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Building Energy Performance Gap: A Bibliometric Analysis and Systematic Review of Global Research Themes

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Abstract

Building energy simulations are useful for analyzing decisions impacting energy performance. However, significant discrepancies exist between simulated building energy performance and real-world measured performance, thus inhibiting progress towards sustainability. This paper examines recent Building Energy Performance Gaps (BEPG) research trends using bibliometric measures. It also aims to assess global research trends by examining global research engagement and thematic development to build a more comprehensive understanding of BEPG. The systematic review of the Web of Science (WoS) database identified 331 relevant articles published between 2012 and July 2023. A quantitative approach of bibliometric procedures (including title, abstract and keywords) was used for analyzing the documents, alongside the VOSviewer software program. This methodology enabled the authors to produce scientometric maps, showcasing the relationships in authorship, citation, occurrences, and bibliometric coupling. The results indicate that BEPG research is primarily conducted in more developed regions such as Europe and North America, while severely lacking in many developing countries within the Global South (GS). Results further indicate a broadening research scope, with less than ten percent of the 1,118 keywords used by authors three times or more. Solutions towards resolving BEPG need to be highly contextualized. Therefore, this study identifies major BEPG research areas and highlights the multidisciplinary nature of the field. Additionally, fostering international collaborations and developing building energy performance standards could aid in creating a more sustainable built environment and developing capacities, focusing critically on the needs of GS countries.

Keywords: Building Energy Performance Gaps; Bibliometric Analysis; VOSviewer; Building Energy Simulation; Simulation Optimization.

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1 INTRODUCTION:

Despite the extensive literature on various building energy efficiency themes, three decades of global historic sectorial energy data show annual electricity consumption between 1990 (9,701 TWh) and 2021 (24,155 TWh) increased by nearly 149 percent and that buildings remain major contributors to increased energy use and CO2 emissions (International Energy Agency (IEA) 2022a). Furthermore, the IEA tracking report for 2022 indicates that it is unlikely for the global building sector's energy consumption and emissions to meet the 2050 Net Zero efficiency targets (IEA 2022b). One possible reason for the limited improvement is performance discrepancies, also known as Building Energy Performance Gaps (BEPG). This challenge requires urgent attention from both climate change stakeholders and built environment professionals, in an attempt to develop more energy-efficient buildings and standards.

Built environment professionals use Building Energy Modelling (BEM) principles and processes to prepare Building Performance Models (BPM) and analyze decisions impacting energy performance (Rysanek and Choudhary 2013). The potential to optimize operational energy use in buildings at predefined building conditions provides opportunities to further limit energy consumption levels, thereby fostering a more sustainable built environment globally (Coakley et al. 2014, Hemsath, and Bandhosseini 2018). However, BEPGs imply that the expected progress towards reducing energy-related emissions and fostering sustainability in the built environment does not fully materialize in the real world.

BEPG and related discrepancies have been documented in several studies over the years, demonstrating it as a persisting challenge for energy modellers (van Dronkelaar et al. 2016; Jradi et al. 2018). A study by Zou et al. (2018) provides extensive reviews of the causes of discrepancies associated with the different phases of a building's life cycle.

Category	Causes of BEPG	Reference
Process	• Design complexity. • Variations and errors in design. • Inaccurate modelling assumptions. • Uncertainties such as occupant behavior. • Microclimatic differences and the reliability of weather files. • Oversimplification of building energy models.	(Yan et al. 2015; Alencastro et al. 2018; Eon et al. 2020; Shi et al. 2019)
Product	• Faulty installation of equipment. • Faulty construction practices and inefficiencies. • Inaccurate specification of components and equipment. • Inadequate maintenance of lighting, metering, heating, ventilation, and air-conditioning (HVAC) systems.	(Turner and Frankel, 2008; Jradi et al., 2018; Zou et al. 2018)
Policy	• Limited enforcement of building energy efficiency codes leading to a "policy gap." • Lack of performance verification post-occupancy of the building. • Inappropriate interpretation and application of building energy regulations, focusing on compliance modelling.	(Burman et al. 2014; Cozza et al. 2021; de Wilde, 2014; López-González et al. 2016)
People	• Limited expertise of the modeller. • Limited sustainable design knowledge. • Lack of effective collaboration among project consultants. • Stakeholders often do not prioritise optimising real-world performance; decisions are mostly economically centred. • Absence of a facility manager for effective coordination, especially in large-footprint buildings.	(Alencastro et al. 2018; Gram-Hanssen et al. 2018; Imam et al. 2017; Zou et al. 2018)

Table 1. Summary of factors and classifications influencing BEPG

Table 1 presents a synthesized overview of the various causes of BEPG, as discussed by the different authors. Studies typically use the stages of the building lifecycle (i.e., design, construction, and operational phases) to classify and examine the causes of BEPG (Jradi et al. 2018, Zheng et al. 2024, de Wilde, 2014, Mahdavi et al. 2021, Igugu et al. 2024). Additionally, the causes of BEPG can be grouped and understood in four spheres of factors, namely:

Process: Refers to the simulation procedures, the performance targets, the software parameters, and data which need to be specified.

Product: Refers to the services, equipment, and building envelope.

Policy: Refers to mandatory protocols and industry standards regulating building energy simulation practices.

People: Refers to stakeholders involved in the building delivery, including the client, project consultants, and building occupants.

In essence, the presence of BEPG implies that buildings often fail to meet their energy performance targets, resulting in minimal practical progress towards achieving sustainability. Over the span of thirty years, from 1990 to 2020, global historical sectoral energy consumption data provided by the IEA (2022b) supports this claim, highlighting that buildings account for about forty-eight percent of electricity consumption. Thus, the sector remains a significant contributor to increasing energy use and emissions. Considering the urgent need for energy-efficient buildings within the context of limiting global greenhouse gas (GHG) emissions and ensuring sustainability, especially in the built environment, it is essential to develop a more holistic understanding of the concept of BEPG.

Table 2 describes previous meta-analyses and reviews of BEPG. It outlines the central question that the researchers investigated, the number of articles included in the review, and provides a brief summary of the key findings. Notably, most of these reviews largely explored specific aspects of BEPG research or tools to alleviate performance gaps. Explored areas include BIM-based methods (Muta et al. 2025), AI-integration for system optimization (Ali et al. 2024), trends in low-energy buildings (Bai et al. 2024), and building automation systems (BAS) (Qiang et al. 2023). Other studies focused on specific building categories such as school buildings (Franceschini and Neves 2022), and residential buildings (Cozza et al. 2021). In addition, Mahdavi et al. (2021) examined the impact of building occupants on performance gaps, while Alencastro et al. (2018) also reviewed the impact of building construction quality defects.

Despite existing meta-analyses of BEPG research, a holistic view of the research landscape and activity is lacking. To address this gap, this paper aims to (1) examine recent BEPG research trends using bibliometric measurements and (2) identify the thematic landscape of performance gap research, with its multifaceted and transdisciplinary nature. The findings may facilitate new thematic explorations and cross-contextual collaborations.

The paper is organized as follows: Section 2 outlines the methodology, Section 3 presents the results and discusses bibliometric trends in publication, authorship, and thematic interests, and Section 4 considers the implications of the findings and concludes the study by outlining potential areas for future research.

2. METHODOLOGY

The methodology for this study uses a systematic decision-making approach in selecting journal sources, mined data analysis tools and data presentation. The study uses the Preferred Reporting Items for Systematic Reviews and Meta-Analyzed (PRISMA) approach to identify published research based on keywords and thereby screening sources for inclusion and further evaluation (Page et al. 2021).

