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Review

A systematic review of barriers to implementing net zero energy buildings in Australia

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ABSTRACT

Building operations use 45% of the total energy in Australia, and Net-Zero Energy Buildings (NZEBs) are instrumental in achieving net zero emissions by 2050. However, research reveals that various factors hinder NZEB adoption in Australia, and it is imperative to contextualise the barriers, thereby highlighting clear gaps that can be addressed to enhance the implementation of NZEB in Australia. This study presents a systematic literature review and bibliometric analysis to examine the barriers that hinder the implementation of NZEB contextualised within the Australian building industry. The paper's novelty resides in its contextualisation of barriers to NZEB thereby highlighting clear gaps that can be addressed to enhance the implementation of NZEB in Australia. Emergent results reveal the most impactful barriers experienced and the inter-relatedness between barriers and their effects on each other. These identified barriers are also compared with comparable countries, including the UK, China, Italy and the US. New insight and knowledge acquired provide a basis for assessing potential solutions to the main barriers. Findings show that a lack of knowledge, climate issues, and cost issues, in addition to government policy factors, are considered primary barriers encountered by the industry, hindering the achievement of NZEBs. It is imperative that future studies and initiatives counteract these impacts to realise a better implementation of NZEB in the Australian context.

1. Introduction

Building accounts for approximately 40% of world's annual consumption and 55% of electrical consumption (IEA, 2022). Consequently, Net-Zero Energy buildings (NZEBs) are gaining popularity globally as a solution to reduce operational energy usage and limit greenhouse gas (GHG) emissions. Furthermore, many country-level commitments fail to provide clarity regarding the scope of emission reductions, barriers inherent and tangible actions required to achieve NZEB (Masood, 2021). In Australia specifically, building operations use 45% of the total energy consumed, and NZEBs have been recognised as important in achieving net-zero emissions by 2050 (Sabour et al., 2023). Adopting NZEBs and technologies require the collective effort of all stakeholders (including clients, architects, builders and contractors) (Falana et al., 2023) because there are many technical, economic and political barriers that influence NZEB and the interrelationships between these disparate considerations are unclear. Vats and Mathur (2022) therefore concluded that the successful implementation and penetration of NZEB will require enhanced public awareness, enlightened behavioural shifts, innovative business models and contextual capacity building among stakeholders.

NZEBs have been defined as buildings that generate or procure their own energy wholly through renewable sources to meet their annual energy requirements (Too et al., 2022). Wells et al. (2018) espoused that NZEBs provide a goal for the world's building stock to address multiple issues such as global warming, resource management, energy security and resilience. Singh and Verma (2014) estimated that over 200 examples of successful NZEB projects exist worldwide and thousands have been studied through simulation. The recent exponential growth in net-zero projects has been fuelled by better availability of energy-efficient and renewable energy technologies and increased awareness among stakeholders involved in sustainable construction (Sabour et al., 2023). According to Singh and Verma (2014), those professionals interested in NZEBs stem from a research or design background, or individuals or organisations seeking to decrease their energy

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costs to generate a competitive advantage.

Previous literature by Wells et al. (2018) indicates a notable propensity to define NZEBs, and the US Department of Energy (2015) provides the most internationally agreed definition within the Net Zero Energy research field. In addition to establishing a singular definition for NZEBs, the US Department of Energy (DoE) also harmonised existing definitions to accommodate the heterogeneous mix of buildings where renewable energy resources were shared. To meet this need, the US DoE provided variations on the NZEB definitions, such as Zero Energy Community and Zero Energy Resource, both of which have specific applications to building typologies and scenarios. Wells et al. (2018) proffer that an NZEB is characterised by a building whereby for every unit of energy consumed, the building must also generate a commensurate unit of energy; where the energy is consumed and generated at the site, regardless of its origin. This definition is practical for buildings connected to an electricity grid because it accounts for each unit of energy regardless of its source. Inherently, Australia has reached a pivotal point in terms of its sustainable construction quest, with the next stage of evolution for energy-efficient buildings being the implementation of these NZEB concepts.

Given the significant increase in current NZEB research over the past decade, a greater understanding of this concept is being developed (Li et al., 2016; Li et al., 2017). Although a large body of knowledge concerning NZEBs is currently available, there is a notable dearth of literature that directly relates significant barriers to its successful adoption and implementation (Too et al., 2022). Furthermore, even less literature relates to the Australian building industry. Although countries like Australia and New Zealand show limited support for NZEB initiatives, the existence of related enabling policies demonstrates their potential for adoption to accommodate NZEB goals (Bamdad et al., 2021). The conjunction of these factors, engenders the research question: *"what barriers may be encountered when NZEBs become the mainstream in Australia?"* It remains unclear how these barriers play a role in potentially preventing a successful net zero energy building project (Miller et al., 2018).

NZEBs provide solutions to various problems affecting modern-day construction in Australia and key benefits include: (1) ***cost savings over building life-cycle***: Although the capital cost of NZEBs is higher than conventional buildings, the overall cost saving across the life cycle of NZEBs has been proven (Hu, 2019; Vats and Mathur, 2022); (2) ***energy savings and enhanced indoor environment for the end-users***: NEZBs have various other benefits for end-users, including energy-savings, increased energy-security and enhanced indoor environment (Mavrigiannaki et al., 2021; Too et al., 2022); and (3) ***environmental benefits:*** the introduction of NZEB to the building industry has drastically lowered the total GHG produced in both residential and commercial buildings (Australian Bureau of Statistics, 2019; Too et al., 2022). However, almost 80% of Australia's 9.1 million dwellings were constructed before the introduction of energy-efficiency regulations in 2003 (Australian Bureau of Statistics, 2003), and hence, it can be inferred that the net zero energy concept was largely unknown prior to this date. Although there are limited existing NZEBs, a dramatic increase in renewable technologies applicable to them has been witnessed over the past few years (Miller et al., 2018). For example, most Australians have embraced rooftop photovoltaics (PV), as evidenced by the 1.6 million small-scale (1.5–5 kW) rooftop PV systems and becoming the world's highest proportion of households with these systems (16.5%) (Roberts et al., 2019). Regards recent Australian Government initiatives towards achieving net zero, there has only been one landmark agreement which sought to transform the energy-efficiency of residential, commercial and industrial buildings – namely, the National Strategy on Energy Efficiency 2009 (Bond, 20111). For the residential sector, key measures to drive growth in the number of highly energy-efficient homes across Australia include: increasing energy-efficiency requirements for new residential buildings; providing relevant information to the housing market; and developing a national building framework to deliver consistency in how building energy-efficiency is assessed and rated (Bond, 2011). Although these existing technology implementations work towards more sustainable buildings overall, a lack of government policy to support successful NZEBs is apparent (Vora et al., 2016). Furthermore, it is recognised that there is a lack of research awareness in specific geographical contexts leading to a lag in innovative approaches (Saini et al., 2022; Too et al., 2022; Zhang et al., 2020). In recent publications, it has been espoused that barrier to implementing NZEB also pertains to limited understanding of the carbon emissions of buildings in the life cycle and the role of insulation in buildings (Su et al., 2023), in addition to the incomplete considerations such as exclusive use of electrical energy in use phase, and inexact allocation of waste heat (Maierhofer et al., 2022). Reconciling the differences between carbon emissions in embodied stage and operational stage of NZEB will, therefore, require concerted efforts from all stakeholders (Falana et al., 2023).

This research presents a systematic literature review and bibliometric analysis to examine the primary barriers encountered by the building industry that hinder the implementation of NZEB contextualised within Australia. This study fills this research gap by examining concomitant benefits of exploring the inter-relatedness of barriers include contributing heavily to knowledge creation and the development of future initiatives that can support the optimal implementation of NZEBs in Australia. With Australia currently lagging in terms of Net Zero Energy implementation, this research provides a timely reflection on the opportunities and barriers for national implementation of NZEBs. The paper's novelty resides in the contextualisation of barriers to NZEB thereby providing clear gaps that can be addressed to enhance the implementation of NZEB in Australia.

