designer may also be reduced because of time and resource constraints. With the development of energy monitoring technology, the building energy monitoring accuracy has been increased. It can be said that the measured energy performance is the actual energy performance.

As shown in Fig. 1, two kinds of energy performance gap exist. The first is the gap between the predicted (or simulated) and measured (or actual) building energy performance (Gap 1), which attracts most attention from researchers; the second is the gap between the target set by specification (or standard) and measured (or actual) building energy performance (Gap 2) that is the focus of governments. It can be found that if “Gap 1” is filled, “Gap 2” would no longer exist. In this paper, BEPG refers to the first gap.

Literature review is a useful method to evaluate the state-of-the-art of a particular research field and inform future research directions, as has been well evidenced by numerous of papers [16–18]. Over the last 10 years, a multitude of researchers have explored the building energy performance gap and several literature reviews had been conducted in relation to building energy performance, such as De Wilde [11], Hong, Koo, Kim, Lee and Jeong [19], Jia, Srinivasan and Raheem [20]. Although these attempts have been devoted to exploring BEPG, there remains a lack of systematic and comprehensive research that studies the root causes of BEPG and their corresponding strategies. To be more specific, (1) there is still no clear definition for BEPG; (2) some critical causes, such as user experience [21] and information integrity [21] were not taken into consideration; (3) the relationships among different root causes, which has been proved to have a significant impact on building energy performance gap (BEPG) [10,15], were overlooked; and (4) detail description of strategies for closing BEPG is still absence. In the recent five years, more than 100 papers related to BEPG have been published, along with the rise of new ideas (e.g., pre-occupancy evaluation) and new application technology (e.g., augmented reality and virtual reality). It can be said that the field of building energy management had undergone enormous changes. Therefore, it is necessary to evaluate the existing research and identify the current research gap and future research needs.

This study aims to analyze and summarize the researches that were conducted in the past ten years to study the root causes of BEPG and corresponding strategies, and to provide recommendations for future research directions. Based on this aim, three research objectives are formulated as follows:

1. Develop a framework of previous BEPG research;
2. Understand and provide detail descriptions of the root causes of BEPG and corresponding strategies, and the limitations of these strategies;
3. Understand the current research gap and propose a future research for addressing the gap.

To achieve these aim and objectives, this paper presents detail description of the methodology (Section 2), a framework for understanding BEPG (Section 3), root causes of BEPG (Section 4), strategies for closing BEPG (Section 5), future research directions (Section 6) and conclusion (Section 7).

2. Research methods

This study applies systematic review as methodology to analyze the status quo of BEPG to identify current knowledge gaps and future research needs. Fig. 1 presents the main process of systematic review in this study. The first step is data collection. The main type of data in this study is publications. In the second step (data analysis), a framework based on the analysis of collected publications were developed for obtaining an overview of BEPG research. The publications were analyzed for identifying root causes of BEPG and strategies for closing BEPG. The limitations of current strategies were then discussed for finally identifying research gaps and future research directions. According to the process of systematic review, there are two main methods used in this study, namely publications collection and content analysis, which are described in detail in later sections.

2.1. Retrieving publications

The work commenced with the identification of publications related to BEPG, including journal articles, conference papers and reports. Research in BEPG can be seen as a combination of multiple

Table 1
Number of publications by source.

Source	No. of publications
Energy and Buildings	27
Building Research & Information	15
Building Simulation	14
Applied Energy	14
Journal of Building Performance Simulation	12
Building and Environment	11
Energy	11
Architectural Science Review	11
Journal of computing in civil engineering	10
Automation in Construction	10
Renewable and Sustainable Energy Reviews	9
Energy Efficiency	7
Energy Policy	6
Science and Technology for the Built Environment	6
Strategic Planning for Energy and the Environment	6
Energy Conversion and Management	5
Building Services Engineering Research and Technology	4
Journal of building survey, Appraisal & Valuation	4
Architectural Engineering and Design Management	4
Journal of Cleaner Production	3
HVAC&R Research	3
IEEE Transactions on Automation Science and Engineering	3
Advances in Building Energy Research	3
Sustainable Cities and Society	3
International Journal of Sustainable Built Environment	2
Construction Management and Economics	1
Conference papers and reports	23
Total	227

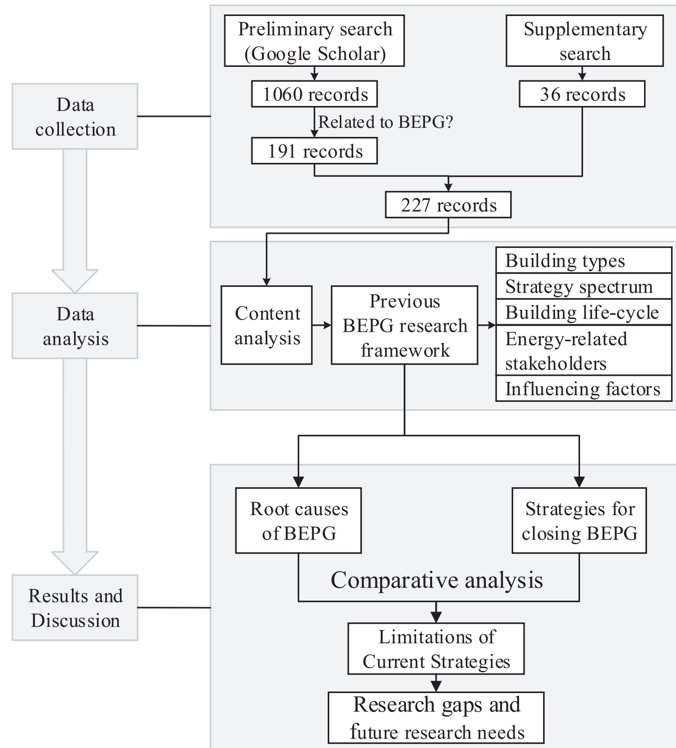

Fig. 2. Process of systematic review on BEPG research.

disciplines, including but not limited to computer science, management, behavior, statistics, psychology, engineering and informatics [10,11,22]. Therefore, it is not enough to select target publications from only one database for providing a comprehensive search of BEPG. For example, *Building Research & Information* is published by Taylor & Francis, which cannot be found in ScienceDirect. To avoid missing important publications, Google Scholar was used at the first stage. As stated by Nicolás Robinson-Garcia (a bibliometric researcher at the University of Granada in Spain), "Google Scholar's compendium of articles is at least as comprehensive as the leading commercial academic search databases-Thomson Reuters' Web of Science and Elsevier's Scopus-and for many disciplines in the social sciences and humanities, even better" [23]. The comprehensiveness of Google Scholar is well evidenced by publications every now and then [24–27]. However, due to the issues related to updating frequency, some new publications may not be found in Google Scholar [24]. Therefore, it is also necessary to conduct a supplementary search in *Web of Science, ScienceDirect, Ei CompenexWeb, Taylor & Francis, Emerald*.

Firstly, two key phrases "building energy" and "performance gap" were used to search in Google Scholar and 1060 records (from 2007 to 2017) were found. Each of these publications was examined to identify whether they are related to BEPG, and this effort resulted in 191 publications extracted from 1060 records. Afterward, 36 extra publications were identified from *Web of Science, ScienceDirect, Ei CompenexWeb, Taylor & Francis, Emerald*. Finally, a total of 227 publications were collected. Table 1 shows the number of identified publications from different sources.

2.2. Analyzing contents using NVivo®

Given the large amount of data (227 publications), NVivo® was used in this study. NVivo® is a famous qualitative data analysis computer software, which has been used in numerous researches [18,28]. All publications imported into NVivo® in this study are treated as "Sources", which were analyzed by using "Node" function. A node is a collection of references (including sentence, paragraph, the whole paper, and report) about a specific topic, theme or relationship. In this study, the references about the same theme will be gathered to a node by "coding". Take a paper titled "A virtual reality integrated design approach to improving occupancy information integrity for closing the building energy performance gap" as an example, the sentence "In the operation stage, occupants may not usually perform in accordance with building designers' design assumptions" is related to operation, occupant and design assumption, three nodes are created, namely "operation", "occupant" and "design", and code the sentence under them. In most cases, nodes may have two or more than two level node structure. For example, for the content about occupant, we could create a three-level node structure where the first level includes "Operation", the second level includes "Occupant", and the third level contains "Occupant characteristics", "Occupant comfort", "Occupant experience" and "Occupant behavior". Then we could analyze the content and code it under "Occupant characteristics", "Occupant comfort", "Occupant experience" or "Occupant behavior". According to this approach, all sources can be coded. It should be noted that initial codes might be iteratively revised and refined throughout the coding process [28]. In order to ensure the reliability and validity of the analytical results, several rounds of coding were conducted.

