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Bibliometric review of smart and sustainable student residence models in developing economies

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Abstract The future of student housing in developing countries is increasingly being defined by a transition towards smart and sustainable student accommodation, a shift which is relevant to the higher education institutional student residences of South Africa. The aim of this paper is to explore global research trends in relation to new models of student accommodation, with particular emphasis on the integration of renewable energy, smart housing technology, and sustainable building methods. Using the Elsevier Scopus as the primary database, bibliometric analysis and network visualisation (VOS viewer) were applied to 38 retrieved publications between 2014 and 2025. The search combined the following terms, ("student residence" OR "student housing" OR "university accommodation" OR "smart housing" OR "sustainable housing") AND ("IoT in housing" OR "smart campus" OR "renewable" AND "energy"). The findings identify six primary thematic clusters: (1) Low-Carbon and Energy-Efficient Building Systems, (2) Economics and Policy of Sustainable Urban Housing, (3) Design Innovation and Renewable Integration, (4) Zero-Energy Housing and Educational Integration, (5) Climate-Responsive Housing and Emissions Mitigation, and (6) Retrofitting and Material Strategies for Low-Energy Housing. The main challenges that are indicated are policy misalignment, budgetary constraints, and technological adoption barriers, which limit the attainment of net-zero and climate-resilient student accommodation. The study limitations are the exclusion of non-English literature and a single bibliographic database being used. The paper contributes to literature by providing a comprehensive, evidence-based synthesis of global research trends and making strategic policy recommendations for policymakers, academic scholars, and industry stakeholders that prioritize bringing holistic energy, design, and policy innovations to improve the sustainability of student housing.

Index Terms : bibliometric analysis, innovative models, renewable energy, smart student housing, sustainable construction

I. Introduction

The transformation of student accommodation is becoming increasingly important as universities strive to integrate smart and sustainable models that promote energy efficiency, environmental sustainability, and student well-being [1]. Universities worldwide are revisiting their infrastructure to meet the double imperatives of sustainability and smart technology integration [2], [3]. In South Africa, there is a growing demand for sustainable student accommodation due to rapid urbanization, rising energy costs, and the urgency of mitigating climate change. In South Africa, where security issues, fast-tracking urbanization, and resource constraints intersect, innovative residence prototypes are leading the way in research and practice [4]–[6]. The purpose of such innovative housing models serves a dual purpose to mitigate environmental effects and improve student quality life through the implementation of smart technologies, sustainable design principles, and integrative safety systems [7], [8].

This bibliometric review sweeps across emerging trends of smart and sustainable student residences and reveals the issues of integration of renewable energy, eco-design, retrofitting, zero-energy dwellings, and climate-responsive design. By examining these critical areas, this study provides an overview of the evolution of student residences and how it connects with South Africa's broader sustainability agendas. This review serves as a foundational study on which existing frameworks can use with regards to smart campus development, green architectural practices for campuses, and safety measures for students, all within the context of the issues and prospects for higher education housing in South Africa.

II. Literature review

The concept of the "smart campus" is derived from that of the smart city. Malatji [9] argues that although most of the international frameworks have been borrowed from European models, African universities require strategies that consider local infrastructural and socio-economic realities. The localization involves leveraging locally sourced technologies, workforces, and governance structures that are adapted to the local situation. To supplement this idea, Martins et al. [10] propose an applicationoriented architecture that streamlines digitization while maximizing sustainability in campus operations. Their architecture not only guarantees energy efficiency and optimization of resources but also aligns legacy systems with modern IoT-based solutions, a move that is imperative towards making residences that are not only ecologically sustainable but also technologically advanced. Jernsand [11] also provides a compelling framework for discussing smart and sustainable student accommodation by illustrating the concept of student living labs as innovative environments for co-creation and hands-on engagement. These labs serve as a model for transforming traditional university housing into spaces that prioritize sustainability and collaboration. Romdhane et al. [12] highlights critical aspects of sustainable living within the context of university students in the United Arab Emirates. The study demonstrates the degree of sustainable living knowledge significantly influences the intentions of students to engage in sustainable practices. As smart and sustainable student accommodations transition from traditional university housing, understanding these dynamics is essential. The study's findings stress that enhancing sustainability education can lead to increased environmentally conscious behaviors, indicating that effective communication and educational interventions can play a vital role in shaping students' housing preferences. Consequently, integrating sustainable practices into the design and management of student accommodations is not only beneficial for the individuals residing there but also fosters broader community sustainability efforts, making this research a foundational pillar in discussing the transformation of traditional housing models in universities.