To accomplish this, the study employs bibliometric processes to analyze BEPG-related papers retrieved

	Article title	Year	Central Question	# of studies	Summary of Key Findings	Times Cited	Reference
1	Enhancing energy performance assessment and labeling in buildings: A review of BIM-based approaches	2025	How effective is building information modeling (BIM) for reducing performance gaps and enhancing the accuracy and reliability of energy labeling?	106	BIM can improve the quality of the models through technologies such as digital twins and the process of energy labeling or compliance. It can also improve the data integration and management processes. However, the need for more accurate data, standards and tools exists.	1	(Muta et al. 2025)

2	AI-Driven Innovations in Building Energy Management Systems: A Review of Potential Applications and Energy Savings	2024	What is the impact of AI-based models for reducing performance gaps via optimizing the actual energy consumed by various building systems across building categories?	148	The impact of AI models integrating with building energy systems is potentially the most effective in office buildings when compared with educational or residential structures.	12	(Ali et al. 2024)
3	Systematic examination of energy performance gap in low-energy buildings	2024	What insights can be derived about the complexities of performance gaps in low-energy buildings using a dialectical system framework and a lifecycle human-technology-organization model?	76	Low-energy buildings can consume less energy than predicted but over 80% consume considerably more. On average, refurbished and new low-energy buildings consume 58-62% more energy. In addition, there is an identified need for studies to investigate the organizational and systemic issues that contribute to performance gaps.	7	(Bai et al. 2024)
4	Review of the building energy performance gap from simulation and building lifecycle perspectives: Magnitude, causes, and solutions	2024	What are the main causes, drivers, and solutions to mitigate the growing magnitude of energy performance gaps across different building types?	223	The magnitude of the energy performance gap varies significantly across building types, reaching up to 400 percent in educational buildings. It largely originates from building envelope, system, occupant behavior, and weather data uncertainties. To mitigate the occurrence of performance gap, a mix of technical and soft strategies are required.	13	(Zheng et al. 2024)
5	Building automation systems for energy and comfort management in green buildings: A critical review and future directions	2023	How are building automation systems (BAS) integrated across the lifecycle of green buildings to facilitate user comfort and reduce performance gap?	143	Integrating BAS and green buildings can be structured into five key methods with a focus on prediction, control, and trade-offs. Among other issues, data privacy and security concerns, and uncertainties are significant barriers.	47	(Qiang et al. 2023)
6	A critical review on occupant behavior modelling for building performance simulation of naturally ventilated school buildings and potential changes due to the COVID-19 pandemic	2022	What are the focus areas of occupant behavior modelling studies and the drivers of behavioral dynamics in naturally ventilated education buildings?	278	There are three steps needed to model occupant behavior effectively, but not all education building-based studies adopt the systematic framework. There is also an identified need to study the impact of the behavioral patterns among teachers and groups in classrooms as main drivers.	42	(Franceschini and Neves, 2022)
7	In search of optimal consumption: A review of causes and solutions to the Energy Performance Gap in residential buildings	2021	What strategies have researchers investigated to mitigate performance gaps in the analysis of space heating loads for residences?	160	Uncertainties around building envelope characteristics and occupant behavior are drivers of performance gaps. To mitigate the discrepancies, some researchers either seek to adopt more accurate assumptions and parameters for the simulations, while others aim to enhance the building's measured performance via more effective monitoring, building maintenance, and operational practices.	79	(Cozza et al. 2021)

Table 2. Previous review studies on the energy performance gap in buildings

from the Web of Science (WoS) database, up until 4 July 2023. Following the systematic review, the analysis and visualizations are prepared using VOSviewer software, and finally key conclusions and recommendations for future research are discussed.

2.1 DATA SOURCE, IDENTIFICATION, AND MINING STRATEGY

The WoS database, provided by Clarivate Analytics, was utilised to collect data, due to its extensive collection of scholarly articles, conference proceedings, and other research outputs from various disciplines, such as sciences, humanities, engineering, and arts. The WoS is widely used and acknowledged by academics, researchers, and institutions globally. Therefore, the researchers leveraged the comprehensive WoS database to extract a variety of materials for further analysis using the VOSviewer software tool. To establish prioritising criteria and define the scope of the search results, the WoS was limited to the "Topic" field. This systematic approach included searching within document titles, abstracts, and keywords, ensuring a focused and relevant dataset for analysis.

A major hurdle with conducting the search and retrieving papers was the variety of phrases that can be used to describe the Building Energy Performance Gap (BEPG). These variations include terms such as building performance gap (Jradi et al. 2020), energy performance gap in buildings (Jain et al. 2020), and discrepancy between predicted and measured energy consumption (van Dronkelaar et al. 2019), among many others. Such variations can lead to the omission of relevant documents or the inclusion of irrelevant ones (Zou et al. 2018). To address this challenge, the study conducted multiple searches, each emphasizing different parts of the entire search phrase using quotation marks (""). For example, searching the database with the keywords "building performance gap", returned only twenty-one documents. However, expanding the search to encompass various individual terms of the phrase BEPG or collectively, yielded up to 9,914 initial documents. The central theme remained BEPG, and Table 3 presents the results from these different WoS search queries.

2.2 DATA SCREENING AND INCLUSION

Data screening and inclusion in a systematic review are critical to determine variables for elimination that could affect the interpretation of results.

The initial search results varied from twenty-one documents to 9,914 documents. The search queries were scrutinized to refine and exclude sources not directly related to the specific subject area. Using the advanced search option in WoS, relevant query numbers (#) were combined via the OR function to produce a

Query No.	Search phrase	Search phrase	Used
#1	building energy "performance gap*"	434	X
#2	"building energy performance"	1,560	
#3	search within #2 "gap*"	164	X
#4	"building energy" AND "performance gap*"	169	X
#5	"energy performance gap*"	143	
#6	search within #5 "building*"	138	X
#7	Building "energy performance"	9,914	
#8	"energy performance" AND "building*"	9,731	
#9	search within #8 "gap*"	829	
#10	search within #8 "performance gap*"	268	X
#11	"Building performance gap*"	21	X
#12	#1 OR #3 OR #4 OR #6 OR #10 OR #11	543	
#13	#12 Refined by: Document Types: Articles	413	

Table 3. The outcome of search queries on BEPG research records in WoS

unified result. Specifically, Query No. #12, as shown in Table 3, combined Queries #1, #3, #4, #6, #10, and #11, resulting in a total of 543 documents. The results were then further restricted to include only journal articles published in English, yielding a final total of 413 documents.

The resulting 413 documents were further screened by reading titles, abstracts, keywords, and intermittently the full text of articles to ascertain the relevance to the study. This step was necessary due to the variety of ways researchers describe BEPG. Some of these variations include: predicted vs. measured, theoretical vs. actual (Coyne and Denny 2021), designed vs. as-built (Uriarte et al. 2021), design vs. in-use (Shrubsole et al. 2019), modeled vs in situ measured (Marshall et al. 2017), calculated vs. actual (Cholewa et al. 2020), among others.

Following this screening, the authors identified eighty-two documents as not relevant to the specific subject area and therefore excluded from the search results using their accession numbers, which are unique WoS identifiers assigned to each record.

From the extensive data screening, a final number of 331 documents were identified for the bibliometric analysis. Figure 1 summarizes the data screening and mining process.

The 331 documents, along with their reference and bibliographic content, were successfully exported as comma-separated value (CSV) files. Essential bibliometric details such as author names, affiliations, journal types, and rankings, mostly sourced from the WoS database, were consolidated into a Microsoft Excel file. Finally, the data were imported into the VOSviewer software program to conduct the comprehensive bibliometric analysis. The WoS database was deemed sufficient for t further analysis, as it allows the export of 1,000 to2,000 documents to the VOSviewer at a time.

Lastly, conducting an in-depth systematic review of some of the articles assisted the author in appropriately analyzing the variables and identifying research trends and gaps for further study.