2. Research Methodology

The systematic review of NZEB literature is crucial as the multi-facet scope and accelerated pace of research is necessitated to achieve a state-of-art of knowledge. There has been growing interest in NZEB reviews across the literature. With regards to barriers, Vats and Mathur (2022) acknowledge that there are limited resources, infrastructure, cost, policy and behavioural initiatives to support practical implementation of NZEB. Furthermore, many country-level commitments fail to provide clarity regarding the scope of emission reductions, barriers inherent and tangible actions required to achieved NZEB (Masood, 2021).

The research adopts an interpretivist philosophical stance and inductive reasoning to develop a new theory on the phenomenon under investigation (Posillico et al., 2022). In terms of approach, Fig. 1 illustrates that a combination of systematic literature review using a PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol and quantitative analyses via bibliometric analysis (Newman et al., 2021) used to achieve the research aim. The PRISMA statement and its extensions are defined as an evidence-based, minimum set of recommendations designed primarily to encourage transparent and complete reporting of systematic reviews (Sarkis-Onofre et al., 2021). A systematic literature review and bibliometric analysis is a contemporary research framework that has been previously adopted in contemporary research (Sabour et al., 2023). This will allow the concepts and key themes surrounding NZEBs and the barriers which inhibit their achievement to be further understood. Additionally, based on the analysis in the Australian context, it will be beneficial to compare the barriers and concepts experienced in other relevant countries.

Google Scholar and ScienceDirect databases were selected as the largest proprietary databases for searching extant literature and are specifically useful for retrieving literature based on construction and building disciplines. As of 2018, it was estimated that Google Scholar comprised over 389 million articles (Gusenbauer and Haddaway, 2020) and ScienceDirect comprises over one-quarter of the world's technical and scientific literature, containing 13.9 million publications. Both of these databases were highly efficient in proceeding with a systematic

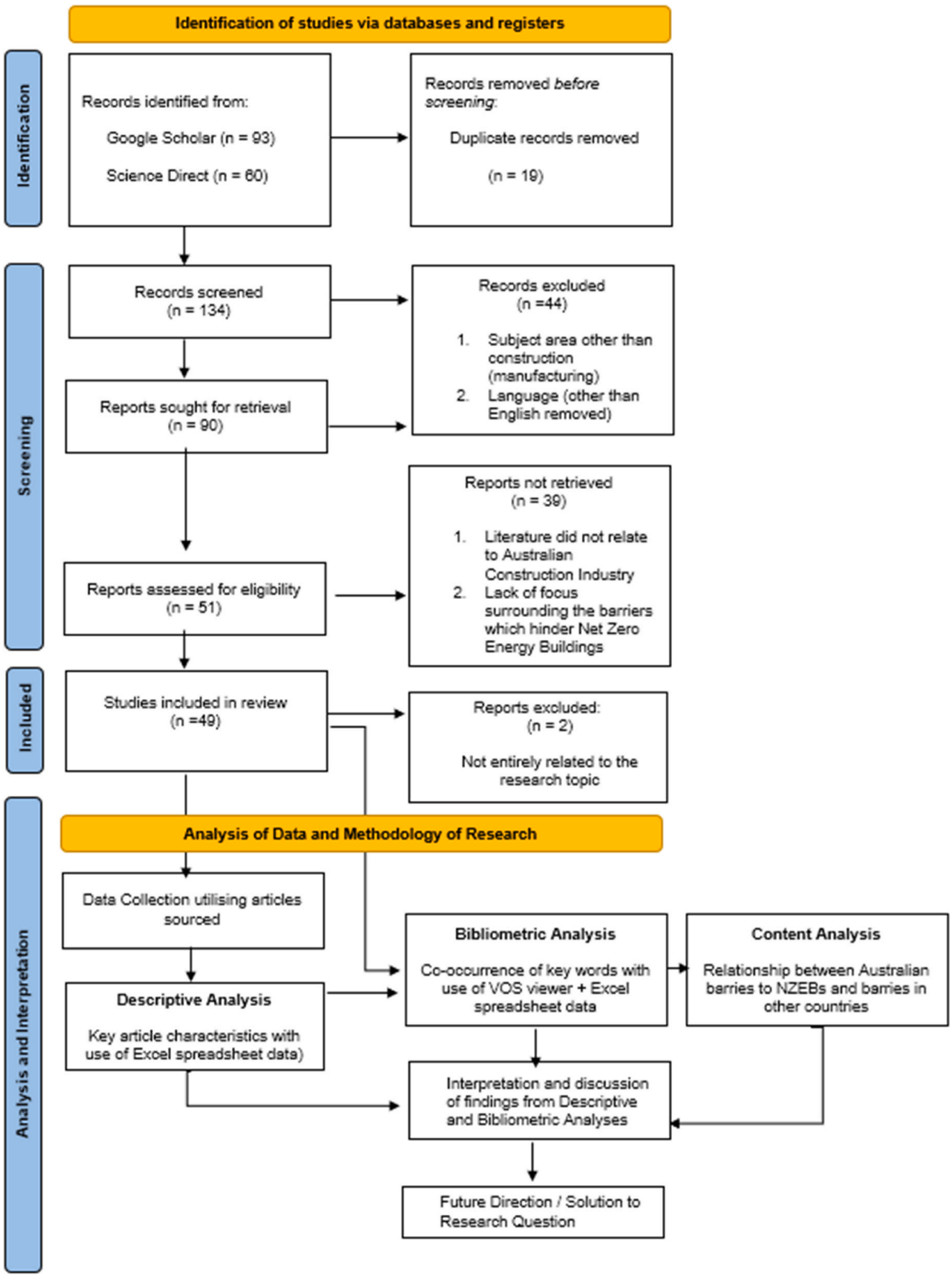


Fig. 1. PRISMA Protocol screening process and Research Methodology.

literature review due to the ability to outsource data utilising keywords, journal types, authors and disciplinary areas. This study utilised three phases of PRISMA, namely: (1) in the identification phase, relevant peer-reviewed journal articles were collected by utilising the data search; (2) in the screen phase, the range of the search was narrowed down to produce specific data results; and (3) in the analysis phase, the bibliometric and descriptive techniques were applied to the data found through the PRISMA protocol to highlight common themes within the literature.

The PRISMA meta-analyses flow diagram by Page et al. (2021) was adopted due to its many advantages. These include the identification of scientific articles in large literature databases through the use of keywords, search strategies, exclusion screening and an eligibility process used to perform analysis. PRISMA is a consistent meta-analysis technique because it follows a methodological process that can be universally implemented into a literature review to produce an unbiased and accurate range of data and findings.

2.1. Selection criteria

A literature search commenced with the investigation of citation databases using search strings. Underpinning the research aim, the keywords utilised within the search include the terms: "Net Zero Energy buildings", "Australia", "barriers" and "case study." The period of literature review included journal publications in English from 2012 to 2022, considering the origins of NZEB dates back to 1977 and NZEB research has been on the rise since 2011 (Sabour et al., 2023). The first retrieval of articles identified a total of 153 publications – 93 were obtained through the Google Scholar, while 60 were retrieved from Science Direct. Duplicate records were removed in the identification phase and 19 publications were excluded. The screening phase of the PRISMA process involved filtering the articles to exclude: (1) publications that were derived from an unrelated disciplinary area, such as manufacturing or production; and (2) publications that were not in the English language or did not have the full text available for access. A total of 44 were excluded using these criteria delineated and 90 publications continued to be screened through title and abstract analysis. The next set of criteria involved excluding articles that did not relate to the Australian building industry or lacked focus on NZEBs. From this screening section, a further 39 reports were excluded (constituting 102 journal articles in total), leaving a total of 49 publications to advance to the final phase of PRISMA.