According to the International Finance Corporation's 2020 report on the state of student housing in South Africa, the country's student housing market is the most mature among its African counterparts and is comparable to those in developed countries, such as the United Kingdom. The student housing typology in South Africa is diverse, ranging from high-rise buildings to state-of-the-art, purpose-built student accommodations. Notable differences exist between public student residences, which are provided by educational institutions, and private housing developed by independent developers [5]. The report further emphasizes the need for security to be integrated into student housing, along with a strong demand for quality and affordable accommodations within South Africa's student housing sector. In South Africa, the architecture of student residences must be a response to a special set of problems, which includes security concerns, budget limitations, and the necessity for inclusiveness. Mofokeng et al. [6] point out that most campuses, especially those in urban areas, experience ongoing problems like theft, violence, and poor security measures.

These challenges, along with socio-economic disparities, demand housing forms that blend smart technology with sustainable design so that security and efficiency do not have to be trade-offs. Besides, the incorporation of sustainable development goals (SDGs) into higher learning institutions renders campuses representative samples of wider society changes [13]. Mawonde and Togo [14] illustrate through a case study at the University of South Africa that even institutions with budgetary limitations can align with SDG 4 (quality education) alongside other sustainability objectives, showing the significance of residential frameworks that support environmental along with human capital growth.

A key component of successful smart residential models is the adept integration of technology that delivers operational efficiencies while encouraging student engagement. Al-Dmour [15] emphasizes the central role of student experience in enhancing the corporate reputation of a university after green-smart initiatives have been implemented. In residence halls, smart technologies from IoT sensors that monitor energy usage to mobile apps that provide real-time security alerts allow students to play an active part in regulating and preserving their living environment [16]. Data-informed decision-making and composite systems enable campus managers to optimize resource distribution, limit wastage, and provide security measures in an effective and timely manner. This technology-enabled platform not only contributes to the operational agenda of the institution but also assists in creating a living-learning community in which the students play their part as co-producers of campus life [8], [17]–[19]. Abo-Khalil [20] highlights the potential for integration of technical, social, and environmental sciences to facilitate the development of more strong and scalable residential models in South Africa. Smart campus initiatives need to be contextualized with the socio-economic reality of the region as part of investment in technological innovation and human-centric design. As several research shows that student engagement is promoted through active involvement, which enhances security, general satisfaction, and positively influences the institution's image.

Figure 1 shows a visual snapshot of frequently used key words in literature over time. Key words such as "energy," "engineering," "sustainable," "technology" and "housing" dominate the word cloud.

Despite the apparent benefits that come with smart and sustainable housing systems, there remain considerable challenges. Financial limitations and the cost of upgrading existing infrastructure are considerable challenges, particularly for organizations that work on tight budgets. Mofokeng et al. [6]; Mawonde and Togo [14] note that even where strong policy frameworks exist, implementation is impeded by funding problems and opposition to changing dominant systems. The literature converges on the assumption that smart and sustainable housing complexes are a comprehensive change embracing facets of security, efficiency, and community involvement rather than a mere technological advancement. In South African universities, such transformations are imperative in responding to both local and international sustainability agendas. Through embracing revamped smart campus models, IoT and analytics convergence, and student-focused and inclusive governance, universities can create living environments that are safe, sustainable, and responsive to increasing needs of higher education. Future research can thus focus on longitudinal assessment of such combined models and scalable model construction with the ability to address a broad