Having coded all sources, the relationship between the nodes could be structured by using the "Model" function in NVivo® [17]. A tentative framework, as shown in Fig. 3, is developed based on the analysis of the 227 publications (due to the limited space of the paper, only nodes in the first and second levels are shown). In Fig. 2, there are three different shapes that represent different meanings. The diamond shape represents the boundary of this research and contains all publications; the hexagon shape stands for the strategies for closing BEPG, including design concept, new technology and "soft" measures; the ellipses shape represents the nodes created in the coding process. Arrows in the framework mean the relationship between different figures, which includes "results in", "contributes to" and "impact on". For instance, the arrow between "design" and "construction" shows that inappropriate design may have a negative impact on the construction. The number in each shape shows the total number of publications related to a specific theme. For example, there are 120 publications related to the causes of BEPG in design stage and 150 publications related to occupant. Furthermore, the number of each arrow shows the total number of publications connected with a specific relationship between two themes. It is worth noting that a publication may be related to more than one themes and relationships.

3. Summary of previous BEPG research

The tentative framework of BEPG research shown in Fig. 1 is just an initial framework generated from the 227 publications, which may not be easily understood. Therefore, a new framework (Fig. 4), which was based on the tentative framework was developed for better understanding BEPG research. As shown in Fig. 4, there are five major components in this framework: (a) the "Building type" including residential building and non-residential building; (b) the "Strategy" for closing BEPG containing "Design concept", "Technology & Method" and "Soft" measures; (c) the "Building life-cycle" indicating the stages that the causes of BEPG belongs to; (d) the "Energy-related stakeholder" indicating the stakeholders that may have an impact on BEPG; and (e) the "Influencing factors" indicating the factors related to BEPG. Component (a) was developed by synthesizing all nodes focusing on different types of buildings. Component (b) was formed by reviewing all nodes proposing strategies for filling BEPG. Component (c) was developed according to the stage characteristics of nodes. Component (d) was formed by nodes connected with different stakeholders. Component (e) was developed according to the different categories of influencing factors of BEPG.

Based on the BEPG research framework, the existing research can be seen from more than one perspective. For instance, research on occupant behavior simulation can be seen from "Occupant" in the Energy-related stakeholder, "Operation" in the Building life-cycle, "Technology & Method" in the Strategy, and "Behavior" in the Influencing factors. Therefore, the BEPG research framework helps readers to see a "panorama" of the BEPG research as published. Based on the framework, the next three sections will conduct an in-depth analysis of BEPG research.

3.1. Building types

Through utilizing the BEPG research framework, all retrieved BEPG publications can be reviewed from different perspectives according to the components, and thus a comprehensive and systematic overview of BEPG research from 2007 to 2017 can be understood. The framework shows that residential and non-residential buildings (especially commercial buildings) are the focus of research on BEPG since they account for 24% and more than 8% of total global final energy consumption respectively [2]. According to the statistical analysis, 153 publications (67.4%) are related to *Residential buildings* and 175 publications (71.1%) are related to *Non-residential buildings*. It should be noted that the summation of the two numbers exceeds 227 (the same situation can be seen in components (c), (d) and (e)) because there are 101 publications focus on both residential and non-residential buildings. Due to the difference of building function, non-residential building and residential building should be treated differently in research. For example, cooking and water heating are significant energy consumption in residential buildings, while Heating, Ventilation and Air Conditioning (HVAC) and lighting are important end-uses in non-residential buildings.

3.2. Strategy spectrum

There are 184 publications that proposed strategies for closing BEPG, which can be understood by positioning them into a "Strategy spectrum". The first of this spectrum is about *Design concept and method* (40, 17.6%), such as, passive design [21,29,30], active design [31–33], and human-in-the-loop design [10,34]. Passive design is a design concept that incorporate high levels of insulation and airtightness, and effective heat recovery to achieve a very low energy demand [21]. Active design achieves balance between comfort, environment and energy with assistance of building automation system. Nowadays, "human-in-the-loop" is a new concept for designers to get more useful information related to energy-related stakeholders (especially occupant) and reduce BEPG [35]. However, only having the design concept is inadequate, technology is also needed to implement design concept, and thus the second of component spectrum is related to technology. It is found that sustained research efforts have been devoted to "hard" technologies and methods (134, 59.0%), including Building Information Modelling (BIM) [15,36], Radio Frequency Identification (RFID) [35], Virtual Reality (VR) [10,37], Augmented Reality (AR) [35,38], data mining [39], machine learning [40], artificial intelligence [41] and etc. The third component of this spectrum is about "soft" measures, which is more focused on the communication between energy-related stakeholders [42,43], occupants' comfort [44,45], occupants' experience [21], rebound effect [21], "Soft Landings" process [15,46], information disclosure [47] and etc. It is well acknowledged that BEPG cannot be filled only with advanced technologies, "soft" measures are equally important. Although the number of publications related to "soft" measures is relatively small, it has attracted an increasing attention from researchers.

3.3. Building life-cycle

By projecting the publications onto a building life-cycle, it is found that they fall into four major stages including *Design* (120, 52.9%), *Construction* (18, 7.9%), *Operation* (150, 66.1%) and *Retrofitting* (25, 11.0%). Since the causes of BEPG from different stages could interact with each other, especially the interaction between operation and design [48], a publication may focus on more than one stage. For example, the paper titled "A framework for the utilization of Building Management System data in building information models for building design and operation" explored building design and operation, and the feedbacks from operation to design. It can be seen that a large number of publications were concentrated on operation stage. The reason may be that operation is the stage that directly generates building energy consumption. A full understanding of operation stage could not only help to effectively reduce unnecessary energy consumption but also help to optimize energy efficiency system design [10,34]. Compared with the research on design and operation stages, only 18 publications were related to the construction stage. It should be noted that, although the root causes of BEPG in construction stage may not be as much as that in design or operation stage, they could have a great impact on building energy consumption. For instance, if the quality of a building was not in accordance with the specification, it is difficult for this building to achieve energy conservation goals [11,49]. It is, therefore, proposed that future researchers should pay more attention to the construction stage.

3.4. Energy-related stakeholders

The research on BEPG representing in the 227 publications can be understood from another perspective by projecting them onto energy-related stakeholders. Energy-related stakeholder refers to the stakeholder from building life-cycle that may have an impact on the building energy consumption. There are six major stakeholders in existing researchers, namely *Owner* (39, 17.2%), *Designer* (120, 52.9%), *Contractor* (18, 7.9%), *Supplier* (12, 5.3%), *Occupant* (150, 66.1%), *Energy manager* (32, 14.1%) and *Government* (32, 14.1%), whose activities will directly or indirectly affect building energy consumption, such as owner's and designer's decision, contractor's construction, energy manager's and occupant's behavior [11,50–52]. It is found that a significant proportion of publications was concentrated on occupant, e.g., occupant characteristics, occupant behavior, occupant experience and occupant's comfort. As stated by Wang and Srinivasan [41], occupant plays an important role in building energy consumption. In addition, occupant factors are the focus of designers' attention. It has been proved that if a designer could not evaluate occupant factors well, the predicted energy consumption is lack of reliability [10,41].

3.5. Influencing factors

By classifying the influencing factors, the 227 publications fall into *Information* (186, 89.1%), *Knowledge & Experience* (106, 46.7%), *Behavior* (146, 64.3%), *Modelling & Simulation* (42, 18.5%), and *Environment* (122, 53.7%). As an influencing factor that most publications are concentrated on, the *Behavior* includes those behavior of all energy-related stakeholders, such as the designers' decision-making behavior, the energy managers' management behavior, and the occupants' energy consumption behavior. *Information*, which attracts an increasing attention in both research and practice, refers to the data that is generated from different project stages and is transferred among different project stages and energy related stakeholders. It should be noted that lack of information integrity is identified as one of the main causes of BEPG [10]. In *Modelling & Simulation*, computers and software are used to compute the results of indoor environment and building energy consumption. *Knowledge & Experience* had a great impact on building energy consumption too [42,53], but are largely out of the attention of existing research. Many researches had proved that a lack of knowledge and experience is a root cause of BEPG [54,55] and hence, researches need to be extended to *Knowledge & Experience*. As another influencing factor that should not be ignored, *Environment* is full of uncertainties. As stated by Pollard [12], although the data about weather conditions is sufficient, it may not represent a building's actual prevailing weather conditions.

4. Root causes of BEPG

According to the stages of building lifecycle, the root causes of BEPG can be grouped into three main categories, i.e., causes that arise from the design stage, causes rooted in the construction stage, and causes that pertain to the operation stage [11]. Although retrofitting is viewed as one of the stages of building life cycle in BEPG framework, it can also be divided into design stage, construction stage and operation stage. Therefore, the causes that related to retrofitting are not considered as a separate category.