2.3 DATA COLLECTION AND BIBLIOMETRIC ANALYSIS

This study utilised the VOSviewer software programme, version 1.6.19, (developed by the Centre for Science and Technology Studies, Leiden University, The Netherlands) to illustrate the bibliometric and scientometric data, as well as research networks based on the 331 articles retrieved from WoS. A comprehensive description of scientometrics and the VOSviewer is provided by van Eck and Waltman (2010). It is a free software application used to produce graphical content from scientific data analysis by converting qualitative data into graphical maps, enabling pragmatic explorations, and establishing relationships (van Eck and Waltman 2022). The main types of analysis implemented in this study were the co-authorship analysis, used to determine active role players, and the co-occurrence analysis, which identifies

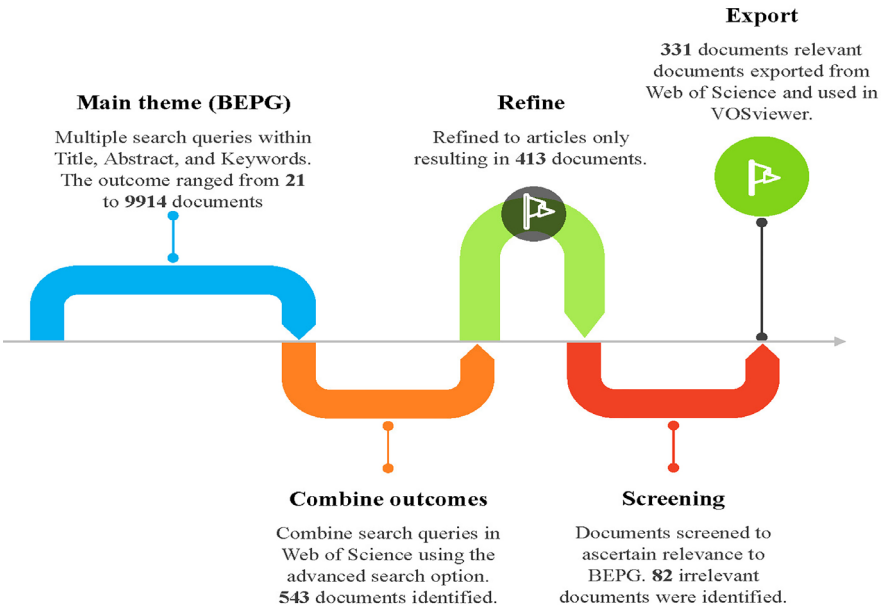


Figure 1: Summary of data mining strategy for publication on BEPG research.

thematic trends. Specifically, co-authorship refers to the publications jointly authored by two researchers, while co-occurrence determines instances where two keywords are jointly mentioned in publications (van Eck and Waltman 2013). The significance of a node (i.e., active role players or keywords) and the strength of its relationship to other nodes or clusters are scaled in VOSviewer by size and distance (van Eck and Waltman 2010), thereby creating a distance-based network map.

The co-authorship analysis included only authors with a minimum of two articles, refining the VOSviewer dataset from 984 to 169 authors. Additionally, the co-authorship analysis of institutions encompassed 387 organizations across fifty-four different countries. These countries span five continents: Europe, North America, Asia, Africa, and Australia.

The co-occurrence analysis included 1,118 author keywords across the entire dataset. The minimum keyword occurrence threshold (not WoS indexed keywords i.e., keywords plus) was set to one, to ensure that all 1,118 author keywords were included in the VOSviewer analysis. However, visualisations were set to include author keywords with a minimum of two occurrences, resulting in 219 keywords. Additionally, the average publication year of keywords was examined using VOSviewer's overlay visualization mode, where keyword colors represent the average publication year of articles mentioning them.

The study includes a periodic analysis using VOSviewer's co-occurrence analysis function, in order to understand the approach to BEPG and its development. Based on the total number of documents, it is evident that BEPG is still a developing research landscape that warrants further investigation.

3. RESULTS AND DISCUSSIONS

This section presents the key findings from the scientometric review, based on the bibliometric analysis obtained from the WoS database and presented graphically using the VOSviewer program. The results showcase the mostprominent journals, affiliations, geographical regions, authors, and cited papers to reveal trending keywords in BEPG research.

3.1 ANNUAL PUBLICATION OUTPUT AND GROWTH TRENDS

Based on publications indexed in the Web of Science (WoS), research in the field of BEPG has grown significantly in recent years. The results of the search—conducted twice using specific queries outlined earlier in Table 3—indicate that WoS-indexed literature on BEPG spans from 2012 to July 2023.

The article by Menezes et al. (2012) was the only publication on BEPG that year. It focused on using information gathered during a post-occupancy assessment of a case study building to improve model fidelity. In the four years from 2012 to 2015, only 20 documents were published. However, in the following seven years (2016–2022), that number grew nearly sixteenfold to 309 documents—an increase of approximately 1,445 percent. This reflects a substantial rise in research interest in BEPG, as shown in Figure 2.

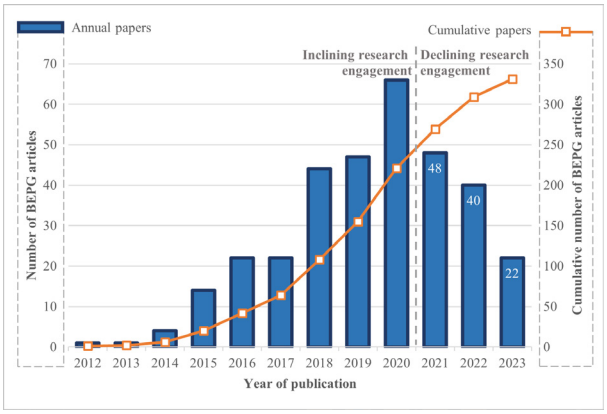


Figure 2. Growth trends in yearly and cumulative publications on BEPG research

From Figure 2, the data also indicate that each year after 2020 has seen fewer BEPG-related papers published than its previous year, with 2023 on-track to barely surpass 2022 (based on the data mining date, only articles published until 4 July 2023 were retrieved). However, Wang et al. (2019) observed a peak-and-decline pattern similar to Figure 2 in the development field and concluded that it presents increased prospects for future research. While the growth trend is significant and desirable, it is important to understand and address the observed variances in building energy performance.

Reflecting on the outcome of the WoS search queries in Table 3, the comparison of the queries indicates that research on "performance gap" accounted for less than three percent (268 documents) of the combined research on "energy performance" and "building*" (which resulted in 9,731 documents). These results indicate an opportunity to increase BEPG research and achieve the following:

- facilitating an improved grasp of BEPG as a phenomenon,
- case-by-case evidence and analysis of BEPG,

- monitoring and predicting multifaceted factors, and
- urgently changing standard practices in related professional fields.

Several studies support this claim, as previously highlighted in Table 2 (de Wilde, 2014; Cozza et al., 2021; Zheng et al., 2024; Zou et al. 2018). Considering the continuing challenge of high contributions by buildings to energy-related emissions (IEA 2022b), it is essential to maintain high interest in BEPG research and its development.

3.2. GLOBAL ANALYSIS OF BEPG RESEARCH

Further analysis of the research categories indexing the articles in the WoS database indicated a variety of subjects on which the research focused.

The range of BEPG discussions include construction and engineering (Gupta et al. 2015; Hepf et al. 2023; Reguis et al. 2023), chemistry and materiality (Jradi, 2020; Martínez-Comesaña et al., 2020), management (Samarakkody et al. 2022; Alencastro et al., 2018; Rasmussen et al., 2019), mechanics (Yao, 2020), and others.