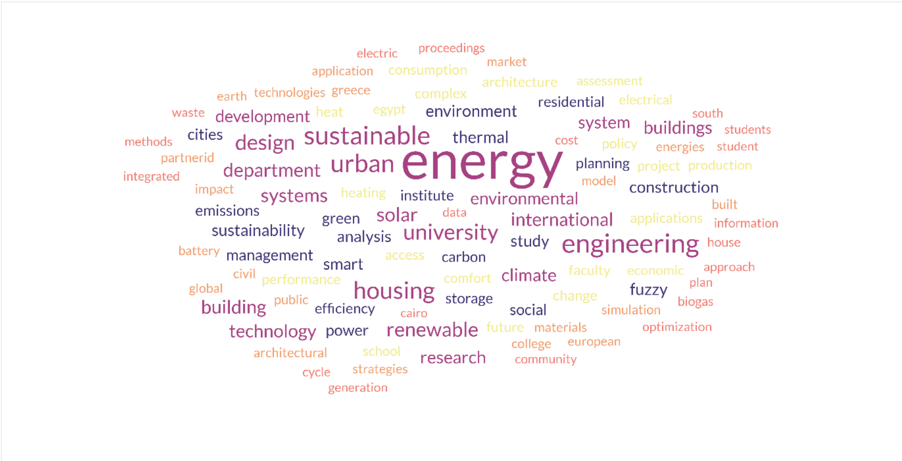

Figure 1: Word cloud of Frequently used keywords. Source: Researcher's construct (Edwordle Software), 2025

spectrum of institutional settings.

III. Methodology

The primary aim of the study is to systematically map global research trends on smart and sustainable student housing between 2014 and 2025, and it adopts a quantitative bibliometric research design. Bibliometric analysis is a well-established method for assessing the intellectual structure and evolution of scientific fields [21], [22]. The selection of the 2014–2025 period is justified by a noticeable acceleration of sustainability-focused research following the launch of the UN Sustainable Development Goals (SDGs) in 2015 as well as emerging attention to smart housing innovations in recent years relating to SDG [13], [23], [24]. The Scopus database was selected as the primary data source due to its broad coverage of peer-reviewed literature and robust search functionalities [25], [26]. The search query was developed to capture publications related to student housing and smart/sustainable energy integration: TITLE-ABS-KEY ("student residence" OR "student housing" OR "university accommodation" OR "smart housing" OR "sustainable housing") AND TITLE-ABS-KEY ("IoT in housing" OR "smart campus" OR "renewable" AND "energy"). The initial search, conducted in March 2025, retrieved 40 documents. The following exclusion criteria were applied to refine the dataset with subject limitation (Engineering, Environmental Science, Social Sciences and Materials Science): LIMIT-TO (SUBJAREA, "ENGI") OR LIMIT-TO (SUBJAREA, "ENVI") OR LIMIT-TO (SUBJAREA, "SOCI") OR LIMIT-TO (SUBJAREA, "MATE"). Further language limitation to exclude (LANGUAGE, "Croatian"). After applying these filters, the final dataset included 38 documents.

VOS viewer (version 1.6.19) a widely used software for constructing and visualizing bibliometric networks was used for the analysis [27]. VOS viewer is particularly suited for mapping co-occurrence of keywords, co-authorship networks, and citation patterns, providing both cluster visualizations and density views. This software has been frequently adopted in construction literature reviews [26], [28]. The bibliometric analysis, therefore, covered the following analytical outputs.

1) **Publication per annum**: Trends in research output across the period 2014–2025 to identify growth patterns.
2) **Publication by Country**: Geographical distribution of research activity to highlight leading nations in this domain.
3) **Document Type**: Classification of publications (e.g., journal articles, conference papers) to understand research dissemination channels.
4) **Publication by source Journals and Most Cited Authors**: Identification of influential journals and key researchers shaping the field.
5) **Cluster Analysis**: Using keyword co-occurrence mapping, six thematic clusters were identified: Energy-Efficient and Low-Carbon Housing Systems, Economics and Policy of Sustainable Urban Housing, Design Innovation and Renewable Integration in Housing, Zero-Energy Housing and Educational Integration, Climate-Responsive Housing and Emissions Mitigation, and Retrofitting and Material Strategies for Low-Energy Housing.
6) **Research Focus by Year**: Manual coding of keywords and thematic emphases per year to track how the field has evolved over time.

The bibliometric approach provides objectivity using quantifiable publication metrics; however, it is limited by the scope and extensiveness of the underlying database. Scopus is noteworthy as highly comprehensive coverage-wise, especially in the case of engineering, environmental, and social sciences publications, and is thus aptly suited for such a cross-disciplinary review [29].

IV. Results and discussions

For this section, the key findings of the bibliometric analysis are presented, giving insights into global research patterns in the field of smart and sustainable student housing between 2014 and 2025. The results are organized to show publication trends by year, country, document type, and the most highly cited journals and authors. In addition, the keyword co-occurrence analysis reveals six large thematic clusters reflecting the intellectual structure of the research field. The results are placed in the context of evolving research priorities, technological advancement, as well as policy development, and more particularly in relation to their focus on the implications to sustainable student housing in South Africa and other developing countries.