4.1. Design and simulation related causes

In the design stage, designers are the critical energy-related stakeholder who has a great impact on building energy [56]. The first type of causes related to designer is lack of appropriate assumption [10,21]. It is not easy for designers to accurately predict the situation in operation with limited data, knowledge and experience, especially the occupant behavior and climate that are full of uncertainty [12,35]. Many researchers stated that if enough data can be attained from the operation stage, the design would be more accurate. However, many barriers to the operational stage data collection are existed [48,57]. The second type of causes coming from designers is energy modeling and simulation. It is well acknowledged that one of the characteristics of models is abstract, and a model is just a simplified version of a complex reality [58]. As stated by Box [59], "all models are wrong, but some are useful". On one hand, it is very important for designers to have a good overview of different models and have correct data input definition [11]; on the other hand, designers cannot rely entirely on modeling and simulation. The third type of causes that pertain to designers is design concept. In practice, most designers believe that the more energy saving technology they use, the higher energy performance the building will have. However, the actual do not perform as predicted. According to the statistics of 100 Leadership in Energy and Environmental Design (LEED) certified commercial and institutional buildings, 28–35% of LEED buildings consumed more energy than their conventional counterparts [49]. The main reason may be that (1) the equipment's actual performance is overestimated by designer [49]; (2) the energy system with poor robustness is difficult to accommodate change of environment, use and occupancy [11,60]; (3) end users do not know how to control and operate energy system efficiently [61]. It should be noted that, even if the design is fully in line with the requirement of target, there also can be a BEPG if the design is lack of attention to buildability and simplicity of construction [11,62]. As another key stakeholder in the design stage, owners also have a great impact on building energy, which cannot be overlooked. A lot of engineering practice showed that owner's concept, decision and behavior would affect design, such as mistaken ideas about building energy saving and change orders [11]. In addition, lack of communication between owner and designer could also lead to BEPG [10,11].

4.2. Construction related causes

Within the construction stage, it is the critical cause of BEPG that the onsite construction quality is often not in line with design specifications, especially insulation and airtightness [8,11]. Many reasons could affect construction quality: (1) contractor with limited experience and knowledge often defines details that are left unspecified by designers, which results in the gap between designed and as-built [63]; (2) contractor sometimes cheats in work and cuts down materials to reduce cost [9]; (3) change orders always exacerbate the gap between design and actual building [11]; (4) poor workmanship and improper construction technique make the actual building difficult to meet the requirement of design specification; and (5) hidden problems are always existed and might be hard to spot [11].

4.3. Operation related causes

The operation stage is widely considered as a major contributor to BEPG, and occupant is repeatedly cited as the critical stakeholder responsible for BEPG [10,11,50,51,56]. It is well acknowledged that occupants have a great impact on building energy performance as they control ventilation, lighting, internal temperature and electrical appliance [55]. Therefore, occupant behavior is viewed as a main cause of BEPG [64]. Occupant behavior can be affected by numerous factors, including but not limited to building's characteristics (such as building orientation, insulation and airtightness), occupants' social and personal characteristics (for example lifestyle and cultural background), rebound effect, occupants' energy-related attitude (such as personal comfort, cost and environmental concerns), the interaction among occupants, occupants' knowledge and skills (for example the knowledge for proper use of air conditioning), occupants' experience, and occupants' comfort [65–67]. In addition, occupants' behavior patterns may differ in different buildings. For instance, occupants in residential

Table 2
Causes of BEPG and corresponding stakeholders.

Stage	Cause ID	S. node	Stakeholders	C. node	Causes	Source
Design and simulation stage	S1C1	S1	Designer	C1	Inappropriate assumption	[10,21]
	S1C2	S1	Designer	C2	Difficult to fully predict future	[11,68,69]
	S1C3	S1	Designer	C3	Difficult to complete information collection	[10,37]
	S2C3	S2	Supplier			
	S1C4	S1	Designer	C4	Technology's actual performance is overestimated	[11,13,49]
	S3C4	S3	Owner			
	S1C5	S1	Designer	C5	Energy system with poor robustness	[11,60]
	S1C6	S1	Designer	C6	Lack of attention to end user	[61]
	S1C7	S1	Designer	C7	Lack of attention to buildability and simplicity of construction	[11,13]
	S1C8	S1	Designer	C8	Poor sequencing of the construction process	[13]
	S1C9	S1	Designer	C9	Incorporation of inefficient or oversized system	[13]
	S1C10	S1	Designer	C10	Inappropriate modelling and simulation	[11,13]
	S1C11	S1	Designer	C11	Design details that are left unspecified	[11,13]
	S1C12	S1	Designer	C12	Poor communication	[11,13,70,71]
	S2C12	S2	Supplier			
	S3C12	S3	Owner			
	S4C12	S4	Contractor			
	S5C12	S5	Occupant			
	S6C12	S6	Energy manager			
Construction and commissioning stage	S3C13	S3	Owner	C13	Change orders	[11]
	S3C14	S3	Owner	C14	Unreasonable understanding of building energy saving	[11]
	S1C15	S1	Designer	C15	Limited experience and knowledge	[35,46]
	S3C15	S3	Owner			
	S4C15	S4	Contractor			
	S5C15	S5	Occupant			
	S6C15	S6	Energy manager			
	S4C16	S4	Contractor	C16	Poor building quality	[8,11]
	S4C17	S4	Contractor	C17	Poor workmanship	[9]
	S4C18	S4	Contractor	C18	Cut corners	[9,13]
	S4C19	S4	Contractor	C19	Improper construction technique	[55,72]
	S4C20	S4	Contractor	C20	Fail to uncover hidden problems	[11,13]
	S4C21	S4	Contractor	C21	Full performance testing is not allowed due to time and budget constraints	[13]
	S2C22	S2	Supplier	C22	Poor quality of equipment or materials	[8,73]
Operation stage	S5C23	S5	Occupant	C23	Occupant behavior	[64]
	S5C24	S5	Occupant	C24	Occupants' social and personal characteristics	[66]
	S5C25	S5	Occupant	C25	Interaction and influence among occupants	[90]
	S5C26	S5	Occupant	C26	Occupant's attitude	[21]
	S5C27	S5	Occupant	C27	Occupants' experience	[21]
	S5C28	S5	Occupant	C28	Occupants' comfort	[29]
	S5C29	S5	Occupant	C29	Rebound effect	[74, 75]
	S5C30	S5	Occupant	C30	Do not know how to control energy system	[61,76]
	S6C30	S6	Energy manager			
	S6C31	S6	Energy manager	C31	Controls do not work as predicted	[55]
	S6C32	S6	Energy manager	C32	Lack of fine-tuning during the first few years of operation stage	[55]
	S6C33	S6	Energy manager	C33	Lack of standardization and continuity of monitoring, analysis, and control	[11]

buildings may care more about energy cost than occupants in office buildings since occupants in office buildings do not need to pay for energy consumption. Energy manager is another important stakeholder that cannot be ignored, especially in large commercial buildings. Good controls conducted by energy manager can not only lead to a reduction in building energy consumption but also lead to increasing building occupants' comfort [55]. However, many energy managers do not know how to conduct proper control strategies. The reason may be that (1) energy managers do not have enough knowledge and skills to control energy system; (2) control systems/strategies do not work as predicted; (3) there may be lack of fine-tuning of the strategy during the first few years of operation stage [55].

Based on literature review, a total of 33 causes of BEPG were identified, with six respective stakeholder groups generating 45 nodes. The causes and related stakeholders are summarized in Table 2. Each cause and its related stakeholder are seen as a node, which was coded numerically into S_aC_b (a represents a specific stakeholder group, and b indicates the related cause of BEPG).

After all cause nodes are identified and coded, the arrows in the network representing the effects of causes on other causes are further identified based on literature review (Fig. 5). For example, if S_aC_b can affect S_cC_d, there will be an arrow from S_aC_b to S_cC_d. Fig. 5 provides an insight into the overall network structure. Arrows in Fig. 5 only represent an influence between causes, and do not represent influence level. It can be seen that all causes are interconnected, implying great complexities in analyzing the causes of BEPG. To be more specific, even a small cause of BEPG might also turn into a huge threat to building energy through the cause network. It can also be found that many arrows are between different stakeholders, indicating the interaction among stakeholders plays an important role in the cause network. Future research on the causes of BEPG should be carried out from a systematic stakeholder network perspective.

5. Strategies for closing BEPG

Having realized the root causes of BEPG, researchers and practitioners proposed many strategies, which can be grouped into design concept, technology & methods and "soft" measures. Each of these groups is discussed in the following sections.