Figure 3 illustrates the distribution of various subject areas or disciplines from the documents analyzed. The results indicate that twenty-eight percent falls into Construction Building Technology, twenty-five percent Engineering, twenty-three percent Energy Fuels, eight percent Science Technology, and seven percent Environmental Science Ecology. Other less predominant disciples include research areas such as, thermodynamics, business, architecture, computer science, physics, education, and others.

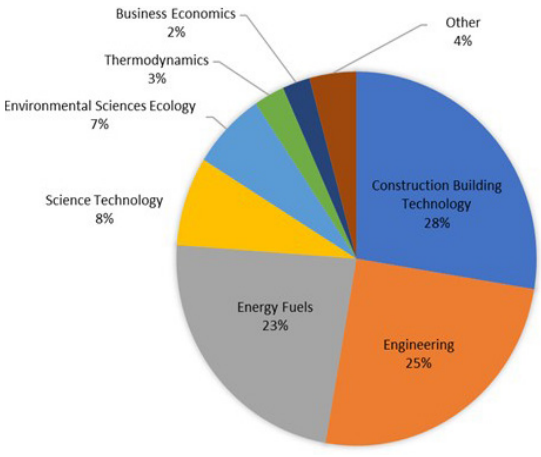


Figure 3: Distribution of WoS articles based on various subject areas.

The research areas in the WoS database with more than ten documents on BEPG research include the following: construction and building technology (190 articles); engineering (173 articles); energy fuels (161 articles); science and technology topics (fifty-three articles); environmental studies and ecology (forty-six articles); thermodynamics (nineteen articles); and business economics (seventeen articles). This substantiates that the performance gap is as much an economic and sociological challenge as a technical one and requires multidisciplinary investigation to be addressed effectively. It also demonstrates that policy and management issues related to the accuracy of building energy performance need to be researched alongside technological and environmental concerns.

The 331 articles used in this paper for the bibliometric analysis were published across sixty-six journals. Similar to the large distribution of research areas, the journals originate from a variety of themes beyond construction, engineering, and building. These include social science, policy, and management (including facilities management, environmental management, business and strategy), among others. This variety of themes vis-à-vis the relatively large number of journals demonstrates the thematic complexity and interdisciplinary nature of BEPG.

3.3 LEADING AUTHORS IN BEPG RESEARCH

The following section presents the most cited authors with at least five articles on BEPG from the query search. This includes author names, total publications, total citations, affiliations, and geographical information. It is necessary to identify the top researchers in the field of BEPG, as it can enhance networking, improve interdisciplinary productivity, and establish potential collaborations. Furthermore, this provides young researchers with guidance on leading authors within various disciplines related to BEPG research.

The results from the bibliometric analysis showed that the 331 publications were written by a total of 984 authors. However, a list of the most productive authors in BEPG research is presented in Table 4, featuring authors with a minimum of five articles among the documents.

The top fourteen authors identified are affiliated with nine academic institutions, spread across five countries. Similarly, regional analysis shows that England accounts for eight authors, China three authors, Spain one author, India one author, and South Korea one author. All fourteen authors have collectively published ninety-seven articles. This translates to approximately 29.3 percent of the BEPG publications.

From Table 4 it is evident that the most productive authors in BEPG research are D. Mumovic affiliated with the University College London in England and E. Burman from the Bartlett Faculty of the Built Environment, University College London in England, with twelve articles each. Additionally, D. Mumovic has a total of 128 publications (TPs), 3,033 total citations (TCs), and an h-index of twenty-seve. E. Burman has a total of thirty-one publications, 486 TCs, and an h-index of twelve. The authors, M. Davies and R. Gupta tie for third with a total of eight BEPG articles each. The remaining ten authors complete the research query, with at least five publications each. The researchers collectively authored fifty-two of the 331 publications included in this study. Table S1 in the supplementary materials lists the publications.

Among the top fourteen authors with a minimum of five articles, the year of first publication ranges from 1972 to 2016, nearly forty-five years. In addition, the total publications on BEPG (TPb) by each recognized author is presented, comparing the data indexed in WoS (TPw) against data indexed in Scopus (TPs). Notably, substantial differences appear in total publication accounts. These observed differences range from as few as two articles, seen with C.F. Bandera [TPw = 28; TPs = 30] to as large as 1,607 articles in M. Davies (TPw = 339; TPs = 1946). This brief comparison underlines a substantial disparity which can influence the perception of the research community about authors' productivity considering the wide scale of adoption of these databases across an extensive range of research fields (Hallinger and Kovačević 2019; Det Udomsap and Hallinger 2020;

#	Author	TPb	TPw	TPs	Author ID[1]	Year 1st pub*[1]	h-index[1]	TCs[1]	Current affiliation1	Country
1	Mumovic, Dejan Builtenvironment	12	93	128	14040664500	2005[b]	27	3 033	University College London, London	England
2	Burman, Esfand Builtenvironment	12	19	31	55843415200	2012[b]	12	486	University College London (The Bartlett), London	England
3	Davies, Michael Builtenvironment	8	1946	339	57202098246	1995[a]	63	14 108	University College London (The Bartlett), London	England
4	Gupta, Rajat Architecture	8	58	181	7501323603	1972[a]	31	2 817	Oxford Brookes University, Oxford	England
5	Johnston, David Builtenvironment	7	45	32	55725429600	2000[b]	10	529	Leeds Beckett University, Leeds	England
6	Xu, Xiaoxiao Engineering	7	116	48	57188580287	2016[a]	23	1 284	Nanjing Forestry University, Nanjing	Peoples R China
7	Farmer, David Builtenvironment	6	10	16	56425342700	2012[b]	8	263	Leeds Beckett University, Leeds	England
8	Gregg, Matthew Architecture	6	18	39	46661023500	2011[b]	12	554	Oxford Brookes University, Oxford	England
9	Lin, Borong Architecture	6	153	197	7403508277	2001[a]	37	4 441	Tsinghua University, Beijing	Peoples R China
10	Bandera, Carlos Fernandez Architecture	5	28	30	57201334734	2016[b]	11	603	Universidad de Navarra, Pamplona	Spain
11	Deb, Chirag Architecture	5	27	32	36106838200	2010[a]	17	1 704	Indian Institute of Technology Bombay, Mumbai	India
12	Jain, Nishesh Builtenvironment	5	10	16	56526077900	2014[a]	6	108	University College London	England
13	Park, Choel-Soo Architecture	5	72	97	55505157800	2003[a]	19	1 421	Seoul National University College of Engineering, Seoul	South Korea
14	Zou, Patrick X.W. Engineering	5	117	128	7006775603	2002[b]	38	4 486	Chang'an University, Xi'an	Peoples R China

Table 4. The WoS most productive authors in BEPG research with five papers or more.

TPb: total number of publications within the BEPG search outcomes in WoS;
TPw: total number of author's publications indexed in WoS;
TPs: total number of author's publications indexed in Scopus;
TCs: Total number of author's citations in WoS;
* Role in joint authorship of the article, identified by the superscripts: a first author; b co-author; 1: Scopus as the data source.

Munim et al. 2020). Hence, some researchers have stated the need for a comprehensive comparison of bibliometric information in the WoS and the Scopus databases (Md Khudzari et al. 2018).

The findings further show that around twenty percent of the top authors in this study are within the engineering field, while the majority (eighty percent) is in the architecture and built environment profession. This distribution further demonstrates the crucial role of architecture and built environment disciplines in creating a more sustainable built environment and achieving 2050 targets. In addition, seven of the top ten authors are affiliated with institutions in England. This suggests that BEPG research is well-established in the region, and it could serve as a basis for international collaboration. However, it also reveals a geographic and contextual disparity, which is further discussed in Section 3.5.

This section provides insight into recognizing key connections and the most influential contributors to the BEPG research field. The study includes prominent authors, their publications, affiliations, geographical regions, and disciplinary impact, showcasing the importance of BEPG research, specifically in architecture and the built environment.