IV. A. Publication per year and document type

The results show the trend of publication between 2014 and 2025 to be an overall upward with fluctuations. After a modest start in 2014 and 2015 (1 publication each year), there is a noticeable increase from 2016, peaking in 2023 at 7 publications. This shows increasing academic and policy interest, likely due to growing awareness of sustainable development issues and technological innovation affecting student accommodation [4], [11], [15], [16], [23], [30]. Early years (2014-2015), in this period the output of publications might be suggesting that sustainability in student accommodation was a new research focus at the time with the establishment of the Sustainable Development Goals [31]. Then from 2016-2019, there is an increasing trend which corresponds to worldwide trends focusing on sustainable development goals (SDGs), perhaps instigated by projects such as the 2015 UN Sustainable Development Goals. While in 2020 there is a nadir of research production, this is likely because of interruptions such as the COVID-19 pandemic, which has probably had an impact on research productivity also as well as changing immediate research priorities [32]. The high point of most publications was in the year 2023 with 7 publications showing higher urgency or innovations in the topic, demonstrating policy changes and rollout of new technology/materials to housing [33]–[35]. Again, during 2024-2025 there is a small decrease from 6 to 3 papers which may be caused by saturation in some research field or shifting scholarly interest. In developing countries like South Africa, the trend demonstrates greater scholarly concern in sustainable housing in line with broader concerns over urbanization, affordable housing, and conservation of the environment. Figure 2 shows the graphical representation of annual publications (2014-2025).

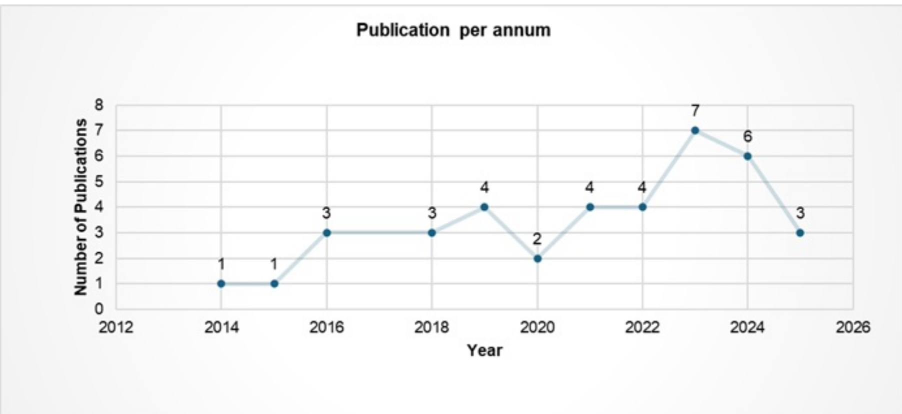

Figure 2: Publication per annum. Source: Authors' construct, 2025

As indicated 38 documents were reviewed in total comprising 11 journal articles, 18 conference papers, 1 book, and 8 book chapters. This shows that 45% of the total publications accessed are conference papers showing a dynamic field where researchers prefer quick dissemination and feedback over completely published journal articles. This means that scholars are actively exploring concepts and responding to current issues which is important for areas like sustainable housing where policies and technologies are in a state of flux. Journal articles contribute to a significant proportion with 27.5% of all publications accessed, meaning that the field is maturing with more rigorously peer-reviewed and widely citable output. This demonstrates an educational validity and a body of work in the field of researching sustainable and intelligent housing.

IV. B. Publication by country

These results highlight the country-by-country distribution of publications on Smart and Sustainable student Housing, showcasing the number of documents and citations by country. Data was analysed using a VOS viewer with a minimum threshold of two publications per country, reveal 10 countries (depicted in the world map Figure 3).

Table 1 shows the top 5 countries with most publications and impact in this research domain and is discussed in this section.