The inclusion phase of the systematic literature review provided a final additional criterion as the articles' focus on the research topic was further analysed. Although all articles were relevant, a further two publications were excluded because they did not encompass the same relation to the research topic as the remaining publications. The final exclusions were made to ensure that all articles gathered remained in line with the research question and will provide the best possible discussion and analyses of the secondary data acquired. At the completion of the inclusion phase, a total of 49 journal articles remained at the end of the PRISMA protocol.

A meta-analysis of the secondary data set (where each publication constituted a unit of analysis) provided a basis for research articles that were credible and relevant to the issue. This led to the dissection of data through Microsoft Excel spreadsheets and the co-occurrence of words via the scientometric software tool VOSviewer. Adopting this approach allowed for a more conclusive interpretation of the literature reviewed to address the research aim. A final step in the methodological flow chart determined how the data was interpreted to form a cohesive discussion on the future research direction. When used in conjunction, the combination of all these methodological steps provided un-bias and well-interpreted data from the most relevant journal articles available.

2.2. Literature analysis

The established techniques of descriptive and bibliometric analyses are utilised in analysing the publication trends. In combination, these two analyses provides both a statistical overview of the literature and a snapshot of key research topics through visuals and mapping (Vats and Mathur, 2022). To effectively utilise a systematic literature review and obtain valuable information on the research topic, the first stage of the quantitative analysis involves a descriptive analysis. Descriptive analysis undertaken presented an overview of the included publications and important relationships between the journal articles (Saini et al., 2022). Descriptive analysis is conducted to establish the general patterns in the sources, scope and of information on NZEBs. This approach allows the key research findings to be presented in an accessible manner while also complementing the results derived from the PRISMA protocol. Using a descriptive analysis was determined to be the most effective way to analyse the data obtained from the retrieved journal articles. A descriptive analysis, in conjunction with charts and visualisation, allows for a sensory evaluation of the data and for relationships between key data to be connected and signified (Sabour et al., 2023). Descriptive analyses undertaken followed the dissection of all retrieved articles to sort data into several categories to identify data outliers and similar variables. The descriptive analyses of included papers consisted of the numbers of papers per year, analysis of publication outlets, analysis of barriers examined within the papers, and the number of building types and structures that were studied within the articles.

Descriptive analysis with graphs gives a snapshot of the data which was retrieved from the PRISMA protocol. Bibliometric analysis, on the other hand, was formed from the eligibility phase of the PRISMA protocol and provides a network visualisation map that highlights the co-occurrence of keywords and emergent research themes uncovered within the literature. VOSviewer was used for the generation of visual scientific landscapes of the screened papers (Van Eck and Waltman, 2010). Unlike descriptive analysis, bibliometric analysis used all the records that were identified in the PRISMA protocol to form an analysis with the aim of finding unbiased data linkage within the entire research topic (Hirsch et al., 2019).

Bibliometrics is an effective approach to analysing the structure and content of narrative, to identify the trends, gaps, authorship and interests using publication data (Camarasa et al., 2019). The bibliometric network map allows for a visualisation of key themes and aspects of the research that was undertaken (Van Eck and Waltman, 2010). Furthermore, it also used to measure the significance of certain journals, keywords, authors and keywords, which ultimately provides valuable analysis while removing the subjectivity issues among the literature retrieved. Utilising VOSviewer allowed for the generation of visual scientific landscapes about authors, keywords, journal organisations and countries of origin based on co-authorship, co-occurrence, co-citation or bibliographic coupling (Hirsch et al., 2019). It can count the number of links and the total strength of those links that are found throughout a set of literature and prepare a graphical network visualisation.

To further examine the barriers to NZEBs, further bibliometric analysis was completed to determine the similarities between barriers found in Australia and other comparable countries. These comparable countries were determined using a co-authorship network map, which analysed the articles' country of origin and provided a visualisation of the total link strength between Australia's barriers to NZEB and other countries. A combination of bibliometric analysis and further research on comparable countries provides the context of the research undertaken and assists in the determination of the relevance of data on a world scale. The comparable countries were then cross-analysed with the barriers identified to determine if the same barriers are experienced in the Australian NZEB field as in other parts of the world.

2.3. Content analysis of comparable countries

Since the advent of NZEB, researchers from 88 countries have contributed to NZEB, with Italy being the most prominent (Sabour et al., 2023). An important discussion question within this research topic remains, and that is how barriers that impact NZEBs in Australia compare to barriers impacting NZEB in other countries. To determine the most relevant comparable countries when discussing NZEBs and their barriers, an additional bibliometric visual analysis is conducted. The comparable country analysis shows the country of article origin, and all countries shown have a minimum of five articles that include the terms "Net Zero Energy Building", "Barriers" and "Australia." By the specific selection of these keywords in the article search, the results that are derived indicate that the countries shown have been linked through co-authorship. This therefore, identifies collaboration patterns on the topic of NZEB barriers that are relevant to Australia and other countries of authorship and the total link strength between them. A content analysis of comparable countries was completed to indicate the barriers that impact NZEB in countries other than Australia. 20 articles from the initial PRISMA protocol phase were sourced based on the research question relevance and barriers were identified for these countries. This provided a basis for comparison between Australia and the relevant countries chosen for evaluation. The frequency of barriers, direction and intensity of direction relating to barriers were analysed to form the comparison to the assessment of barriers to NZEB in Australia.

Content analysis was undertaken by coding the data derived from the 20 articles. Detailed interpretation and sense-making of the information gathered was done in the following manner: (1) becoming thoroughly familiar with the case studies in the articles by critically reading and re-reading all the transcripts and documents gathered; and (2) synthesising the barriers found across the literature (Sabour et al., 2023).

3. Results and analysis

3.1. Results from bibliometric analysis

Co-occurrence of keywords bibliometric analysis: the mapping of co-occurrence of keywords indicates the frequency of appearance of study topics in one paper and the inter-relatedness of the study topics across all the literature (Jin et al., 2018). Through the screening of titles, abstracts and keywords in the literature, VOSviewer was able to generate a network map (refer to Fig. 2) to provide insight into the selected data from the eligibility phase of the PRISMA protocol and demonstrate the important keywords in the data. The differentiation in the colour brightness and transparency of keywords shown in the visualisation denotes the interconnections of keywords, while the size of the nodes highlights the weight of the keyword in terms of their prominence within the literature. The larger the node of an item, the higher the weight in the network. The distance between the circles also represents the relatedness among the keywords, emphasising the co-occurrence linkage. Therefore, if two keywords are positioned close together, the connection between them is stronger. Keywords within the map have clusters that surround them, which shows the interdependencies among them (Jin et al., 2018). Additionally, this visualisation helps to identify the clusters and frequency of keywords addressed.

Since ‘energy building’, ‘construction’ and ‘climate’ and ‘cost’ have the largest circles on the network map, they have the highest weight in the literature. ‘Energy building’, which was mostly used in the literature as ‘Net Zero Energy Building’, has by far the largest circle, meaning that it is the most connected keywords in the literature, followed along with the other keywords of ‘construction’ and ‘climate’ and ‘cost.’ This indicates that these keywords are research hotspots within the research domain. The links between ‘net zero energy building’ and the other clusters emphasise its powerful relationship with other topics of construction.

Key barriers such as climate and cost had a significant weighting, while the keyword ‘definition’ also had a strong connection to the barrier cluster, indicating that it was often discussed due to the lack of a universally agreed upon definition of NZEBs. Residential building was also a frequently occurring keyword, and it also demonstrated strong links to the barriers mentioned above, which indicates that the barriers are mostly linked to residential construction within Australia.