3.4 LEADING JOURNALS PUBLISHING BEPG RESEARCH

This section explores the leading journals in which the 331 articles from the WoS database were published. Similar to the vast range of research areas from the bibliometric analysis, the articles were published across 66 journals, with a variety of themes beyond construction, engineering, and buildings. These journals' themes include social science (Energy Research Social Science), policy (Energy Policy) and management (Journal of Facilities Management, Journal of Environmental Management, and Business Strategy and the Environment), to name a few. The diverse range of themes across the journals clearly illustrates the thematic complexity and interdisciplinary nature of BEPG.

It is crucial for scholars to identify leading journals, as this can assist in identifying gaps, current trends, and global issues within BEPG research. In Table 5, the top ten most prolific journals are ranked according to their percentage representation of articles included in the WoS search query. The table further includes the journal impact factor (JIF) for the year 2022, and their respective most cited articles within the documents.

From the bibliometric analysis, the top ten journals represent approximately 15.2 percent of the total journals included in the study, and account for nearly two-thirds (65.6 percent) of the total publications. It is evident from Table 5 that Energy and Buildings is the leading source for BEPG research with seventy-eight articles, translating to nearly 23.6 percent of the total publications. This is followed by Energies with twenty-four articles (7.3 percent), Building and Environment (twenty articles), Building Research and Information (seventeen articles), and Sustainability with sixteen articles.

In addition, the researchers investigated the number of citations, impact factor, publishers, and identified the most cited article for each journal. Among the top ten journals from the WoS database, Sustainability had the highest total citations (187, 953), followed by Applied Energy (156, 087), Energy (156, 083), and Energies (103 643). The study reveals the most cited article among the 331 documents is by de Wilde (2014) with 579 citations and published in the Automation in Construction.

Table 5 also includes the JIF of the top ten journals, alongside their ranking based on the 2022 metric value. The journal with the highest JIF is Applied Energy (11.2), followed by Energy Policy (9.2), Energy (9.0), Building and Environment (7.4), and Energy and Buildings (6.7). The JIF rank reflects the journal's position within its assigned WoS category. Some journals such as Energies are only indexed in one WoS category, while others such as Sustainability are indexed under multiple categories depending on their theme. This indexing across categories can affect the total reach of the journal.

Researchers often aim to publish in journals with higher impact factors. However, considerations such as the capacity of a journal in terms of audience and research engagement should be a key factor in deciding where to publish (Md Khudzari et al. 2018). Given the need for BEPG research and application, it is important that relevant stakeholders can access significant research findings readily.

#	Journal	TP (%)	TC	JIF 2022	Rank by JIF 2022 [WoS Category]	The most cited article [reference]	Times cited	Publisher
1	Energy and Buildings	78 (23.6)	59 418	6.7	12/139 [EGC]; 10/68 [CBT]; 37/115 [EFU]	Energy performance gap in refurbished German dwellings: Lesson learned from a field test (Calì et al. 2016)	137	Elsevier
2	Energies	24 (7.3)	103 643	3.2	78/115 [EFU]	Optimizing energy efficiency in operating built environment assets through building information modeling: A Case Study (Petri et al. 2017)	50	MDPI
3	Building and Environment	20 (6.0)	53 430	7.4	6/139 [EGC]; 7/68 [CBT]; 14/55 [EGE]	Ten questions concerning occupant behavior in buildings: The big picture (Hong et al., 2017)	285	Elsevier
4	Building Research and Information	17 (5.1)	4 077	3.9	22/68 [CBT]	Performance gaps in energy consumption: Household groups and building characteristics (van den Brom et al. 2018)	82	Taylor & Francis
5	Sustainability	16 (4.8)	187 953	3.9	114/274 [ESC]; 48/127 [EST]; 34/46 [GSST]*; 5/9 [GSST]**	Rethinking performance gaps: A regenerative sustainability approach to built environment performance assessment (Coleman et al. 2018)	19	MDPI
6	Building Services Engineering Research & Technology	16 (4.8)	912	1.7	48/68 [CBT]	Quantifying the domestic building fabric "performance gap" (Johnston et al. 2015)	47	Sage Publications
7	Journal of Building Engineering	14 (4.2)	27 082	6.4	11/68 [CBT]; 13/139 [EGC]	Comparison of EnergyPlus and IES to model a complex university building using three scenarios: Free-floating, ideal air load system, and detailed (Al-janabi et al. 2019)	40	Elsevier
8	Applied Energy	12 (3.6)	156 087	11.2	11/158 [EGCH]; 15/115 [EFU]	Predicted vs. actual energy performance of non-domestic buildings: Using post-occupancy evaluation data to reduce the performance gap (Menezes et al. 2012)	464	Elsevier
9	Energy Policy	11 (3.3)	71 939	9.2	8/380 [ECN]; 22/115 [EFU]; 27/274 [ESC]; 12/127 [EST]	Do residential building energy efficiency standards reduce energy consumption in China? A data-driven method to validate the actual performance of building energy efficiency standards (Wang et al. 2019)	41	Elsevier
						Measuring the thermal energy performance gap of labeled residential buildings in Switzerland (Cozza et al. 2020)	41	
10	Energy	9 (2.7)	156 083	9.0	22/115 [EFU]; 3/62 [TD]	Towards measurement and verification of energy performance under the framework of the European directive for energy performance of buildings (Burman et al. 2014)	114	Elsevier

Table 5. Top 10 WoS ranking of the most productive journals in BEPG research

TP: total publications; TC: total citations; JIF: journal impact factor; WoS: Web of Science; EGC: Engineering, Civil; CBT: Construction, Building & Technology; EFU: Energy & Fuels; EGE: Engineering, Environmental; ESC: Environmental Sciences; EST: Environmental Studies; GSST: Green & Sustainable Science & Technology; EGCH: Engineering, Chemical; ECN: Economics; TD: Thermodynamics; *: Science Citation Index Expanded (SCIE); **: Social Sciences Citation Index (SSCI).

Furthermore, the top ten journals were published by only four different publishers, namely: Elsevier, Multidisciplinary Digital Publishing Institute (MDPI), Taylor & Francis, and Sage Publications. Out of the top ten, Elsevier accounted for six journals, followed by MDPI (two journals), Taylor & Francis (one journal), and Sage (one journal). The study on all 331 documents also revealed that Elsevier comprised the most documents (183 articles), followed by MDPI (forty-four articles), Taylor & Francis (thirty-one articles), Sage (eighteen articles) and Emerald Group Publishing (nine articles). Considering the substantial difference in the number of journal articles published between the first and fifth publisher, concerns around equitable knowledge sharing and its implications for addressing the energy performance gap in buildings may require investigation if the trend continues.

This analysis identified journals with the most citations, total publications, impact factors, and publishers of journals referenced in the WoS database. The analysis highlighted the following journals as the most prominent in BEPG and related research: Energy and Buildings, Energies, Building and Environment, Building Research, and Information and Sustainability.

3.5 THE GEOGRAPHICAL LANDSCAPE OF BEPG RESEARCH

Besides information on journal articles, keywords, citations, publishers and themes, the geographical distribution of authors was also obtained from the WoS database, using the bibliographic information of BEPG authors. Research on the 331 documents indicates that the documents originate from fifty-four countries.