The USA is high on both impact and productivity with 6 published documents and 72 citations. Although not the highest in total document numbers by itself, its citation number (72) shows high influence and applicability [8], [36]. This indicates well-established research infrastructure, funding, and a big scholarly community with a focus on sustainability. Greece is high on high impact per publication (approximately 8.7 cites per document) [2], [37]. This shows concentrated, high-quality research that is highly applicable to the field, though with a smaller volume. Potential drivers: specific areas of interest like energy-efficient building and European Union directives on sustainability. The high citation rate of Japan (approximately 9.5 cites/doc) suggests intense concentrated research. Typical of world-class innovation probably in technology/materials for sustainable housing [38], [39]. A moderate productivity-to-citation ratio with approximate 4 citations per article reflect growing but stable influence, as does Canada's emphasis on sustainable city planning research with 3 documents and 12 citations. Australia works cooperatively but with less influence per article (approximately 1.5 cites/article). This is because it is recent work, expertise in narrow topic areas, or activity that is still gaining world renown [40]. The USA is at the forefront of breadth and depth. Japan and Greece are extremely high impact per size and thus are perfect examples of efficiency and scope in this research domain. Canada and Australia have solid contributions but could be opportunities for wider global involvement or exposure.

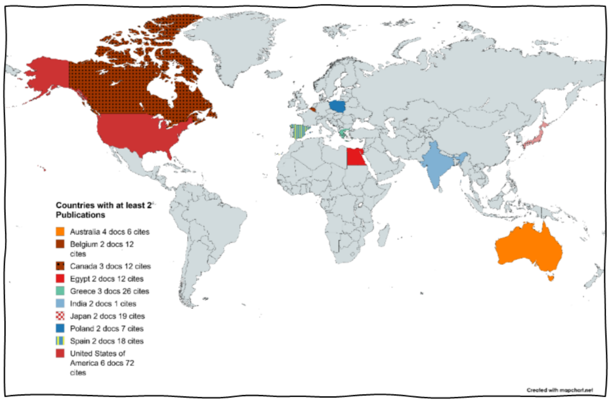

Figure 3: Publication by country

Table 1: Publications by country (Top 5 Countries at least 2 documents). Source: Authors' construct, 2025

Country	Number of publications	Citations
United States of America	6	72
Australia	4	6
Greece	3	26
Canada	3	12
Japan	2	19

The absence of developing countries from the publication's country-by-country focus is a call to action to South African research in this research domain. For other developing countries as well as for South Africa, these trends propose that while the need is to be highly productive, strategic focusing on global goals such as energy efficiency and low-cost house innovations has the potential for high impact even when resources are inadequate.

IV. C. Publication by source

Subsequently, an analysis of the publications by source title was conducted. This analysis aimed to provide insights into the most influential journal sources shaping the research domain in Smart and Sustainable housing models. Of 38 end-extracted documents, four source journals passed the benchmark of having a minimum of 2 published documents. Sustainability (Switzerland) is one of the most highly cited journals in the list (20 cites) and with high impact factor. With high H-index and SJR, it signifies long-term relevance and global availability. Tis journal is best described as being most suitable for policy and interdisciplinary sustainability research. For Lecture Notes in Civil Engineering journal, it is primarily technical and engineering-focused publication. Despite publication output, very low citation count suggests weak influence in shaping the research agenda in this field. It may be an early outlet rather than a high-impact one. IOP Conference Series: Earth and Environmental Science is the highest volume publisher but relatively low citation influence (1.5 per article) from the results. This is an indicator of conference-level visibility, good for timely ideas but less so for citations or long-term influence. It may be appropriate for initial studies or case work. Surprisingly enough, the highest impact factor belongs to the journal Environmental Science and Engineering, and this would typically indicate high-quality research. This lack of citation from your database, however, suggests either extremely recent publications or a break between the general reader base for the journal and that specific topic. Could be a strategic journal for high-visibility technical contributions, although citation return may be delayed.

The results are shown in Table 2, indicating the Impact factor, number of citations per publication and its Scimago ranking in the sustainability research domain.

Table 2: Publications by Source title (At least 2 publications)

Source title	Number of published works (2014-2025)	Cites	H-Index	Scimago journal rank	Impact factor
Sustainability (Switzerland)	2	20	207	0.688	3.3
Lecture notes in civil engineering	2	1	28	0.157	0.42
IOP conference series: Earth and environmental science	4	6	58	0.214	0.55
Environmental science and engineering	2	0	27	0.126	6.75

IV. D. Most cited publications (By authors)

Further analysis examined the most cited authors and their publications over the period with a benchmark criteria of at least 10 times as adopted from Aghimien et al. [41], this threshold indicates it has garnered significant visibility in the field. Analysing these high-impact papers helps clarify which researchers are drawing the most academic attention, and where influential studies are coming from. Table 3 shows the set of most cited publications revealing key thematic priorities and focus diversity in the field of smart and sustainable housing models.