The last notable point derived from the network map is the range of keywords that relate to the potential solutions for the barriers. Keywords such as ‘approach’, ‘application’, ‘integration’ and ‘implementation’ are all weighted significantly and interconnected to the barrier cluster, which suggests that solutions to these potential barriers are often discussed and are a popular research topic within this field. The linkage between these words and the keywords ‘scenario’ and ‘simulation’ also highlights the point that the solutions to these barriers are mostly in trial

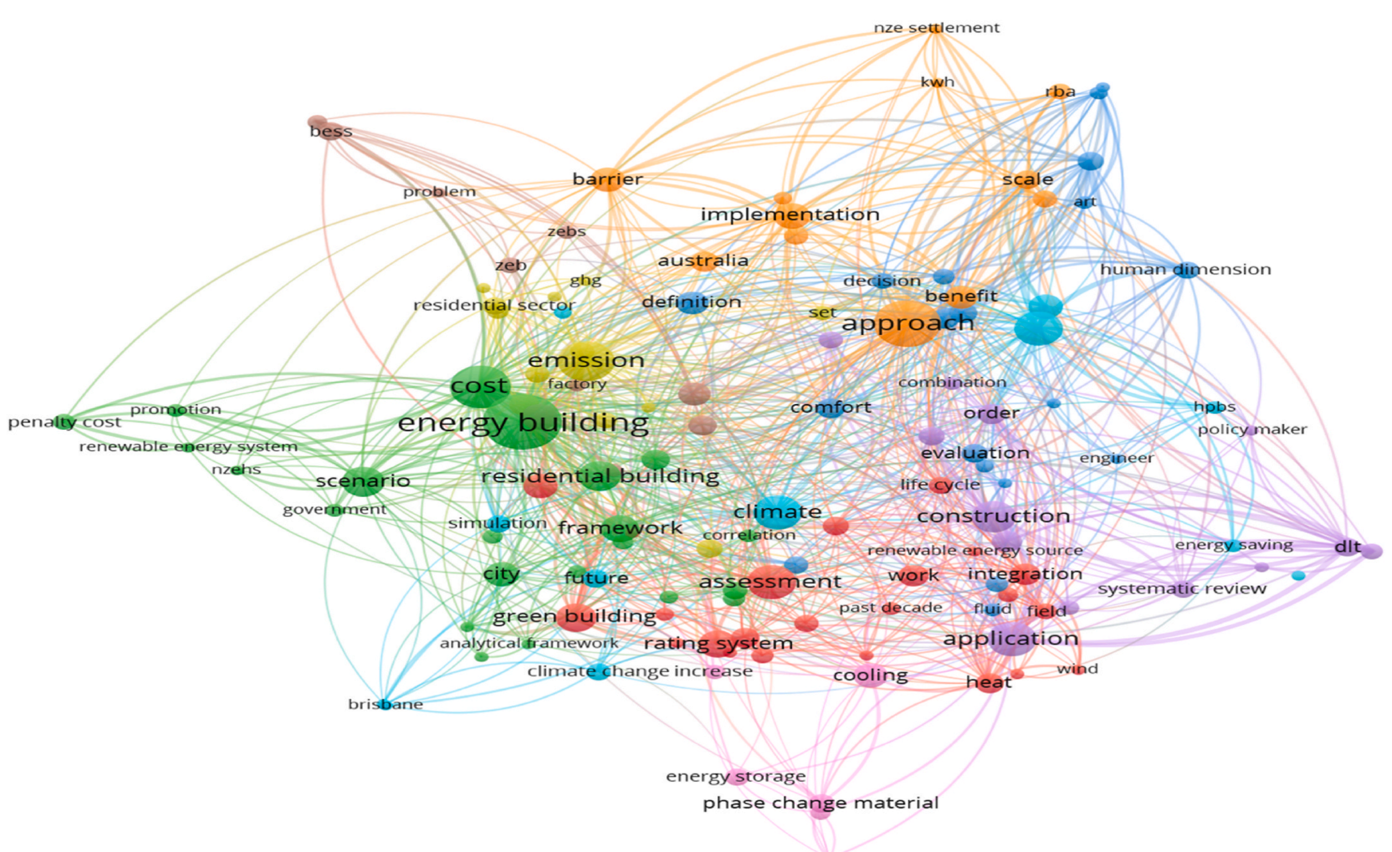


Fig. 2. Bibliometric Analysis Network Map – Keywords by co-occurrence.

and have not been extensively assessed in practice to become effective solutions.

3.2. Results from descriptive analyses

Fig. 3 presents the barriers cited throughout the 49 retrieved articles analysed and also highlights the most impactful barriers that were discovered in the content analysis. A total of 15 different categories of barriers were extracted from the content analysis. Issues revolving around the lack of knowledge and legislative factors surrounding this relatively new concept were the most discussed barriers to net zero energy achievement, accounting for 15/80 (18.8%) and 14/80 (17.5%) of examined hindrances, respectively. Aside from these outliers at the forefront of the topic, other barriers were also deemed to be significant. For example, a lack of government policies and climate issue were the next most reviewed barriers, accounting for 7/80 (8.8%) and 6/80 (7.5%), respectively, and this was closely followed by cost factors (5/80 or 6.3%). Therefore, in addition to government policy factors, lack of knowledge, climate issue and cost factors are the primary issued encountered by the industry when implementing NZEBs.

Despite several examples of successful NZEBs being prevalent in obtained research data, the number of barriers experienced in achieving NZEB success is substantial. Table 1 highlights Australian NZEB case studies in particular that were derived from the research articles as well as their respective location and construction compositions. Table 1 also provides detailed information related to the identified barriers of knowledge, climate and cost encountered in these NZEB case studies.

3.3. Comparability of barriers to other countries

The comparable country analysis provides the visualisation of the linkage between countries on this research topic. Countries of closest relatedness to Australian NZEB barriers are shown in Fig. 4 as the largest nodes with the heaviest weighted links. In completing this additional analysis, Australian NZEBs can be contrasted against the most comparable countries identified.

As highlighted in Fig. 4, the countries which have the highest link strength to Australia in this analysis are the UK and China. Australia is noted as being the highest weighted node in the network map and was included in the analysis to primarily highlight the total link strength between the nations. Despite this, other comparable countries, including Italy and the United States, are also considered important when determining comparability to Australian NZEB barriers - this was obtained by utilising the term ‘Australia’ in the article search. In doing this, the countries derived have a unique national origin, while subsequently linking to Australia specifically through citations and total link strength. Fig. 5 illustrates the frequency of detailed factors of the identified barriers of knowledge, climate and cost encountered in each comparable country.

3.3.1. Comparable countries – knowledge barriers

Lack of knowledge remained a re-occurring barrier within the comparable countries NZEB collected data. Though not specifically and formally identified as a ‘lack of knowledge,’ many of the frequent re-occurring themes found in the data collection had similar implications and have been interpreted within the umbrella category of ‘knowledge barriers’ as the principle of these have a similar impact on hindering NZEB adoption. Based on the papers reviewed, the terms which appeared frequently have similar connotations to lack of knowledge ($f =$ 21/80 or 26.3%) and include ‘lack of awareness’ ($f = 21/80$ or 26.3%), ‘limited government policy’ (16 $f = 16/80$ or 20.0%) and ‘limited NZEB understanding’ ($f = 22/80$ or 27.5%). Vats and Mathur (2022), for instance, corroborated that many NZEB scenarios assume that technologies are operable if they are available, leading to unrealistic expectations of energy performance due to various constraints, including high-energy efficient HVAC system settings systems (Eto et al., 2012). It is also notable that PV and battery systems could be challenging to align with the net-zero agenda due to its design scale requirements in buildings (Franco et al., 2021). The inclusion of innovative architectural designs has potential to enhance space allowance and utilisation in installation of PV arrays (Li et al., 2020).