5.1. Design concepts

5.1.1. Passive and active design

Passive design is not a new design concept, but it has become a useful strategy to reduce BEPG in recent years. Compared with conventional buildings, passive building can reduce unnecessary energy consumption [19]. Taking lighting for example, the lighting energy consumption of conventional buildings is frequently higher than the predicted due to much of the natural lighting not being fully utilized [77]. If adapting passive design, the BEPG in terms of lighting can be reduced. Furthermore, passive building could reduce the impact of occupant behavior on building energy since passive design strategies decrease or eliminate the need for energy [78,79]. A successful passive design heavily relies on a full understanding of climate and energy system by both designer and end user [78]. If designers do not have enough information or occupants do not know how to operate building system effectively, the passive building would have adverse impacts on building energy. In contrast to passive design, active design based on the belief that building energy can be saved while users' comfort improved with the assistance of building automation system. As afore-discussed, active design is a double-edge sword. If designers have complete information and the ability to predict all situations in the operation stage, active design may be successfully implemented. In addition to this, construction quality and equipment performance may also affect the implementation of active design.

5.1.2. Human-in-the-loop

Human-in-the-loop is defined as a model that requires human interaction [80]. Information is always an important factor in building energy. The more information a designer has, the more accurate the design could be [10]. The most important part in "human-in-the-loop" design is data collection. There are two kinds of methods for data collection, i.e., pre-occupancy data collection and post-occupancy data collection. However, both of them have limitations (detailed information can be seen in [10] and [35]). It should be noted that a good "human-in-the-loop" design cannot be independent of advanced technology (e.g., genetic algorithm, machine learning, VR and AR). In the future, more efforts need to be done to combine "human-in-the-loop" design and technology together.

5.2. Technology and method

Most researchers and practitioners believe that adapting new technology and method could be one of the most effective ways to reduce BEPG. Therefore, it is not difficult to understand why technologies and methods account for the largest proportions of all strategies. Technologies and methods (T&M) can be grouped into four categories, namely T&M for calculating energy consumption, T&M for energy-related data collection and analysis, T&M for occupant behavior modeling and simulation, and T&M for energy system controlling.

5.2.1. Technology and method for calculating energy consumption

T&M for estimating energy consumption aims at improving the accuracy and rationality of design as well as design optimization, which can be categorized into black box method, grey box method and white box method [81]. A black box method predicts energy consumption without physical knowledge, such as genetic algorithm [82] and artificial neural networks [83]. In contrast, the white box method, also termed as engineering method, estimates energy consumption by using thermodynamic equations to represent the physical behavior of building and its interactions with external environment according to its physical description [84,85]. EnergyPlus, Ecotect, and DOE-2 are mature tools based on white box method. However, they require a lot of data and the output is difficult to calibrate [84]. The grey box methods are the combination of the black and white box method, which eliminates the limitations inherent in each method [41]. For example the combination of EnergyPlus with particle swarm optimization [86] and genetic algorithm [87]. Although the above methods provide sharp tools for researchers and practitioners to predict and optimize energy consumption, they need to pass a serious of rigorous tests, otherwise researchers and practitioners could be using a wrong method to solve problems. Considering the importance of calibration, many methods for model calibration were proposed, such as Bayesian approach [88] and iterative update approach [89].

5.2.2. Technology and method for data collection and analysis

In T&M for energy-related data collection and analysis, occupant behavior data and building operation data attract most attention. There are mainly two kinds of data collection methods, namely post-occupancy data collection and pre-occupancy data collection. Post-occupancy data collection, based on the actual energy-related data in the operation stage [10], is not very easy to be conducted since most occupants do not want to be disturbed. To solve this problem, RFID [90], sensors [29,51], electricity meter [91], building automation system [92], Wi-Fi [93,94], and wireless camera networks [95] were used for data collection, as shown in Fig. 6. Different methods or technologies may be used for collecting different kinds of data and have their own shortcomings and strengths. For example, Wi-Fi has great advantages on tracking occupancy and the locations of occupant, but it cannot provide other detailed information related to occupant behavior, such as window open-close status record [20]. To have a systematic and comprehensive understanding of occupant behavior, including not only behavior pattern but also deep-seated causes of behavior, technologies and methods should be used in combination. However, few existing researches have used combined technologies and methods due to the limitations of time and resource constraints.

Although post-occupancy data collection is the most commonly used method for data collection, it is limited in guiding new buildings because there are no two buildings with exactly the same building physics, outdoor environment and occupant group [10]. Niu, Pan and Zhao [10] pointed out that post-occupancy data collection lacks of the consideration of "timeliness" (i.e. to observe occupant behavior in the design stage), "customization" (i.e. to collect data from the building that is to be built) and "interactivity" (i.e. there is information interaction between designer and occupant). To overcome the shortcomings of post-occupancy data collection, a new data collection method named pre-occupancy data collection was proposed with the development of information technology (e.g. virtual reality and building information modelling). Pre-occupancy data collection could help designers to evaluate and optimize a design prior to construction in the virtual space of the design [96]. This method is also the way to achieve "human-in-the-loop" design from technical level. It should be noted that pre-occupancy data collection is not omnipotent because occupants' experience in the virtual world is not exactly the same as that in the real building. The comparison of pre-occupancy data collection and post-occupancy data collection is shown in Table 3.

There are two types of data analysis methods: statistical analysis and data mining. Statistical analysis is mainly used to establish a numerical relationship among energy consumption, occupant behavior and other information (such as indoor/outdoor environment and time series) [20,51], including statistical tests, regression analysis, and curve fitting. For example, Haldi and Robinson [97] used logistic regression to explore the impact of temperature on occupants' behavior; Li, Li, Fan and Jia [98] applied multi-factors variance analysis to find the statistical significance of indoor/outdoor temperature, indoor/outdoor humidity, indoor CO_2 concentration

Table 3
Comparison of pre-occupancy data collection and post-occupancy data collection [10,35].

	Pre-occupancy data collection	Post-occupancy data collection
Method or technology	Prototyping with sensor, virtual reality	Questionnaire, interview, sensor, meter, camera, Wi-Fi and building automation system
Project stage	Information is collected in the design stage	Information is collected in the operation stage
Customization for design	Knowledge obtained from the collected information is applied to the same building	Knowledge obtained from the collected information is applied to subsequent projects
Customization for operation	Knowledge obtained from the collected information is applied to the same building	Knowledge obtained from the collected information is applied to the same building
Type of information	Dynamic: both the processes and the results of occupant behavior in the building can be observed and recorded	Dynamic (sensor, meter, camera, Wi-Fi camera, Wi-Fi and building automation system) or static (questionnaire & interview: only the results of occupant behavior in the building can be observed and recorded)
Source of information	Direct	Direct (sensor, meter, camera and Wi-Fi camera, Wi-Fi and building automation system) or indirect (questionnaire & interview)
Strength	Low cost; provide useful suggestions and a powerful design review; enhance the information interaction between designers and users	Highlight inefficient operations and optimize them
Shortcoming	Limited in minimizing uncertainty in smart buildings	Limited in guiding new projects; high cost; challenged by authenticity

and outdoor wind speed to occupant operation of windows. It should be noted that the volume of data collected by the above-mentioned data collection methods is extremely large, and statistical analysis may seem to be slow and expensive when processing massive and unstructured data [51].

Data mining, as an emerging powerful technology in the field of computer science, has great potential to discover hidden knowledge from big data [99]. Nowadays, data mining is increasingly used in building energy data analysis. Through the intersection of machine learning, artificial intelligence (AI), database systems, statistics and pattern recognition, data mining could discover interesting and potentially useful knowledge (e.g., behavior pattern and power consumption patterns) based on massive energy-related data. Currently, data mining mainly has two directions, one is building energy consumption data analysis. For instance, Xiao and Fan [99] applied data mining techniques to identify the typical power/electricity consumption patterns and associations among power/electricity consumptions. The research finally found four rules for improving building energy performance, which cannot be deduced from domain knowledge [99]. The other one is occupancy and occupant behavior data analysis. In the research of Liang, Hong and Shen [51], a data mining based approach was used to learn and predict occupancy presence in office buildings. In fact, data mining for occupancy and occupant behavior analysis is still in its infancy and has potential room for improvement. Jia, Srinivasan and Raheem [20] pointed out that "data mining is confined to predefined occupant behaviors or merely occupancy, and it is hard to link to energy simulation program" which is due to the lack of multidimensional data of occupant behavior. This proves once again the importance of integrating different kinds of information related to occupant behavior.