Table 3: Most cited publications by Authors

Authors	Year	Document Title	Cites	Title Focus	Research Theme
Perrucci Vazquez and Aktas [36]	2016	Sustainable Temporary Housing: Global Trends and Outlook	31	Global trends in sustainable temporary housing	Global policy & emergency housing-Focuses on temporary solutions, likely linked to displacement, disasters, or migration. Sets foundational knowledge.
Birge and Berger [42]	2019	Transitioning to low-carbon suburbs in hot-arid regions: A case-study of Emirati villas in Abu Dhabi	27	Low-carbon suburban housing in Abu Dhabi	Urban energy transitions -Addresses sustainability in hot-arid climates, relevant to Gulf and African regions.
Kubota, Rijal and Takaguchi [39]	2018	Sustainable houses and living in the hot-humid climates of Asia	19	Sustainable housing in hot-humid Asia	Climate-adapted housing -Context-specific design in tropical Asia. Emphasizes passive cooling and environmental responsiveness.
Botsaris et al. [37]	2021	Developing a business case for a renewable energy community in a public housing settlement in Greece the case of a student housing and its challenges, prospects and barriers	18	Renewable energy in Greek student housing	Energy communities & student housing-Applies renewable systems in a real-world Greek case; barriers and stakeholder engagement explored.
Appleyard et al. [43]	2018	Pathways toward zero-carbon campus commuting: Innovative approaches in measuring, understanding, and reducing greenhouse gas emissions	13	Zero-carbon university commuting	Transport emissions -Expands “sustainable housing” to include campus lifestyle and commuting, suggesting integrated planning.
Fahmy, Elwy and Mahmoud [44]	2022	Back from parcel planning to future heritage of urban courtyard: The 5th generation of Egyptian cities as a sustainable design manifesto for neo-arid neighbourhoods	12	Urban design in neo-arid Egyptian cities	Sustainable urban morphology- Innovative city planning for dry environments; heritage and design combined.
Elnagar, Munde and Lemort [3]	2021	Energy efficiency measures applied to heritage retrofit buildings: A simulated student housing case study in vienna	12	Energy retrofits in heritage student housing	Energy efficiency in existing structures-Deals with upgrading heritage buildings, highlighting retrofit feasibility for sustainability.

Studies from Asia [39] and the Middle East [42] focus on climate-resilient housing, showing that geographic and environmental contexts drive design decisions. The most cited work [36] shows high interest in transitional and mobile housing, which is relevant for disaster relief, refugee crises, and low-income populations. Studies from Botsaris et al. [2], (Greece); Elnagar and Munde (Vienna) reflect a growing emphasis on sustainable retrofits and renewable integration in student housing, a key niche within broader sustainable architecture. Urban layout [44] and transportation studies [43] suggest a systems-level view; housing is tied to mobility and city structure, not just building performance. Overall, findings reveal high-impact publications emphasize context-specific, climate-adapted, and systems-level approaches to sustainability. Student housing is a recurring focus, especially in retrofit and renewable contexts. There’s growing integration of energy, mobility, and urban form in sustainable housing discourse over the timeframe.

V. Cluster Analysis and Discussion

In concept analysis the use of keywords is very critical, particularly with sustainable construction studies. A network visualization map was developed from the data retrieved on Scopus with the VOS viewer software for the cluster thematic analysis. In the diagram keyword proximity and similarity indicate the degree of co-occurrence and for this analysis a network was generated from 380 keywords, with 59 keywords meeting the threshold of at least two co-occurrences. However, for the final visualisation only 57 keywords had strong link. Table 4 reveal the various keywords in each cluster on the network visualization map (see Figure 4).