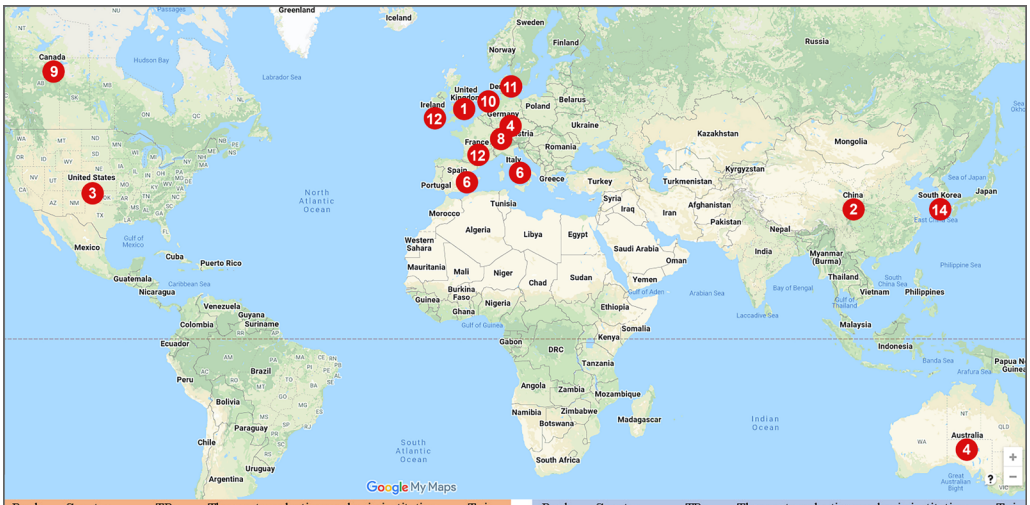
The geographical spread of articles was ranked according to total publications in the BEPG research field as indexed in the WoS database. In Figure 4, the top fourteen countries (TPc) and their respective rankings are indicated, including each country's most active academic institution. Studies have indicated that it is crucial for researchers to familiarise themselves with authors working on similar projects to establish possible networks globally (Md Khudzari et al. 2018; Krauskopf 2018).

The total publications (TPc) of a particular country encompassed both singularly and jointly authored articles. An analysis of the data focusing on the regional distribution indicates that among the top fourteen countries, Europe accounts for nine countries publishing BEPG related work. This was followed by North America and Asia with two countries each, and one in Australia. It is evident from Figure 4 that the most active country in terms of total publications with ninety-four articles is the United Kingdom, followed by China (thirty-nine), United States (twenty-four), Australia (twenty-three), Germany (twenty-three), Italy (twenty-two), and Spain (twenty-two). This disparity demonstrates the need for increased research activity in the BEPG field globally, and specifically the Global South.

Considering all 331 documents included in the study, countries actively publishing BEPG research are mostly concentrated in Europe (thirty-one countries) and Asia (fifteen countries), with a total of eighty and seventy-five publications, respectively. Among the other countries, North America has the highest activity via the contributions of the United States (twenty-four publications), Canada (fourteen publications), and Mexico (three publications). In South America, Brazil, and Chile contributed to BEPG research with four and two publications respectively. Only two articles originate from the African continent, one from Egypt and the other from Ghana. (Table S2 in the supplementary data provides the full list of publications by country). The Egyptian study focused on heat transfer coefficient and was conducted in collaboration with researchers from China, Iraq and Saudi Arabia (Zhang et al. 2023). The other publication studied occupant behavior in air-conditioned public buildings in Ghana and was conducted solely by Ghanaian researchers (Ahadzie et al. 2021). These two studies present the cases of inter-country and intra-country collaboration, which can be effective mechanisms to grow BEPG research in regions with minimal BEPG research activity and ultimately facilitate a sustainable built environment. The extent of collaborations across the global community of researchers in the BEPG field is displayed in Figure 5.

The results from Figure 5 further reveal that within the context of collaborations, countries are fragmented into two categories. The first consists of a cluster of countries conducting research within a "closed cell." The second category includes "lone countries" demonstrating no observable interaction with other regions, emphasized by their distance from the closed cell.

This division has several implications for both the built environment and global sustainability. On one hand, the potential for the built environment community to maximize the applicability of BEPG research findings may be hindered due to the limited scope of context and investigation. On the other hand, it suggests insufficient knowledge and expertise transfer among both academic and non-academic (governmental) research institutions globally. To adequately address the issues of BEPG and energy efficiency in the built environment, improving international collaborations could play a significant role towards achieving 2050 climate change targets (Tian et al. 2022).



Rank	Country	TPc	The most productive academic institution	Tpi	Rank	Country	TPc	The most productive academic institution	Tpi
1	United Kingdom	94	University College London	23	8	Switzerland	15	ETH Zurich	6
			University of London	23					
2	Peoples R China	39	Tsinghua University	11	9	Canada	14	University of Toronto	4
3	United States	24	Georgia Institute of Technology	3	10	Netherlands	13	Delft University of Technology	8
4	Australia	23	Swinburne University of Technology	8	11	Denmark	12	Technical University of Denmark	6
4	Germany	23	RWTH Aachen University	9	12	France	10	n/a	n/a
6	Italy	22	Polytechnic University of Milan	5	12	Ireland	10	University College Dublin	5
6	Spain	22	University of Navarra	5	14	S. Korea	9	Sungkyunkwan University	3

Tpc: total publications of the country. Tpi: total publications of the academic institution. n/a: no academic institution with more than one (1) publication.

Figure 4. Most active countries in BEPG research based on WoS

The geographic distribution of BEPG research across continents is clearly illustrated in Figure 4 and Fi5, indicating that leading countries are predominantly those falling under the "developed" category. Developed countries usually have stable economies, structured governments, reliable electricity supply, and technological advancement beyond that of developing or emerging countries (World Economic Forum 2019).

Given the expected population and built environment energy consumption increases (Siirola, 2014), especially in developing regions such as Africa (Rupp et al. 2015), it is necessary to examine BEPG factors and issues that are contextual for these areas. Essentially, it presents an opportunity for more case-by-case evidence and analysis of BEPG research that can be useful in limiting GHG emissions from buildings in the coming decades (de Wilde 2014).

3.6 THEMATIC INTERESTS IN GLOBAL BEPG RESEARCH

In this section, the author keywords from all 331 articles are further explored to determine the key terminologies and themes in BEPG research. Given the developing stage of BEPG research and the numerous variations of key phrases (as outlined in the methodology), keywords were not relabeled before the bibliometric mapping using VOSviewer. Subsequently, variations resulting from plurals, acronyms or abbreviations, and grammatical differences (e.g., behavior vs behaviour) were identified, summarized, and relabeled accordingly. Additionally, variations resulting from the use of different words such as occupant vs user were also identified, summarized, and included for discussion purposes.

The results of the bibliometric analysis and mapping shown in Figure 6 illustrate the most prominent keywords used in the BEPG research field and their respective average year of publication. Consequently, the VOSviewer keyword analysis identified five key themes, with "performance gap" being the most used keyword by authors in describing BEPG research, occurring eighty times with a total link strength of 420 links to other keywords. This is followed by energy performance gap (forty-one occurrences, 187 links), occupant behavior (thirty-six occurrences, 173 links), energy efficiency (twenty-seven occurrences, 143 links), and buildings (twenty-one occurrences, 118 links). Various terms describe efficiency in buildings, including energy performance (twenty occurrences, eighty-eight links), building performance (fifteen occurrences, eighty-three links), and building energy performance (fifteen occurrences, seventy-five links), among others. Similarly, a variation of occupant behavior was also written as user behavior with six occurrences and thirty-four links.