A comparison between Figs. 3 and 5 indicated that lack of knowledge is more prevalent in Australia than it is in the comparable countries of China, the United Kingdom, Italy and the United States. The data

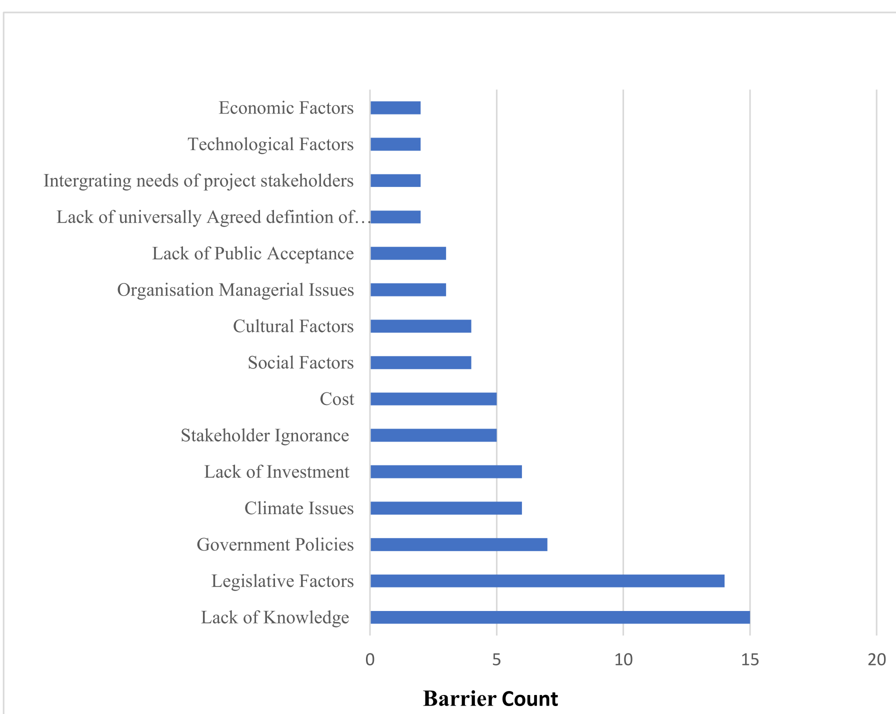


Fig. 3. Barriers to achieving NZEB.

Table 1
Australian NZEB Case Studies and barriers experienced.

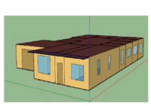
Case	Image of Case study	Location	Climate Zone	Building Type/ Size	Building Composition	Knowledge Barriers Experienced	Climate Barriers Experienced	Cost Barriers Experienced
Case 1 – Medium Density High Rise Building – Alawode, A & Rajagopalan, P 2022		Melbourne, Victoria	6 (Mild temperate)	26 Storey Multi-level residential apartment building consisting of 396 individual apartments.	Concrete core structure with glass curtain wall façade exterior.	Limited existing data to draw upon during construction. Overshading from other buildings was not considered and affected the efficiency.	Low temperatures (Climate zone 6). Limited sunlight access due to overshading. Unpredictable weather events.	Increased capital cost Limited government incentives for implementing NZEB strategies.
Case 2 – SJD Net Zero Energy Home (Z Range Homes)		Melbourne, Victoria	6 Mild temperate)	255 square metre single storey 4-bedroom residential dwelling.	Timber frame construction, with external brick cladding and colourbond sheeting roof composition.	Construction required by specialised trades and consultants. Limited buyer interest due to lack of knowledge of NZEB benefits.	Low temperatures (Climate zone 6). Surrounding areas prone to weather events and natural disasters such as bushfires.	Increased capital cost. Creation of net zero energy features while maintaining affordability for buyers.
Case 3 – Net Zero Energy Retrofit in Sub Tropical Australia Miller et al., 2018		Maleny, Queensland	2 (Warm, humid summer, mild winter)	530 square metre Single storey residential dwelling.	Timber frame construction, with external brick cladding and metal roof sheeting composition.	Construction required by specialised trades and consultants. Owners are required to be trained and understand NZEB systems in their own homes to maximise efficiency.	Area prone to storms and significant rainfall/floods. The dwelling was not constructed to maximise solar energy absorption. Warm climate requires increased HVAC capabilities.	Increased capital cost. Increased material transportation costs due to location. Increased planning costs due to retrofit rather than new build.
Case 4 – CSIRO Energy Research Centre Wells et al. (2018)		Newcastle, New South Wales	5 (Warm temperate)	Multi-level solar field and energy research facility, including energy storage unit.	Brick external/ aluminium cladding façade with integrated solar photovoltaic panels.	Limited knowledge of integrating future renewable energy methods. Lack of knowledge of occupant behaviour and energy consumption.	Warmer temperatures require an increase HVAC system capacity. Unpredictable weather events Incorporating minimisation of emissions into design while maintaining business productivity.	Expenditure for additional energy storage. Lack of government incentives. High initial capital costs.
Case 5 – Brisbane Zero Energy House (Kwan and Guan, 2015)		Brisbane, Queensland	2 (Warm, humid summer, mild winter)	272 square metre single-storey residential dwelling, selected as a sample by the Australian Building Codes Board.	brick external construction with a concrete ceiling, single glazed windows, insulated walls with gyprock plasterboard internal cladding.	Required to be designed by experts in the field. Lack of knowledge by occupants on utilising NZEB systems. Additional research required to determine the feasibility of the same design in other regions of Australia.	Area prone to storms and significant rainfall. Warm temperate requires higher capacity HVAC system usage.	Additional 8.9% capital outlay required compared to traditional construction. No government incentive. High price of Photovoltaic panels at the time of construction.
Case 6 – University of Wollongong Sustainable Buildings Research Centre (SBRC) Robati et al., 2019		Wollongong, New South Wales	5 (Warm temperate)	900 square metre multi-disciplinary research facility split between 2 buildings (North and South) with landscape	Brick and timber construction. Heavy use of recycled materials, including railway tracks, bridge timber and telephone poles.	Lack of knowledge surrounding the use of unique construction materials and NZEB systems requiring additional expert trades. Lack of	High humidity during warmer months. Varying building occupancy requiring additional solar PV absorption.	Increased capital cost Material sourcing issues and requirements to refurbish recycled materials. Lack of government

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Table 1 (*continued*)

Case	Image of Case study	Location	Climate Zone	Building Type/ Size	Building Composition	Knowledge Barriers Experienced	Climate Barriers Experienced	Cost Barriers Experienced
				corridor divider.		government policy implementation.		incentive. Difficulty obtaining funding.

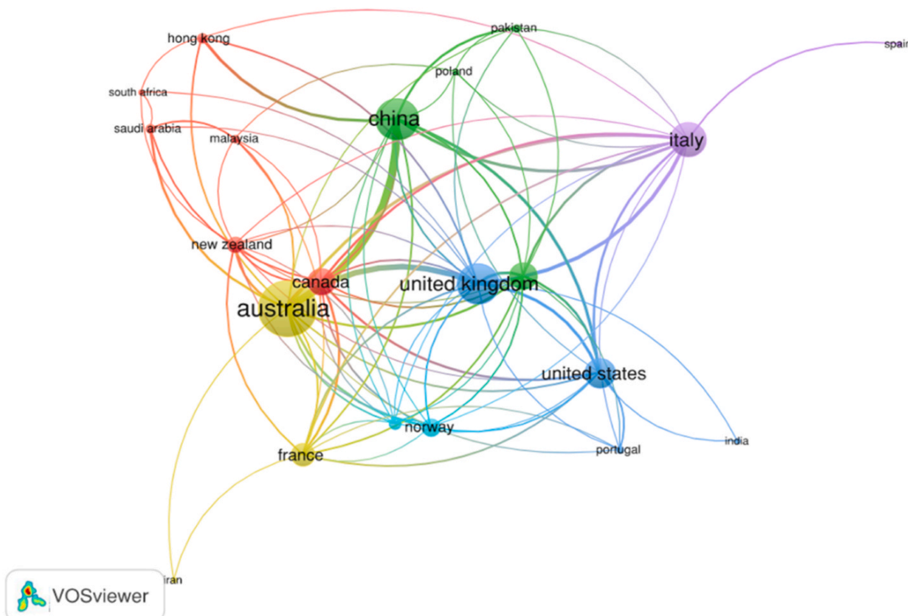

Fig. 4. Bibliometric network map – Australian barriers to NZEB – Total link strength between countries.

highlighted that overall, a lack of skilled labour with adequate knowledge was the most consistently re-occurring theme within the knowledge barrier umbrella, with the US experiencing the highest frequency of this barrier with seven references. One article by Godin et al. (2021) dissected this barrier in relation to some of the comparable countries. They explained that since NZEB differs from conventional buildings in that additional energy and resource-saving measures are utilised, the advanced knowledge in various aspects of NZEB construction required by project teams is often the reason not to undertake NZEB projects in the US.