Table 4: List of clusters and co-occurring keywords

Cluster label	Keywords
Cluster 1 (Red)	carbon dioxide, carbon sequestration, cooling systems, energy, energy conservation, energy efficiency, energy management systems, energy storage, fossil fuels, Iithium-ion batteries, solar energy, sustainable housing
Cluster 2 (Green)	alternative energy, construction industry, costs, energy management, energy transfer, investments, real estate market, renewable energy sources, social housing, sustainable construction, urban development, use of renewable energies
Cluster 3 (Blue)	Bipv, building integrated photovolta, compressed earth block, court-yarded cluster, ecodesign, energy policy, solar power generation, solar radiation, sustainable development, thermal comfort
Cluster 4 (Yellow)	architectural design, developing countries, engineering education, renewable energy generation, renewable energy resources, renewable energy systems, student housing, students, zero energy buildings
Cluster 5 (Purple)	Carbon, climate change, energy utilization, gas emissions, greenhouse gases, heating, housing, planning, surveys
Cluster 6 (Turquoise)	heating demand, historical retrofit, low energy buildings, renewable energies, sustainable materials

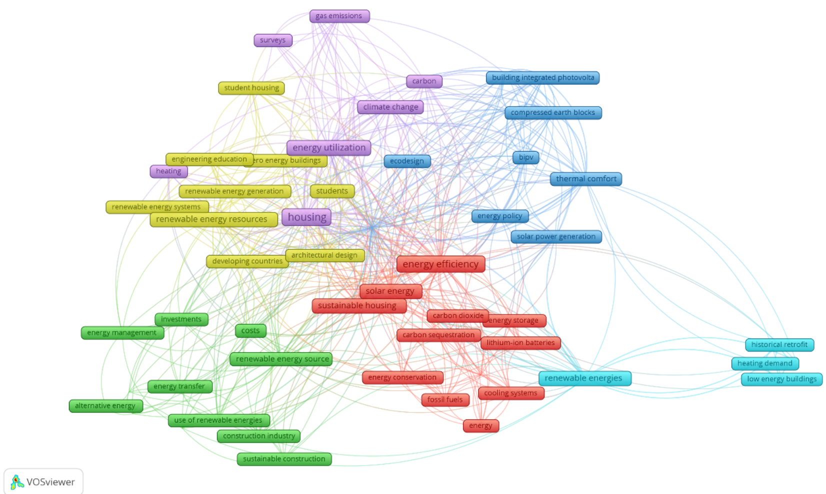

Figure 4: A Network visualization of Co-occurring Keywords

Cluster 1: Energy-efficient and low-carbon housing systems

This theme captures the essence of how energy technologies (e.g., solar, batteries, energy management systems) combines with carbon reduction strategies (carbon sequestration, lower fossil fuel reliance), which are essential to smart and sustainable student housing. The theme highlights studies conducted on the need of energy systems and carbon management in the development of sustainable student housing models [2], [30]. In South Africa, where energy insecurity and high carbon footprints are significant challenges, smart housing solutions must integrate renewable energy sources such as solar energy and energy storage systems like lithium-ion batteries to ensure continuous power supply and reduce dependence on fossil fuels [45], [46]. The mention of carbon dioxide and carbon sequestration points to the broader goal of achieving carbon neutrality or at least significant emissions reduction within residential developments [47], [48]. Vaishnavi et al. [49] and Palaniswamy et al. [50] indicates integrating energy conservation measures through smart energy management systems (EMS), energy-efficient appliances, and passive cooling systems further aligns with sustainable housing goals. For student housing specifically, the operational phase tends to have high energy use (lighting, electronics, water heating), making energy efficiency and management critical [30], [34]. Cooling systems are also particularly relevant in the South African climate, where high temperatures can increase cooling loads; thus, incorporating passive and active cooling technologies is key [6], [51]. The cluster reveals research inclusion of "**sustainable housing**" as a keyword which ties the technological focus back to the broader goal: ensuring that housing is not only smart and liveable but also aligned with global sustainability targets such as the UN's Sustainable Development Goals (SDGs), especially SDG 7 (Affordable and Clean Energy) and SDG 11 (Sustainable Cities and Communities).