As stated earlier in the methodology, the variation of words describing a similar or singular phenomenon can pose some challenges to the larger research and

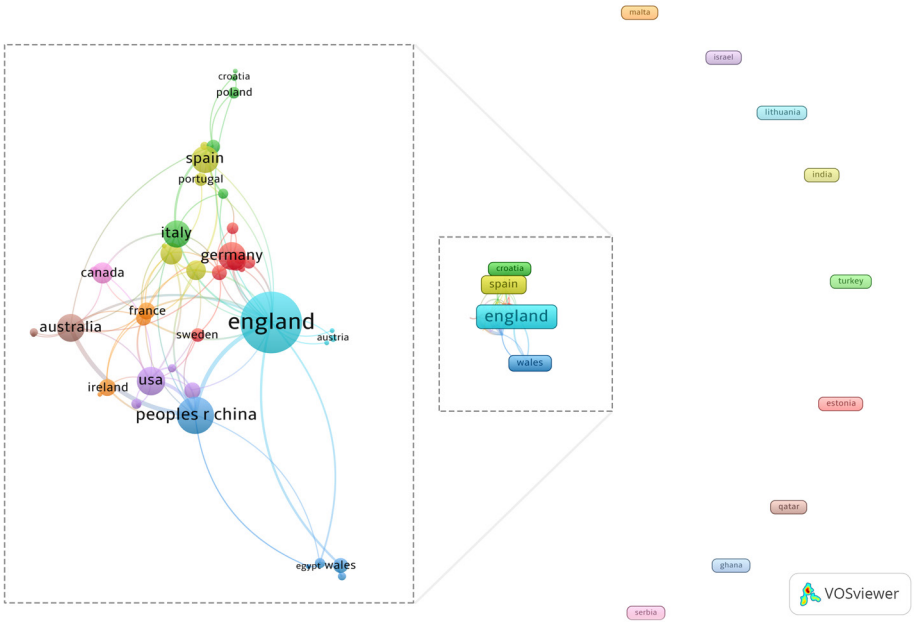


Figure 5. A visualization of international collaborations in BEPG research using VOSviewer

professional community due to the risk of losing key information. The researcher suggests that some measure of standardizing terms may assist readers and researchers in accessing information readily, while also improving best practices in the larger industry. This is demonstrated by the standardisation of the term "building information modelling,", shortened to the well-known acronym 'BIM' (Ghaffarianhoseini et al. 2017).

Furthermore, the results illustrate a large variety of BEPG themes within the contextual investigation. Some of the research focused on building typologies including, social housing (five occurrences, eighteen links) (Filippi and Sirombo, 2019; Ozarisoy and Altan 2022), non-residential buildings (four occurrences, fourteen links) (Ji et al. 2022), and office buildings (six occurrences, thirty-seven links), including sub-classifications and qualifying keywords such as office spaces, shared offices, and green office buildings. Other studies focused more on the building phase with keywords such as post-occupancy evaluation (nine occurrences, fifty-one links), retrofit (eleven occurrences, sixty-nine links), and soft landings (five occurrences, twenty-eight links) (Gana et al. 2018). The term soft landings refers to an effective framework and adaptable strategy that facilitates the seamless transition between building phases, generating substantial interest amongst stakeholders and governments (Samarakkody et al. 2022).

In the spirit of an environmental epistemology, students learned about the underlying systems, instead of from it, merely imitating them. By studying the structure and inexhaustible resourcefulness of nature, they became better equipped to design for delicate ecosystems in a productive and supportive manner. This approach encouraged the development of strategies that respect and enhance the natural environment, rather than imposing upon it.

Moreover, another significant theme within BEPG research is the investigation into the role of weather data, especially within the context of climate change. Several keywords regarding weather information were observed including, climate change (seven occurrences, twenty-six links), cold climate (three occurrences, fourteen links), temperate climate (two occurrences, ten links), urban climate (two occurrences, eight links), weather forecast (one occurrence, six links), tropical weather (one occurrences, five links), weather file (one occurrence, four links), and future weather (one occurrence, three links).

Understanding the climatic context of a location is essential in energy modelling and producing accurate data. However, given the shifting climate patterns, some researchers argue that climate change needs to be factored into weather data, citing an insufficiency of historical weather data for predicting a building's future energy performance (Farah et al. 2019; Guan 2009). As a result, simulating building energy performance using

forecasted weather data can become part of standard procedures and provide more accurate results for the future.

This study identifies emerging trends and pertinent research themes within BEPG research, highlighting the complexity of BEPG with the magnitude of keywords and associations, including building typologies, machine learning, climatic data, building envelope, and energy standards. These findings underpin the dynamic evolution of BEPG research, while simultaneously emphasizing the need for scholars and researchers to foster impactful and collaborative projects related to these themes.

3.7 THE IMPACT OF BUILDING ENERGY CODES ON BEPG

To further explore the details of BEPG, the authors studied the correlation between building energy regulations and related performance gaps. Studies highlight that building energy regulations are foundational for building performance analysis as they often provide mandatory minimum building energy performance requirements (Ürge-Vorsatz et al. 2012). However, many countries globally currently lack the necessary building energy performance standards, especially in the Global South, when compared to countries in the Global North (Gaum and Laubscher 2021). In addition, building performance codes are context-specific and influenced mainly by building methods and materials. These vary between countries in the Global North and South. When modelling programs are generic in structure and building components are generalized, predictions are affected.

Thus, the lack of building performance codes presents significant hurdles for building performance prediction, which potentially exacerbates the challenge of BEPG and the lack of building performance simulation practices in the Global South (Gaum et al. 2022).

To determine the BEPG papers that incorporate policy and energy regulations as components of the research, the following search phrases were identified from the keywords, and employed to refine the results: "energy policy" or "energy rating*" or "building regulation*" or "governance" or "policy" or "building code*" or "building energy code*" or "building codes and standard*" or "building energy conservation code*" or "building energy rating" or "building standard*" or "epbd" or "energy performance of buildings directive" or "environmental policy target*" or "2050 climate target*" or "national energy rating". The search phrase resulted in eighty-seven articles from thirty-eight countries which the authors further delineated as Global North and Global South based on the updated Brandt Line, systematically developed by Gaum and Laubscher

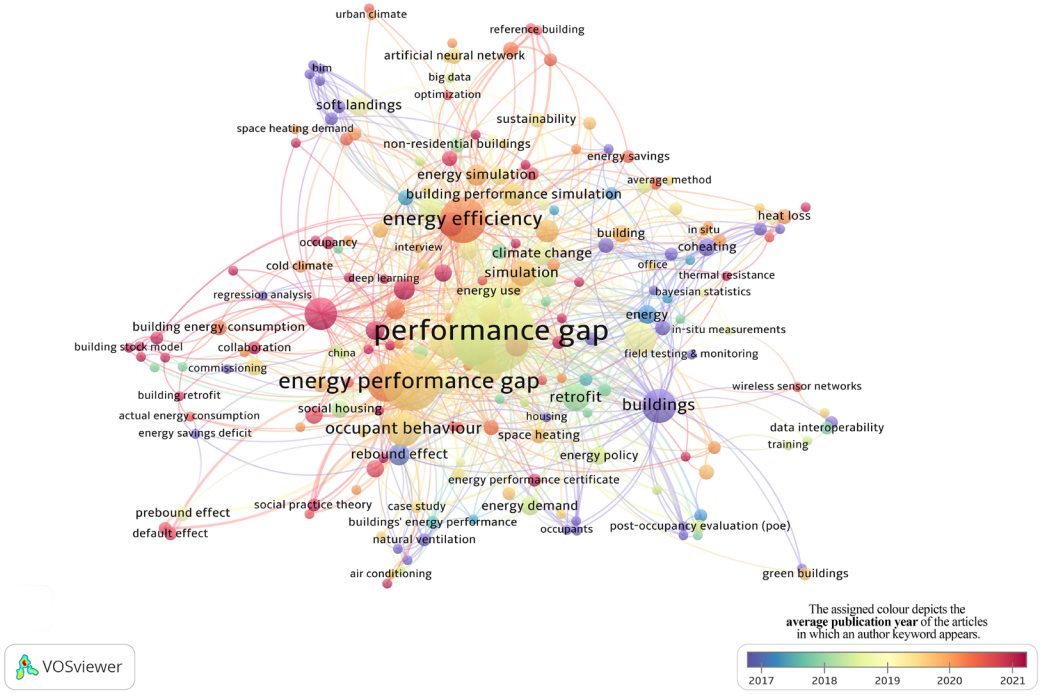


Figure 6. Bibliometric map of author keywords using VOSviewer

(2021). Following a manual screening of the articles, the study identified three main approaches that capture the policy-BEPG research intersection:

1. Building energy codes as the research context (Aldabesh et al. 2021).

2. Focusing on energy codes as the subject of the investigation (Wang et al. 2019).

3. Implications of the findings for policy development such as the need for better simulation parameters or assumptions and theoretical values (Bauer et al. 2021).