5.2.3. Technology and method for occupant behavior modeling and simulation

To bridge BEPG, the modeling and simulation of occupant behavior are greatly needed since occupant behavior is one of the key reasons for discrepancies between predicted and measured energy consumption. In this paper, T&M for occupant behavior modeling and simulation are categorized into two major areas, namely agent-based modeling and stochastic process modeling.

Agent-based modeling (ABM), as a kind of computational model, simulates the actions and interactions of agents (e.g., individual, group or equipment) with a view to assessing the effects on the whole system [20]. Its strong potential of simulating the interaction of human and building energy system is well evidenced by works published every now and then [100–102]. The emphasis of ABM-based studies consists of the following two aspects. First, some of the researchers focused on the interaction between occupants and building system. For example, Alfakara and Croxford [103] developed a simulation method using ABM that tried to explore the interaction between occupant and room system for controlling mechanical cooling system and window. Second, some researchers addressed the interrelation between different occupants. For instance, Langevin, Wen and Gurian [102] considered user-defined social constraints from other occupants on an agent's certain behavior. Although ABM is a relatively new method for occupant behavior modeling and simulation, it has become one of the most popular methods for researchers to quantitatively analyze occupant behavior. This is not only because ABM is suitable for sophisticated pattern of interaction and uncertainty, but also because its potential capability to integrate with energy simulation program [20,104]. But the limitations of this method could not be ignored. At present, ABM in occupant behavior modeling and simulation are more dependent on assumptions rather than actual data [20]. In addition, it is difficult to verify a model based on ABM.

It is well acknowledged that one important nature of occupant behavior is randomness [20]. Accordingly, stochastic modeling is applied in many researches since it is suitable for estimating probability distributions of occupant behavior. Most researchers using stochastic modeling are based on Markov chains. More specifically, predicted future occupant behavior in Markov chains depends solely on current occupant behavior [105]. In the past decade, Markov chains has been improved according to different research objectives. For example, Dong and Andrews [106] applied semi-Markov chain models to discover occupancy behavioral pattern for energy and comfort management; Chen, Xu and Soh [107] proposed two novel inhomogeneous Markov chain models for the purpose of modelling regular occupancy; Dong and Lam [105] contributed to correlating occupancy numbers and environmental conditions by developing a Hidden Markov chain model. Broadly speaking, stochastic modeling in most researches have been focused on relatively long-term occupancy prediction or classification while few focused on the numbers of occupancy and detailed occupant behavior (e.g. behavior to open/close air-conditioning, window, door or blind). It can be found that stochastic modeling is more susceptible to time step therefore it is very important for researchers to set an appropriate time step, not too long or too short. The comparison of ABM and stochastic modeling is presented in Table 4.

5.2.4. Technology and method for building mechanical system controlling

T&M for energy system controlling aims at reducing building energy consumption without sacrificing the occupants' comfort

Table 4
Comparison of ABM and stochastic modeling [20].

	Agent-based modeling	Stochastic modeling
Building type (s) that is more suitable	Both residential and commercial buildings	More on commercial buildings
Suitable for real-time modeling	Yes	Yes
Ability to integrate with energy simulation program	High	Medium
Strengths	Suitable for sophisticated pattern of interaction and uncertainty	Suitable for occupancy prediction and classification
Shortcomings	Difficult to be verified; lack of actual data for support	Susceptible to time step

satisfaction, which can be divided into three groups: intelligent HVAC system, artificial lighting and occupancy-based control system [19]. In the research of Colmenar-Santos, de Lober, Borge-Diez and Castro-Gil [108], it was concluded that up to 30% building energy can be saved with the assistance of system technique optimization. Broadly speaking, T&M for energy system controlling relies heavily on algorithms and monitoring facilities. On one hand, it is difficult for the existing monitoring facilities to collect complete information, however, the algorithm relies entirely on the collected information to control the energy system. This will inevitably affect the operating results of energy system; on the other hand, as mentioned before, the indoor and outdoor environment are full of uncertainty, it is impossible for an algorithm to consider all kinds of situations [11].

5.3. "Soft" measures

5.3.1. Policy

Many policies aiming to improve the industry process and building performance are proposed in recent years, such as Display Energy Certificate (DEC), Energy Performance Certifications (EPCs), Soft Landings and other building regulations. DEC focuses on public buildings in the UK over 250 m^2, which is based on actual energy consumption and use a scale that runs from "A" (the most efficient) to "G" (the least efficient). With the help of DEC, the transparency about the energy performance of public buildings could be increased. However, it does not include environmental performance, which is closely related to energy consumption [15]. EPCs were first introduced in England and Wales for domestic buildings. Currently, it can be divided into domestic EPCs and non-domestic EPCs. The process of EPCs is entirely non-invasive and mainly based on predicted performance. Thus, EPCs' quality is always questioned. Soft landings, developed in the UK, aims to keep designers and contractors involved in the operation stage to address the performance gap. However, it has some drawbacks. It is overly dependent on individual expert consultant [15]; furthermore, stakeholders are reluctant to cooperate since there is no direct interest. As pointed out by Way and Bordass [109], for example, "most designers and contractors have traditionally shown little interest in learning from how their buildings actually perform in use; and most owners have certainly not wanted to pay them to do so". The detailed information about policies is shown in Table 5.

5.3.2. Rating systems, benchmarking and standards

There are many rating systems, benchmarking and standards developed to improve building energy performance, including National Australia Building Environment Rating Standard (NA BERS), US Energy Star, UK's Building Research Establishment Environment Assessment Method (BREEAM), US's Leadership in Energy and Environmental Design (LEED), Australia's Green Star, European Union Passive House (detailed information about them can be seen in [15]). Most of these initiatives can be used to closing BEPG in different stages of building life-cycle. As shown in Table 5, the detailed information about different initiatives is presented in different stages. It can be found that these initiatives largely rely on predicted building comfort and energy performance, which may be far from the actual [15]. The deeper underlying reason for this phenomenon is related to the lack of information. On one hand, the accountability for actual building performance has not yet been established and thus there is not enough information for initiatives to become more reasonable. On the other hand, there are significant disconnects between different buildings, which makes it difficult to transfer information and knowledge from building to building. The detailed information about rating system, benchmarking and standard is shown in Table 6.

5.3.3. Collaboration and communication

A number of researches have pointed out the importance of collaboration and communication among different energy related stakeholders [43,46,47,110]. However, this is not easy since different stakeholders may have different objectives, experience, and knowledge. There are three main obstacles to communication and collaboration, namely knowledge, technology and implementation. At the knowledge level, due to the lack of life cycle thinking and integrated delivery methods, energy related stakeholders rarely communicate, let alone collaborate. Regarding technology, researchers tried to applied BIM, AR and cloud platform to facilitate communication and collaboration. However, these technologies are still in their embryonic stage. For implementation, collaboration and communication are difficult to directly link with the interest of stakeholders and thus, stakeholders would not take the initiative to communicate and collaborate. To date, the collaboration and communication system is imperfect, both in terms of technology and management. More efforts need to be done in this area.

5.4. Limitations of current strategies

Various strategies have been developed to cope with the identified root causes. In this paper, three categories of strategies were identified, namely design concept, technologies & methods, and "soft" measures. Table 7 presents the strategies, corresponding causes to be coped with, and limitations of strategies. There are two ways to identify the limitations. Firstly, the limitations of strategies listed in previous studies were collected and collated. Secondly, the characteristics of the causes and corresponding strategies were thoroughly analyzed to find the reason why the effect of the strategies is not good.

6. Future research needs

Based on the comprehensive and systematic literature review, the main issues needing further research for closing the BEPG include:

1. *Building energy performance life cycle thinking*. From Fig. 4, there were 52.9% and 66.1% researches concentrating on design and operation stages respectively. Only 7.9% researches were related to the construction stage. This shows that the thinking of BEPG research should be extended to the whole

Table 5
Relevant building energy performance policies.

Stage	UK Display Energy Certificate (DEC) (public buildings in England, Wales and N. Ireland)	UK building regulation compliance	Soft Landings	Energy Performance of Buildings Directive	Energy Performance Certificates (EPC)	Energy Policy and Conservation Act (EPCA)
Reporting of actual performance (energy and user)	Yes, mandatory public reporting (energy)	No (Energy Performance Certificates are based on predicted performance only)	Yes, voluntary reporting encouraged, Usable Buildings Trust (UBT), CarbonBuzz (energy, user)	Yes, voluntary reporting encouraged	No (Energy Performance Certificates are based on predicted performance only)	Yes, voluntary reporting encouraged
Concept design		Based on predicted performance, accredited component performance data	Expert reviews, participative process	Based on predicted performance, accredited component performance data	Based on predicted performance, accredited component performance data	Based on predicted performance, accredited component performance data
Detailed design		Based on compliance with regulatory minimums	Expert reviews, participative process	Based on compliance with regulatory minimums	Based on compliance with regulatory minimums	Based on compliance with regulatory minimums
Implementation		Some guidance documents referenced	Expert reviews, participative process	Some guidance documents referenced	Some guidance documents referenced	Some guidance documents referenced
Validation		Building control process	Expert reviews, participative process	Expert reviews, participative process	Building control process	Expert reviews, participative process
Operation	Energy evaluations against benchmarks	Guidance on user manuals	Expert reviews, participative proves, energy and user evaluations against targets. 3-year handover	Expert reviews	Guidance on user manuals	Expert reviews

Table 6
Building energy performance system, benchmarking and standard.