The content analysis highlighted similar comparisons in terms of government incentives and policies. Fig. 5 highlighted that the US experiences the highest level of this barrier ($f = 26/80$ or 32.5%), followed by China ($f = 22/80$ or 27.5%) and the UK ($f = 19/80$ or 23.8%). The significant frequency of this barrier in the comparable countries' data could be attributed to a range of factors. It is understood that the level of government policy implementation presents a recurrent challenge across Australia (Lee et al., 2023; Falana et al., 2023). There is currently limited evidence of a high level of government policy support towards NZEB development in Australia, whereas in comparable countries, the amount of government support, policy and incentives is notably higher. Alawode and Rajagopalan (2022) noted that the European Union currently has the most advanced policies relating to NZEBs and consequently, is the most advanced continent in terms of net zero energy progress and technology. The content analysis data also indicated that the Chinese government policy implementation in support of NZEB was drastically higher than Australia's due to the low frequency of these themes shown in the data.

Although lack of knowledge had less representation in the comparable country analysis, a key similarity between Australia and the comparable countries that was evident throughout the conducting of the content analysis was the lack of understanding of NZEB methods and materials which prevented the adoption of NZEB builds. In a 2005 study of the United Kingdom building industry, Godin et al. (2021) identified that 78% of builders surveyed indicated that a lack of information regarding the cost of constructing an NZEB was a major barrier to purchasing the relevant materials. Alternative approaches to NZEB, for instance, using NZEB cluster suggests that NZEB cluster enables improvement in energy generation by 45%, grid interaction by 82% and cost-effectiveness by 55% (Saini et al., 2022). In addition, life-cycle based approaches will achieve a more resilient framework for NZEB implementation (Too et al., 2022). These findings further re-enforce that lack of knowledge surrounding NZEB should become a priority to progress towards increased Net Zero adoption and success.

3.3.2. *Comparable countries – climate barriers*

Climate issues based on the frequency in the reviewed papers include temperature variances ($f = 12/52$ or 23.1%), level of precipitation ($f = 13/52$ or 25.0%), level of available photovoltaic energy ($f = 13/52$ or 25.0%) and unprecedented weather events ($f = 14/52$ or 26.9%. Data collected on the comparable countries saw these terms appear in moderate frequency and appeared in similar frequencies to that of the Australian research. Fig. 5 indicated that despite climatic variations in all the comparable countries, there was consistency with the frequency of barriers highlighted in the derived articles. Level of precipitation data indicated that the frequency of this barrier across all nations is moderate, while PV availability was only considered a low-impact barrier for all countries while it can be considered a high-level barrier in US studies. The figures derived on climate issues reinforced that within this category, it was evident that some countries experience very specific climate

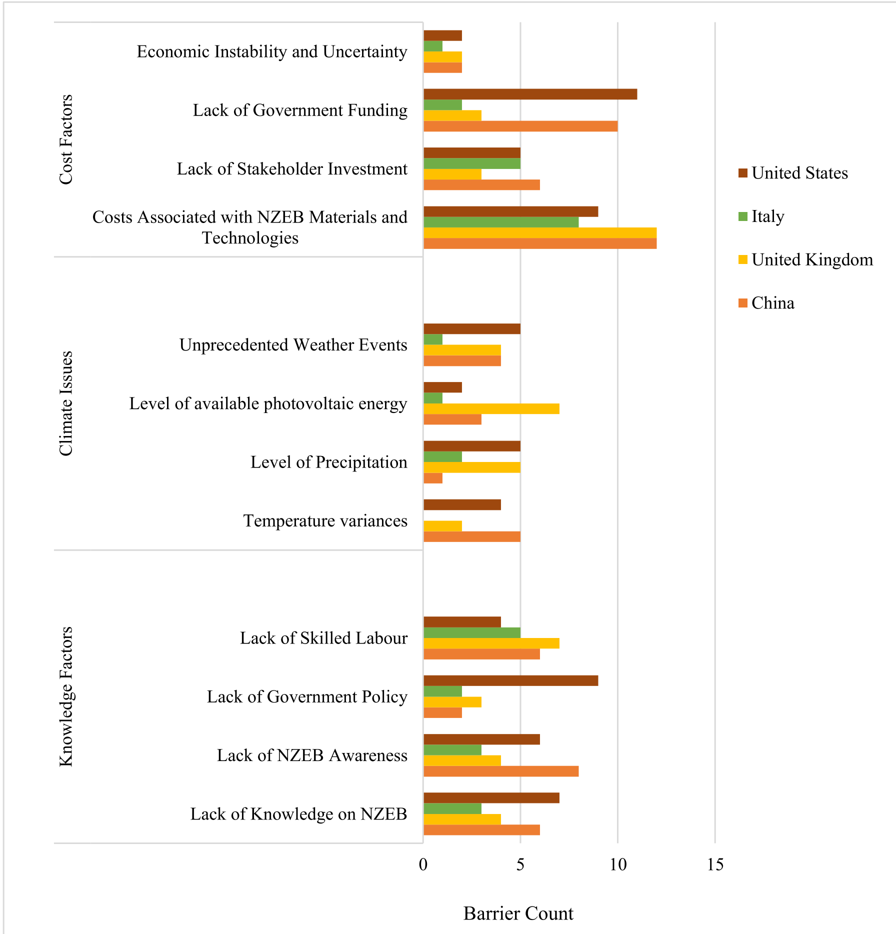

Fig. 5. Barriers to NZEB in comparable countries.

issues that are unique to that country. Research by Kingery (2022) indicated that China experienced a significantly low level of PV energy availability in Eastern areas due to the increased amounts of air pollution which prevents the system from functioning correctly. Additionally, the same study estimated that there are energy losses of 17%–35% in parts of eastern China, depending on how often PV panels are cleaned. The UK also saw the most significant and consistent frequency of climate barriers effect NZEB development (f = 19/52 or 36.5%). This may be due to the inclement weather patterns and low comparative temperatures, which engender the need for increased energy usage and decrease the ability of PV panels to operate at maximum capacity. Overall, climate barriers that hinder the success of NZEB in other countries remained consistent with the data collected in the Australian context. Evidently, these barriers are dependent on location and time of year but must be recognised as a hindrance to NZEB adoption due to its widespread impact across the world.

3.3.3. *Comparable countries – cost barriers*

NZEB barriers relating to cost have also been categorised in this data collection to determine comparability levels to Australian barriers. Frequently re-occurring themes that were found in the papers and categorised under cost barriers included: the costs associated with NZEB materials and technologies (41); the lack of stakeholder investment (19); the lack of government funding (27); economic instability and uncertainty (7) in the categorisation. Evidence from the data collected indicated that cost is the single most significant barrier to NZEB in countries around the world outside of Australia. Fig. 5 demonstrates the comparable country results in relation to cost barriers to NZEBs. Costs associated with NZEB materials and technologies were ranked the highest individual barrier among countries, with Italy having the highest frequency (f = 8/33 or 24.2%), and the UK followed closely with f = 12/59 or 20.3%. China and the US have the frequency of f = 12/65 or 18.5% and f = 9/69 or 13.0%, respectively. When compared to the same data in Fig. 3, the data on comparable countries shown in Fig. 5 emphasises the consistency of these barriers' impact on NZEB development worldwide.