The result indicates that a total of twenty-nine Global North countries and nine Global South countries researched energy regulations and policy for BEPG. In Figure 7, the top twelve most active Global North countries are compared to the nine Global South countries. Excluding China, BEPG research that incorporates themes around energy codes are vastly limited in the Global South despite the significant floor area growth expected between 2030 and 2060 (IEA 2017). These results present several implications including a widening gap between the Global North and Global South capacities, and the possibility that buildings in the Global South may also become locked into BEPG inefficiencies.

Moreover, several BEPG research articles incorporated green building themes and case studies as part of their research design. While analysing the author keywords, the study observed three categories of green building-related themes. These categories refer to the type of rating system, specific reference to resource efficiency in buildings, and distinctive frameworks. Gupta et al. (2015) incorporated the UK's Green Deal scheme that supports energy efficiency home upgrades (UK Government, n.d.) into their BEPG research. A recent study creatively applied the framework of green human resource management (GHRM) to understand BEPG in green buildings and the role of occupants (Parida et al. 2023). The third framework is green financial instruments (GFIs) (such as green insurance, green bonds, green credit, among others), and the impact of BEPG on green building development (He et al. 2023).

A key implication is that BEPG in green buildings exacerbates fiscal investment and economic risks at both governmental and market levels (He et al. 2022). Considering the current drive towards sustainable development globally and especially in developing regions (Chan et al., 2017, International Finance Corporation [IFC] 2019), more engagement into building energy codes, green frameworks, resource use, rating systems, and efficiency methods to alleviate BEPG in buildings will not only be beneficial, but necessary to achieve 2050 climate change targets.

4. CONCLUSION AND FUTURE STUDIES

On a global scale, BEPG poses long-term sustainability challenges for the built environment. This paper provides important insights into the global trends and themes in BEPG research using bibliometric analysis.

The researchers systematically searched the WoS database and found 331 relevant articles published between 2012 and mid-2023. By applying systematic and scientometric analysis techniques and using the VOSviewer program, the study identified and visualized global research engagements, thematic developments, and geographical context of BEPG research. This review ultimately aimed to promote energy efficiency and built environment sustainability, and proposed new research directions for effectively implementing BEPG research, specifically for the Global South.

This paper further sets out to partially address the challenges in BEPG research by examining global engagement and identifying key thematic research areas. The findings provide readers in the field with a holistic understanding of the subject, current status, key actors, and opportunities for further studies.

The study found that while less activity on BEPG research was detected over the past two years (at the time of the analysis), it has increased substantially over the past decade. From the 1,118 author keywords, less than ten percent were utilised three times or more. This trend demonstrates new focus areas are emerging, and the range of BEPG research is broadening. Nonetheless, the researchers believe that there is an increasing need for a deeper understanding of the multifaceted nature of the subject. Achieving this calls for thorough case-by-case evidence of how BEPG is mitigated in different building types and geographic contexts. It also requires the refinement of standards and professional practices. With the global floor area growth expected to double by 2060, it is crucial to alleviate the challenge of BEPG and ensure an energy-efficient building sector.

The study determined that BEPG research is mainly conducted by authors, institutions and countries in developed regions such as Europe and North America. Hence, research in the Global South region, particularly in Africa, is almost non-existent. This gap could be due to several reasons. For instance, one claim would be that regions with less building energy regulations might conduct more performance-gap research to understand their needs. However, a country's lack of building energy regulations suggests that energy-efficient building design and practices are not standardized or legislated

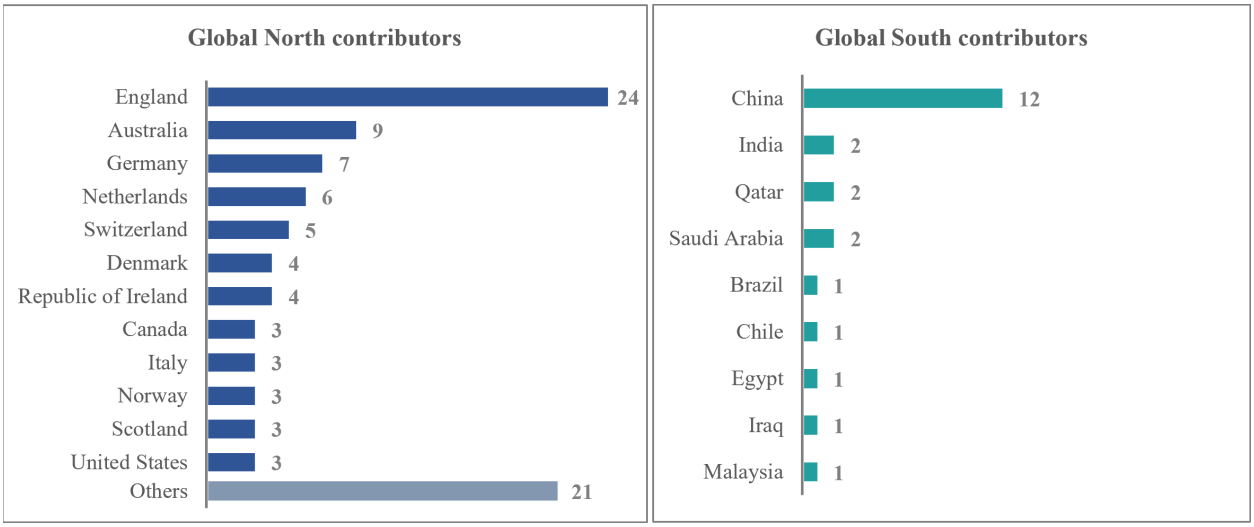


Figure 7. BEPG research from Global North and Global South countries incorporating building regulations

requirements in its building sector. Hence, exploring the energy performance gap in buildings may not be considered necessary. In addition, research connecting BEPG and building energy regulations is relatively limited in the Global South compared to the Global North. For building energy simulation as a practice to grow in the Global South, regulations and policies such as minimum energy performance standards are essential. Another challenge could be a lack of capacity in technical expertise, policy expertise, and research funding. Further studies are also needed to potentially explore the role and impact of industry incentives, and knowledge transfer across contexts in more depth.

In essence, it is crucial to increase research efforts in Africa and the Global South to better understand BEPG in different regional contexts. Using the WoS database, the study identified the authors and institutions which have published in the BEPG research field. Table 4 outlines the authors with at least five publications from the sample of 331 articles, and Table S3 in the supplementary data provides a list of the affiliations with a minimum of three articles in the study's dataset. By identifying the key actors in BEPG research, these findings offer a starting point to foster international collaborations. Furthermore, strategic partnerships between Global North and Global South authors, institutions, and countries can facilitate the transfer of knowledge, best practices, and technical expertise that are needed to ensure a sustainable global built environment.

As the world moves towards Net Zero, green building topics can be expected to play a crucial role in the future (Ohene et al. 2022). BEPG research is beneficial to the real-world performance of this building sector. Additionally, the expanding range of themes helps deepen understanding of BEPG and its multidisciplinary role within global sustainability. Therefore, the researchers believe the future of building energy simulation lies in embracing this multidisciplinary framework, incorporating it into research, and applying it in real-world practice.

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