Stage	US Energy Star, Green Star Performance	Green building rating schemes (Building Research Establishment's Environmental Assessment Method (BREEAM), LEED and Green Star)	EU Passive House	National Australian Building Environmental Rating Standards (NABERS)
Reporting of actual performance (energy and user)	Voluntary public reporting of Energy Star performance (top 25% for energy)	LEED; anonymised data shared in benchmarking reports BREEAM: voluntary, for example, CarbonBuzz (energy, user)	No (certification based on predicted energy + airtightness test)	Public actual performance reporting, league tables (energy) voluntary (indoor environment)
Concept design		Based on predicted performance only	Based on predicted performance, certified components	Access to public performance data, expert reviews, and participative process
Detailed design		Based on compliance with regulatory minimums	Based on compliance with design guidance	Expert reviews, participative process protocol for design based on feedback
Implementation		Some guidance documents referenced	Some guidance documents referenced. Certified designer	Expert reviews, participative process
Validation		Seasonal commissioning and sub-metering credits	Independent certification process (by design + at test)	Expert reviews, participative process
Operation	Energy evaluations against benchmarks	BREEAM: optional credit for 3-year energy and user data to Building Research Establishment (BRE). LEED: Compulsory 5-year energy data to U.S. Green Building Council (USGBC)	Guidance on user manuals	Expert reviews, participative process, energy and user evaluations against benchmarks

building life-cycle since each stage will result in BEPG, either directly or indirectly. As afore-discussed, causes of BEPG could exist in different stages and they are interconnected. Nevertheless, little attention is paid to the interaction among these causes, which is largely due to the lack of life cycle thinking. Life cycle thinking is not only the basis for analyzing the formation mechanism of BEPG but also the premise of ensuring information integrity. Some researchers and practitioners have recognized the importance of life cycle thinking and conducted work by applying some approaches such as pre-occupancy evaluation [10], post-occupancy evaluation [29], BIM [35,71] and soft landings [15]. While acknowledging these contributions, further research following similar way is still needed for proposing systematic approach covering the entire building life-cycle.

2. *Energy performance information integrity*. It is well acknowledged that there is a large amount of energy performance information generated, transferred and applied during building life-cycle. Previous research has revealed many situations in which information integrity is harmed when (1) information is not completely collected [10,11,13]; (2) information is not transferred between different stages or different stakeholders [118–120]; and (3) information is incorrectly used [10]. Currently, the main problems related to building energy performance information integrity are (1) there is no enough information for design, construction and operation [21,111–113]; (2) there exist obstacles in information transfer between different stages or different stakeholders [10,121]; (3) there is a discrepancy between different stakeholders' understanding of the same information [49,61]; and (4) in-

Table 7
Strategies, corresponding causes to be coped with, and limitations of the strategies.

Strategies	Causes to be coped with	Limitations
Passive design	S5C27, S5C28	1. Designers do not have enough information for passive design [21,111–113]; 2. Building quality may not be in line with design specifications [11]; 3. Occupants do not know how to operate building system effectively in passive building [21,78]. 4. Some occupants in the passive building are not satisfied with the indoor climate [21].
Active design	S5C27, S5C28, S5C29, S5C30, S6C30	1. It is difficult for designer to consider all possible situations; 2. Designers overestimate automation system's performance [11].
Human-in-the-loop	S1C1, S1C2, S1C3, S2C3, S1C6, S1C7, S1C10, S1C11, S1C12, S4C12, S5C12, S1C15, S5C23, S5C27, S5C28, S5C30, S6C30	1. It is difficult to collect complete human information [20]; 2. There are differences between different occupants and they may influence each other [114]; 3. The data related to human has uncertainty [10,20].
T&M for estimating energy consumption	S1C1, S1C2, S1C5, S1C10, S6C31	1. No model can accurately predict energy consumption [115]; 2. It is difficult to collect complete information for estimating energy consumption.
T&M for energy-related data collection and analysis	S1C1, S1C2, S1C3, S2C3, S1C4, S3C4, S1C6, S1C10, S6C33	1. There are obstacles to the integration of different kinds of information [116]; 2. It is hard to link the result of data analysis to energy simulation program [20,49]; 3. Few data are collected from the design and construction stage.
T&M for occupant behavior modeling and simulation	S1C1, S1C2, S1C3, S2C3, S1C5, S1C6, S1C10, S5C27, S5C28	1. There are obstacles to using actual data in modeling and simulation [20]; 2. Modeling and simulation are difficult to verify [76]; 3. The formation mechanism of occupant behavior and the relationship between influencing factor and occupant behavior are not clear, which limits the application of T&M for occupant behavior modeling and simulation [20,117].
T&M for energy system controlling	S5C27, S5C28, S5C29	1. It is impossible for an automation system to consider all kinds of situations; 2. Automation systems rely entirely on the collected information to control the energy system, but it is difficult for the existing monitoring facilities to collect complete information [20].
Policy, rating systems, benchmarking and standards	S1C2, S1C3, S1C4, S3C4, S1C5, S1C6, S1C7, S1C9, S1C11, S1C12, S3C12, S4C12 S1C1, S1C2, S1C3, S1C4, S1C6, S1C7, S1C11, S1C12, S2C12, S3C12, S4C12, S5C12, S6C12, S3C14, S1C15, S3C15, S4C15, S5C15, S6C15	1. The accountability for actual building performance has not yet been established [15]; 2. It is difficult to transfer information and knowledge from building to building.
Collaboration and communication	S1C1, S1C2, S1C3, S1C4, S1C6, S1C7, S1C11, S1C12, S2C12, S3C12, S4C12, S5C12, S6C12, S3C14, S1C15, S3C15, S4C15, S5C15, S6C15	1. Different energy related stakeholder may have different attributions [117]; 2. The collaboration and communication system is imperfect, both in terms of technology and management.

formation is unidirectional, lacking the consideration of interactivity [10]. Further research should be carried out to develop ways to ensure information integrity, for instance, establishing a sound information collection system, exploring the perfect mechanism of information transmission, and developing a framework for different stakeholders to gain a consistent understanding and utilization of the same information.

3. *Big data collection and analytical method*. Currently, it is difficult to achieve information interoperability between different buildings since no two buildings have the exact same characteristic and occupants. As mentioned in previous section, the two main methods for data collection (pre-occupancy data collection and post-occupancy data collection) have limitations. It is expected that, if the information and knowledge of one specific building can be used in another, pre-occupancy data collection and post-occupancy data collection could be the organic combination, and their limitations could be overcome. Besides, energy management efficiency in building life-cycle could be greatly improved since more useful data is available. It is therefore important to explore the commonality between buildings and improve the reusability of information. Nowadays, with the development of computer and data science, big data has come into view, which concentrates on advanced data collection and analytics methods that extract value from huge data sets. By analyzing building characteristic data, energy performance data and building life-cycle empirical data, big data analysis could help researchers to discover common features of different buildings. It is believed that, with the assistance of big data, improving the reusability of information in different buildings can be an important area of BEPG research.
4. *Stakeholders' attribution, decision criteria and behavior*. Existing researches indicated that stakeholders' attribution is a critical factor that could have an impact on behavior [21,44,45]. Besides, stakeholders' attribution also plays a critical role in the interaction between stakeholders. For example, occupants with different temperature preferences may have interaction in setting the indoor temperature. A systematic and comprehensive understanding of stakeholders' attribution is conducive to clarifying the interaction between stakeholders. However, stakeholders' attribution contains numerous factors that have extremely complex relationships with decision-making [122]. Although research attempts, such as Guerra-Santin [123], Hong, D'Oca, Turner and Taylor-Lange [122] and Zeiler, Vissers, Maaijen and Boxem [34], have been devoted to stakeholders' attribution, systematic results are currently absent. Stakeholders' decision and behavior are the driving force of interaction between stakeholders. Although stakeholders' behavior, especially occupant behavior, has been investigated in recent years, there is no remarkable improvement in clarifying the mechanism of behavior formation. Few researches had been carried out to clarify stakeholders' decision criteria. It should be noted that the process of decision-making is complex, which cannot be seen as a mode of "if-then". As stated by Jia, Srinivasan and Raheem [20], most driving factors of behavior is influential but not determinate. Furthermore, stakeholders with different attributions may have different decision criterions and behaviors. Therefore, more efforts should