These findings were supported throughout the content analysis, with multiple articles indicating the high-level impact of this barrier and how it inhibits NZEB adoption. A study across many developed countries by Dadzie et al. (2018) identified the high costs of an NZEB home as a significant barrier affecting widespread adoption. Furthermore, according to Karji et al. (2020), building industry professionals studied were deterred from changing their construction methods from conventional styles since obtaining NZEB training can be costly and requires taking teams off other projects to attend training sessions. Moreover, adopting new technologies and building methods can require significant changes to design and build processes, thus contributing to the possibility of risk and economic losses of projects and therefore decreasing the level of adoption (Hakkinen and Belloni, 2011). In fact, Darko et al. (2017) identified resistance to change due to cost implications within the industry as the most important barrier to widespread NZEB adoption in the United States.

In summary, the combination of the descriptive, content and bibliometric analyses provided key quantitative information regarding the literature that was retrieved from the PRISMA protocol. Evidently, the findings from both analyses indicated that certain barriers to achieving NZEBs in Australia are more prevalent than others. The argument that climate, cost and lack of knowledge were heavily focused research topics throughout the gathered literature and this key point was supported further by the results derived from the bibliometric analysis. Heavily weighted keywords from co-occurrence within the journal articles, such as cost, climate and lack of knowledge, further reinforced that these barriers are the most frequently occurring within the Australian residential construction sector.

4. Discussions

Emergent findings found that lack of knowledge of NZEBs in Australia was a barrier that has been most frequently encountered in the industry. It was clear, based on the literature reviewed, that there is a notable lack of research and knowledge about holistically accounting for embodied energy, particularly accounting for energy usage in manufacturing building materials (Wells et al., 2018). Similarly, Belussi et al. (2019) also supported the significance of this barrier by stating that the greatest challenge in the near future is the capability to bridge the existing knowledge gap between design and the completed building. This barrier appeared most regularly among the screened literature, while the results from the bibliometric analysis further supported its significance.

The results that were determined by the analyses are relatively comparable to previous literature regarding some aspects of this research topic. Evidently, the results obtained from the descriptive and bibliometric analysis were well supported by various literature, especially on certain barriers such as cost. Vats and Mathur (2022) stated that the economic feasibility of an NZEB is strictly related to the availability of financial support able to minimise the payback time. Not only was this backed up by the descriptive analysis, which recognised it as the third-most cited barrier, but the bibliometric analysis also emphasised its importance as it was one of the most heavily weighted co-occurring keywords throughout the literature.

It was also recognised that climate issues within Australia played a major role in the feasibility of an NZEB. Climate naturally impacts the most suitable technological choices for a ZEB (Belussi et al., 2019). The uniqueness of Australia's climate is the main reason behind this barrier's prominence. To ensure an NZEB is feasible in Australia, the local climate must be considered to adjust individual design strategies accordingly (Wells et al., 2018). Climate issues is a broad term within the research which has been utilised to incorporate an array of issues that derive from inclement weather or geographical location and the effects that these things have on the successful application of NZEBs within Australia.

It was evident that barriers such as climate and cost were linked within the publications as they were often deliberated in the same articles (Matana-Junior et al., 2023). The bibliometric findings also highlighted the point that NZEB is still a new concept within the topic of sustainable construction and that barriers that were found were often discovered using simulations and scenarios rather than real-world applications. The findings also indicated that Australia's climate, as well as cost issues, played a major role in the feasibility of achieving NZEB. Moreover, single-storey residential buildings were the most targeted application of net-zero and that this type of dwelling also encountered many of the barriers which were discussed in the literature.

The bibliometric analysis identified strong connections between the main barriers that were identified throughout the study. Across the literature, it was observed that lack of knowledge and cost were recurrent themes based on the link between weighted clusters within the VOSviewer map. The argument that a lack of knowledge affects the cost of achieving NZEBs in Australia is well supported. For example, Wells et al. (2018) stated that there is a notable lack of knowledge about holistically accounting for embodied energy, particularly accounting for the energy usage in manufacturing building materials and renewable energy technology apparatus. Without this knowledge, it is extremely difficult to achieve a net-zero building without implementing technology that has an increased cost. Additionally, the connection between cost and lack of knowledge as barriers to achieving net zero may also be experienced during building occupancy. In situations where the building's occupants lack the requisite knowledge of energy systems within their home, it is very likely that incorrect use of energy-efficiency technology will occur and consequently increase the costs associated with building energy consumption. Furthermore, this is likely to lead to a situation that makes achieving net zero energy in a building exceedingly difficult.

The network map derived from the analysis also showed an observable inter-relationship between the barriers of cost and climate, which poses the question of how these two barriers are interrelated in the NZEB topic: do climate issues affect the cost of NZEBs in Australia? The findings from the bibliometric analysis also confirmed observable links between climate and cost in the NZEB context. Alawode and Rajagopalan (2022) are in congruence and suggest that increased capital cost due to climate and weather has been identified as one of the significant barriers to achieving NZEBs, indicating the correlation between cost and climate.

Identifying future initiatives that achieve a successful NZEB is the least researched topic, as corroborated by Saini et al. (2022). There are suggested strategies to mitigate against individual barriers. However, most strategies are isolated and fail to recognise the dynamic interactions between barriers influencing the implementation of NZEB. One approach to establish the interrelationship between barriers to NZEB can be through a system dynamics model. Such an approach will provide a more in-depth understanding of the barriers to NZEB. Nevertheless, it can be inferred that where cost is a barrier, the implementation of government subsidies could incentivise clients to invest in NZEB. Governments are believed to be a crucial driver in creating policies to encourage net zero energy targets and providing the public with awareness of energy issues (Wells et al., 2018). Currently, there is limited support from the Australian government in terms of policies and subsidies. In other countries internationally (e.g. Europe and US), such incentives have been proven to be effective. The North American Union and European Union currently have the most advanced policies relating to NZEBs and consequently, are the most advanced continents in terms of net zero energy progress and technology (Alawode and Rajagopalan, 2022). There is also the argument that cost cannot be deemed a barrier to achieving NZEBs, since NZEB technologies have higher efficiencies, and in turn, benefit from lower average energy consumption. This leads to NZEBs having an overall lower operational expenditure than conventional buildings (Sabour et al., 2022).

From what is considered the most important barrier towards the achievement of NZEBs, a lack of knowledge is arguably the easiest barrier to solve. Education on net zero energy concepts is limited because it resides in an emergent state (Alawode and Rajagopalan, 2022). Therefore, the ability to teach and implement techniques, methods and materials is quite difficult, especially considering that new technology in this field is still in the trial phase. With other nations are leading the way with net zero energy technology developments, it is the perfect time for Australia to better understand and learn which concepts are feasible. Awareness should also be provided on the effective use of Australia's climatic conditions and the benefits that can be derived from implementing NZEBs.

The analysis results emphasised several key points. First, it was clear that a lack of knowledge and climate issues stood out as the barriers that most hinder the achievement of net zero residential buildings. Second, it was notable in analysing the results that issues associated with cost were pivotal in achieving net zero. These three barriers were clearly the most important among the research conducted in this study, although many other barriers were considered to have an influence on NZEB feasibility. The bibliometric analysis concluded that there were strong links between the three most evident barriers of lack of knowledge, climate and cost. It was found that climate and knowledge barriers subsequently increase the cost of net zero buildings. Through further discussion, it was found that there are future initiatives and solutions that can be implemented to combat all three of the major barriers. Each requires different methods of approach, but even the more uncontrollable factors such as climate can be used in a way that can promote the success of NZEBs.

5. Practical and Theoretical implications

The NZEB concept presents an ambitious and promising aspiration for the Australian built environment sector. The barriers and enablers contextualised for Australia can address crucial gaps. For instance, Australian committed to lower emissions by 28% from 2005 levels by 2030. The effectiveness in overcoming the barriers to NZEB are fundamental in realising the net-zero emission targets and in meeting the Paris Climate Change Agreement. Furthermore, it is predicted that building energy demand will increase by 32% by 2050 because of the challenges associated with the COVID-19 pandemic, wars, unanticipated natural disasters and population growth (Sabour et al., 2022). NZEB clusters have been proposed as a significant intervention in overcoming the identified barriers of climate change, knowledge and costs (Saini et al., 2022).