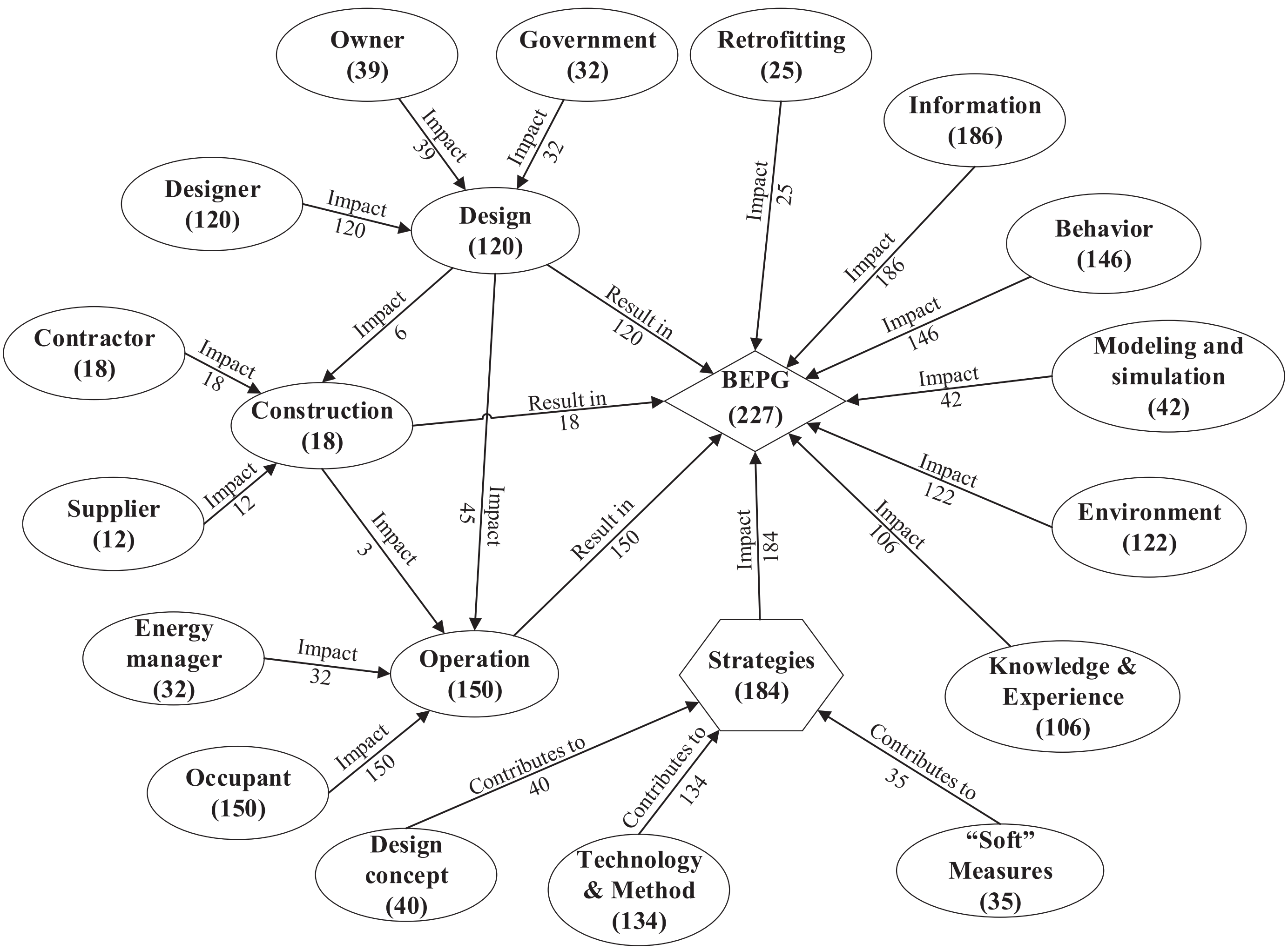

Fig. 3. A tentative framework developed using NVivo®.

be dedicated to investigating stakeholders' decision criteria and behavior.

5. *Stakeholders' interaction mechanism*. There are two ways of interaction between stakeholders. One way is that energy related stakeholders interact with each other by influencing the environment. For example, in an open plan office, one occupant affects another occupant's comfort by changing the indoor temperature. The other way is that stakeholders directly affect each other through behavior, such as communication. Current researches on investigating stakeholders' interaction are limited to the interaction between occupants rather than different stakeholders across the building life-cycle. Furthermore, the positive interaction among stakeholders could be conducive to improving energy efficiency, while the negative interaction and influence may widen BEPG. For instance, peer network could have an impact on either economical or wasteful individual energy consumption behavior [124]. Thus, it is important to develop strategy leading stakeholders to positively interact with each other. Some researchers start to recognize the important role of positive interaction. For instance, Chen, Taylor and Wei [124] explored the relationship between peer networks occupant's energy consumption behaviors; Niu, Pan and Zhao [10] applied virtual reality to enhance the positive interaction between designer and occupants for more reasonable design. These works provided the basis for the establishment of framework for positive interaction. More efforts should be made following the similar path.
6. *Modeling and simulation validation*. Design and operation largely depend on the modeling and simulation results, and thus unreasonable modeling and simulation can easily lead to BEPG [65]. Research on modeling and simulation has always been the focus. Although many new models were developed, none could ensure that the simulation results are in line with the actual situation [115]. The reason is mainly from two aspects, namely "lack of enough data" and "limitations of models". Data is a significant factor to ensure the validity of modeling and simulation. However, most models are based on assumption since there was no sufficient data. Accordingly, future research needs to develop ways to collect data for modeling and simulation, which is also in line with the objective of information integrity. Regarding the limitations of models, the model itself is based on idealization. That is, models are just abstractions of reality. The gap between the model and the reality can only be narrowed and not eliminated. For future research, more efforts should be done to explore the gap between model and reality. What is more important, the compatibility of existing models is poor. For example, it is still difficult to integrate simulated behavior into energy modeling software [20]. In this regard, future research should also be launched to improve the interaction ability between different models.

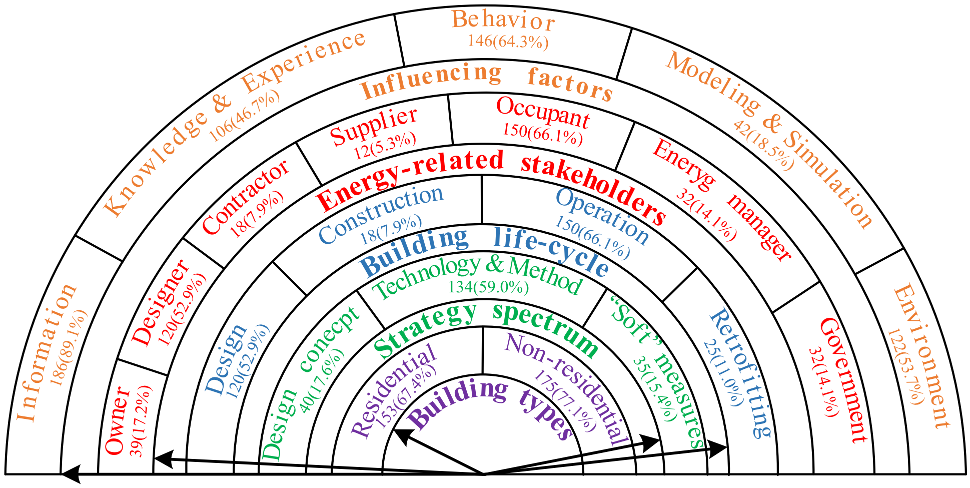

Fig. 4. A BEPG research framework.

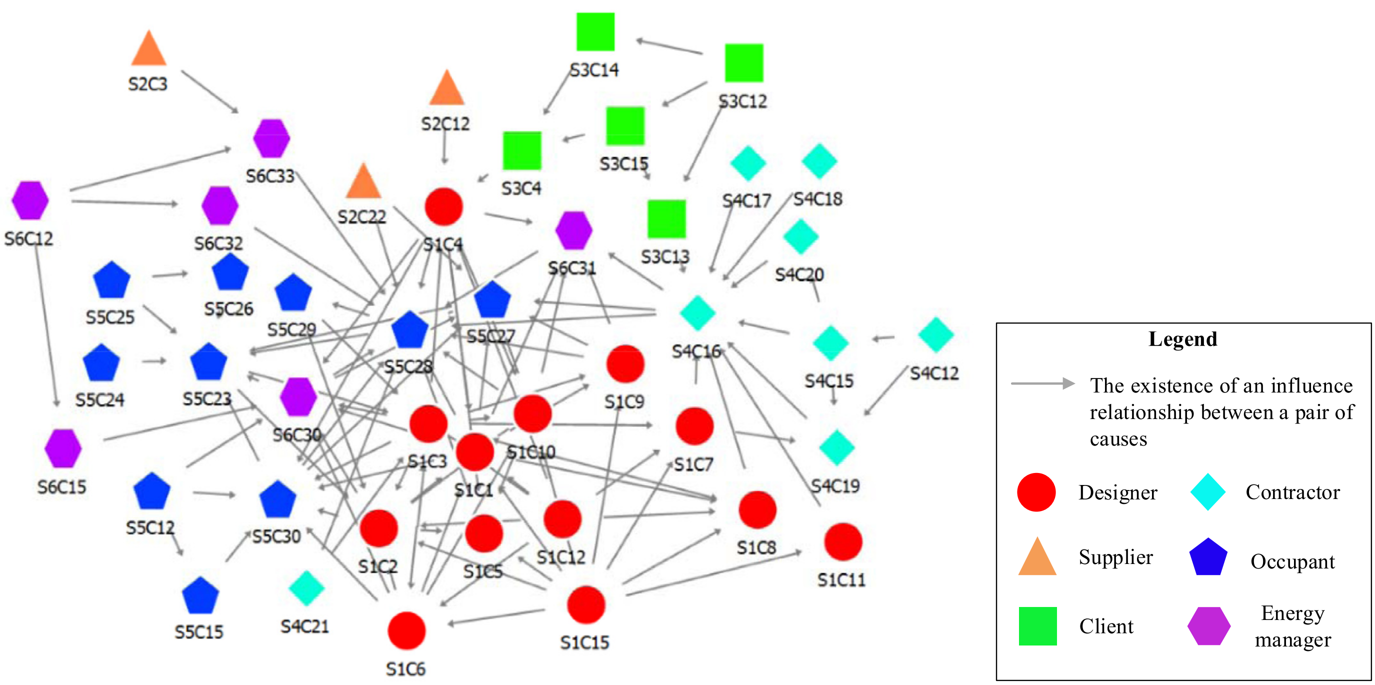

Fig. 5. Stakeholder-associated BEPG cause network.

7. *Multidisciplinary approach*. BEPG research is related to multiple disciplines, including sociology, economics, psychology, physiology and engineering [50,56]. Furthermore, a trend of interdisciplinary research has emerged in this field. Taking occupant behavior for example, it can be affected by comfort (physiology and psychology), culture (sociology) and economy (economics), and it could have an impact on energy consumption (engineering) [125]. Therefore, the strategies for BEPG requires a multidisciplinary effort. As shown in Fig. 3, it is noticed that strategies in previous studies mainly focused on technologies (59.0%) while scant attention was paid to design concept (17.6%) and "soft" measures (15.4%). However, this does not mean that advanced technology is the best coping strategy for closing BEPG. As pointed out by Jia, Srinivasan and Raheem [20] and Masoso and Grobler [114], for example, educating occupants to change their behavior has more benefits for improving building energy efficiency as compared to application of advanced technologies. As discussed in Section 6, any strategy has its strengths and limitations. It is impossible to close BEPG only by a single strategy. How to integrate existing strategies, however, is still an unsolved problem. Therefore, a multidisciplinary approach for strategies integration is an important research direction. It is suggested that future research should be problem-oriented rather than method-oriented. Furthermore, in-depth analysis of the relationship between different disciplines related to research problem should be conducted.
8. *Building system flexibility*. Building systems (e.g., mechanical system and electric system) can be reasonably expected to achieve expected target only if all conditions have been considered. However, it is hard to take into account all possible situations since buildings are not a machine but a complex and dynamic system that includes unpredictable elements such as climate conditions and human behaviors. To make building energy more controllable and predictable, designers often apply fixed system (e.g. fixed windows) instead of

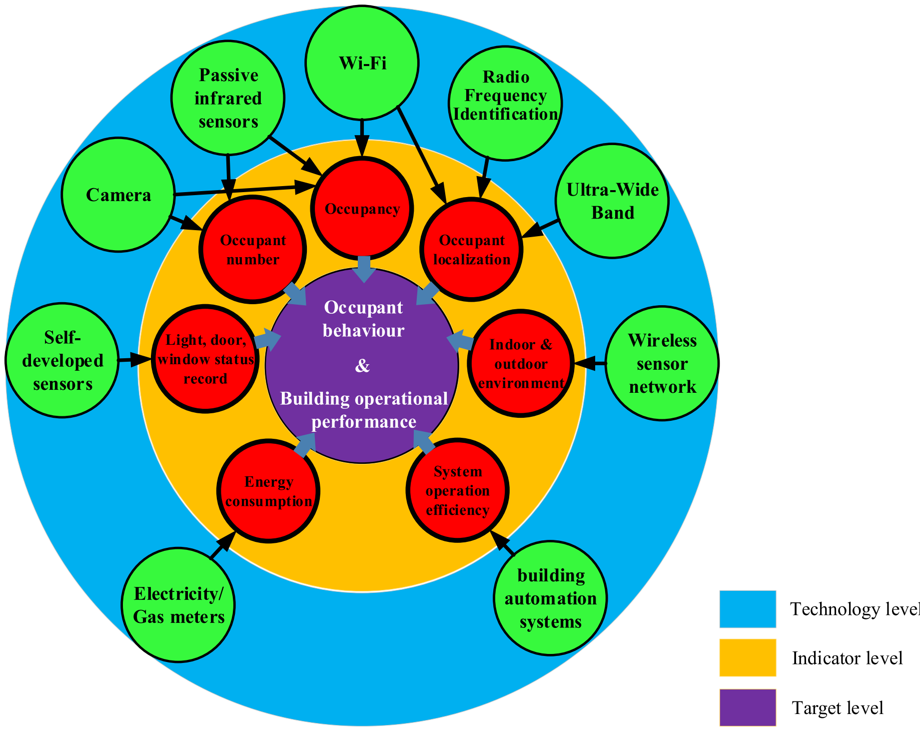

Fig. 6. Technology and method for energy-related data collection, a modified version based on [20].

operable ones. In reality, buildings always go through unpredictable scenarios, such as heatwaves and a failure of the mechanical system itself, that fixed system is difficult to deal with. Building system should be of great flexibility and so, buildings could continually make adjustments for maintaining high energy efficiency according to the changes of the environment. Therefore, future research on improving the flexibility of building system is recommended.

7. Conclusion

Building energy performance gap (BEPG), as a critical factor that hinders the realization of the goal for energy conservation, has been a worldwide concerned issue attracting increasing attention. The aim of this study is to review the researches that were conducted in the past decade to study the causes of BEPG and corresponding strategies, and to propose recommendations for future research. This study first developed a framework for mapping the BEPG researches through reviewing 227 related publications with the assistance of the Qualitative Social Research (QSR) software package NVivo®. The framework consists of five dimensions, including building types, strategies, building life-cycle, energy-related stakeholders and influencing factors, which provides researchers a "panorama" of BEPG research in an effective way. Based on the framework, a content analysis of 227 related publications was conducted and the major conclusions are as follows: (1) occupant behavior in operation stage attracted most attention from researchers; (2) technology and method are the main strategy for bridging BEPG; and (3) information and energy related stakeholders play an important role in BEPG.

An in-depth analysis of BEPG research is further conducted to define BEPG and explore its causes and corresponding strategies. The causes of BEPG are identified according to different building life-cycle stages and energy related stakeholders. It is concluded that the causes of BEPG are not independent, but have complex interactions with each other. The state-of-the-art strategies for closing BEPG were also studied including their characteristics, strengths and limitations. By analyzing the BEPG causes and strategies, it is concluded that future research should focus more on (1) life-cycle thinking of BEPG; (2) energy performance information integrity; (3) big data analytical method; (4) stakeholders' attributions, decision criteria and behavior; (5) stakeholders' interaction; (6) modelling and simulation validation; (7) multidisciplinary approach; and (8) building system flexibility.

It is expected that this paper would be valuable to both researchers and practitioners. It helps researchers to understand the current research status and research needs, so that more focused and effective researches could be carried out. Practitioners will benefit from having a systematic and comprehensive understanding of the causes of BEPG and corresponding strategies, thus selecting proper strategies in their practices.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.enbuild.2018.08.040.

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