The plethora of approaches in advancing NZEB across the literature includes: (1) enhanced adoption of renewable energy (mostly solar) (Lee et al., 2023); (2) deployment of NZEB cluster – a block of interconnected network that share interdependency of energy and have a common off-grid system (Saini et al., 2022); and (3) integration of life cycle perspective into NZEB – considering life cycle cost, whole life cycle energy, exergetic life cycle and whole-life carbon emission (Too et al., 2022). Each of these approaches aim to accomplish national priorities such as energy security, urban sustainability and sustainable development (Vats and Mathur, 2022).

NZEB clusters enable improvement in energy generation by 45%, grid interaction by 82% and cost-effectiveness by 55% (Saini et al., 2022; Lee et al., 2023). Having NZEB clusters alone is not necessarily sufficient to enhance the penetration of NZEB concepts. There is a need to adopt a holistic life cycle perspective in appraising NZEB infrastructure. Four key variables from the life cycle approach will include: (1) life cycle costing; (2) whole life cycle energy use and consumption; (3) exegetic life cycle analyses; and (4) whole life cycle carbon emissions (Too et al., 2022). In addition, conducting life cycle sustainability assessment would provide a balancing act in merging triple-bottom line considerations in the NZEB context (Tokede et al., 2021). Such advanced and holistic appraisal techniques can help in providing a gap analysis and can then link NZEB aspirations with sustainable development goals (SDGs) and support the effectiveness of government initiatives and strategies. Maierhofer et al. (2022) also suggested a top-down planetary boundaries approach will be useful in achieving region-wide quantification of embodied emissions in the NZEB context.

Finally, the need for stakeholder involvement and community participation in driving NZEB penetration cannot be over-estimated. Falana et al. (2023) recognised that active partnerships among all stakeholders will be crucial in meeting NZEB targets. Nine major groups that have been suggested include construction professionals, property/facility users, policy makers, statutory bodies, manufacturer suppliers, community representatives, financiers researchers, Non-government organisations (NGOS), and media professionals. In Australia, indigenous land rights groups and first-nations people will also play a vital role and will inevitably become active partners in achieving NZEB aspirations.

As the concept of net zero energy within the Australian building industry continues to develop at a rapid rate, it is important to understand the key barriers that inhibit its successful implementation. This research paper not only builds upon previous literature on net zero energy but also contributes to filling the gap on this concept in an Australian context and responds to previous research gaps delineated (Zhang et al., 2020). Currently, the Australian building industry is at a pivotal point where targets set towards net zero energy form the basis of new standards. The statistic-based discussion that has been completed in this paper assists in the progression of understanding the net zero energy concept in Australia by re-enforcing information that is specific to Australia's unique building industry (Too et al., 2022). With the limited information on NZEBs in Australia, it was important to provide analysis on barriers, future solutions, and the overall concept of net zero energy as it emerges.

With the effective use of previous literature on this research topic, this paper has allowed for both the primary aim and key research objectives to be met. Progress within the primary objective meant that the paper should highlight the identification and discussion of barriers that specifically affect achieving NZEBs in Australia (Sabour et al., 2023). Emerging from the systematic appraisal of the literature, the barriers affecting NZEBs in Australia were critically examined and compared to those of other countries. In terms of the other key objectives (which included the identification of potential future solutions which could aid the Australian building industry in the quest to successfully achieve net zero), the paper also provides conclusive evidence of initiatives and solutions to the barriers which have been successful. The information that has been gathered has an emphasis on solutions that have been implemented in both other countries and Australian simulations to provide the most useful data for future research. In a similar way to how publications based on this research topic have allowed for the advancement of this identification of key barriers to NZEBs, it is hoped that this paper can assist future publicists in the ever-growing area of net zero energy in Australia.

6. Conclusions and recommendations

NZEBs are effective solutions for achieving net zero emissions by 2050 in Australia. Consequently, NZEBs are currently gathering significant interest within the Australian building industry. This present paper uncovered some key findings on net zero energy advantages through the systematic review of the literature but also provided the primary research objective of identifying the key barriers which hinder the achievement of NZEBs in Australia. This was completed by following a methodological PRISMA protocol, which effectively screened literature on the research topic. During this first stage of research, it became clear that lack of knowledge, climate and cost remained the most significant barriers to net zero, but it was still unclear whether this was universally agreed upon and why these barriers stand out. With further examination and analysis provided through a range of quantitative analysis techniques, other research aims and objectives were met by determining how these barriers impact an NZEB and the interrelatedness between barriers. Furthermore, an understanding of the concept of NZEBs in Australia and the progress towards achieving a net zero future was also assessed. In the final stage of research, with discussion focused primarily on these main objectives, potential future initiatives and solutions to the barriers that most hinder net zero achievements were identified. These potential solutions seem like enormous steps in the right direction of NZEB implementation, especially considering that they all obtain a similar ideology. That is, through the collective efforts of stakeholders and the pooling of resources, greater energy efficiency and barrier mitigation can be achieved. In summary, capability building and bridging the existing knowledge gap between design and the completed building is one of the effective solutions addressing the identified knowledge gaps. Financial support can be used as a vehicle to improve the economic feasibility of an NZEB and minimise the payback time. To ensure an NZEB is feasible in Australia, the local climate must be considered to adjust individual design strategies accordingly. Governments and policy play crucial roles in driving net zero energy development and providing the public with awareness of energy issues. Awareness should also be provided on the effective use of Australia's climatic conditions and the benefits that can be derived from implementing NZEBs. These measures will increase the successful implementation and penetration of NZEB, with enhanced public awareness, enlightened behavioural shifts, innovative business models and contextual capacity building.

Contextualised barriers to NZEB are crucial for achieving NZEB goals in regional settings, providing clear gaps that can be addressed to enhance the implementation of NZEB in Australia. The impact of various barriers differs with each individual project, but it can be concluded that common themes regarding the barriers hindering the achievement of net zero are evident, including.

- There is a notable lack of knowledge surrounding the entirety of net zero energy. A lack of knowledge surrounding net zero energy concepts is considered the most important barrier which inhibits the implementation of NZEBs.
- Among current literature, climate issues and cost issues are also considered to be significant barriers encountered by the industry to achieving a successful NZEB in Australia.
- There are undoubtedly strong links between the key barriers found in the research indicating that the presence of one prominent barrier encourages the existence of another, particularly for the barriers of lack of knowledge, cost and climate.

This study has potential limitations, which particularly relate to the sample size and data selection that was gathered during the systematic literature review undertaken via Google Scholar and Science Direct databases. Although these are enormous databases allow for the retrieval of many publications based on NZEBs in Australia, it can be argued that other databases, including Web of Science or Scopus, could have potentially contained several other useful articles on this research topic. This also leads to the second limitation of the study, which is the data sample size. The total number of publications gathered for screening was 153 articles. This still allowed for conclusive evidence to be gathered on the barriers which inhibit achieving NZEBs, although with a larger sample size, the statistical data generated through the bibliometric analysis and descriptive analysis could have been more accurate. In future research, it could be useful for other publicists to utilise an additional publication database or aim to gather a larger number of articles which will ultimately allow the data to be even more accurate. Furthermore, this will ensure the bibliometric analysis is able to highlight the weightings of keywords that are found and generate more connections between barriers and compare with more other countries. This research identified the primary barriers encountered by the industry, hindering the achievement of NZEBs in Australia, including a lack of knowledge, climate issues, and cost issues. With advancing technology in this construction field, it is imperative that future studies and initiatives counteract these impacts to realise a better implementation of NZEB in the Australian context.

CRediT authorship contribution statement

Darcy Brown: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Olubukola Tokede:** Writing – original draft, Supervision, Methodology. **Hong Xian Li:** Writing – original draft, Validation, Data curation. **David Edwards:** Writing – review & editing, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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