Cluster 2: Economics and policy of sustainable urban housing

This theme captures how investment, construction, renewable energy, and social housing policy intersect in shaping smart and sustainable student housing and its implications in South Africa. The cluster emphasizes the economic and policy dimensions of delivering sustainable student housing [32], [52]. Delapedra-Silva et al. [53] notes that while the shift to alternative and renewable energy sources is technologically feasible, its implementation is deeply shaped by the construction industry's capacity, investment flows, and urban development policies [54]. With key terms like costs, investments, and real estate market several studies have highlighted the financial viability concerns such as sustainable construction and the integration of renewable energy often involve high upfront costs [52], [55]. In South Africa, where housing affordability is a national priority (especially for students from disadvantaged backgrounds), balancing cost efficiency with sustainability goals is a major challenge [56]. The mention of social housing connects to equity and accessibility ensuring that student housing is not just green-based but also affordable and inclusive [57], [58]. This is vital in a country with persistent socioeconomic inequalities. Sustainable housing models must therefore align with government policies and funding schemes that support both environmental and social objectives. Moreover, keywords like urban development and sustainable construction point to the need for integrated urban planning [8]. Student housing, especially in dense urban areas, is part of a larger ecosystem. Its sustainability depends on transport networks, land-use planning, and local energy infrastructure [44], [55]. The inclusion of energy management and energy transfer indicates a focus on building systems that not only generate but also efficiently distribute and manage energy within multi-unit housing complexes. In summary, this cluster of keywords provide insights into technological solutions that must be backed by enabling policies, viable business models, and urban planning frameworks to scale sustainable student housing effectively.

Cluster 3: Design innovation and renewable integration in housing

This theme highlights keywords relating to architectural strategies and technological innovations (e.g., BIPV, ecodesign, thermal comfort) essential for advancing smart, sustainable student housing. Cluster 3 centers on the built environment's physical and design strategies that underpin sustainable housing. Central to this is the use of renewable energy technologies like building-integrated photovoltaics (BIPV) and solar power generation systems, which allow housing units to harvest energy seamlessly within the building envelope [44], [59]. In the South African context with abundant solar radiation, solar integration is one of the most promising avenues for reducing grid dependency [60], [61]. The inclusion of compressed earth blocks and court-yarded clusters reflects a focus on local materials and vernacular architecture, which not only minimize the carbon footprint of construction but also respond well to local climate conditions as indicated in Fahmy et al., [62]. These approaches enhance thermal comfort naturally, reducing reliance on mechanical heating and cooling a key aspect in lowering long-term operational energy use [63]. As Benning et al. [64] renders eco-design principles combine these elements by promoting holistic design that optimizes energy efficiency, materials use, and environmental impact. In student housing, this can translate to buildings that maximize natural light, cross-ventilation, and passive solar heating/cooling while being cost-effective and replicable [40], [49]. energy policy and sustainable development emerging signals that these design innovations must operate within a policy framework that incentivizes or mandates green building practices [65]. This links to larger national goals of decarbonizing the built environment and ensuring that sustainable development is not just an ideal but a practical reality. Thus, overall, the Cluster 3 points to the integration of design, materials, and renewable technologies as foundational to developing resilient, energy-efficient student housing that is both smart and sustainable.

Cluster 4: Zero-energy housing and educational integration

This theme reflects the double focus on architectural and renewable energy strategies and the role of engineering education in driving sustainable student housing in developing countries. The findings positions architectural design and renewable energy systems as central to achieving zero-energy buildings (ZEBs), a critical benchmark for sustainable student housing [66], [67]. The zero-energy concept involves designing buildings that produce as much energy as they consume as stated in Anshu et al. [68], which is especially relevant for student housing where continuous energy demand (lighting, heating, cooling, and digital devices) is high. The presence of keywords developing countries (such as studies in Egypt and Malaysia) and student housing situates this within the broader South African and Global South context, where resource constraints, urbanization, and growing student populations put immense pressure on housing infrastructure [38], [44]. South Africa's unique socio-economic conditions demand affordable, scalable, and context-sensitive zero-energy solutions as previously stated. Interestingly, the inclusion of keywords such as engineering education and students suggests a capacity-building dimension in research. sustainable student housing is therefore not just a design and construction challenge, it is also a learning opportunity. Incorporating renewable energy technologies and sustainable design principles into university curricula equips future engineers and architects with the skills to advance the zero-energy agenda [64], [69]. This also allows student housing developments to serve as living labs, where students can engage with real-world sustainability challenges and innovations [11]. The continuous research emphasis on renewable energy generation, resources, and systems links everything back to the technical foundation needed to support zero-energy buildings such as solar PV, wind, hybrid systems, and smart energy management. This cluster, therefore, reinforces that achieving sustainability is a multidisciplinary effort, blending design innovation, energy systems, and education in a way that is especially impactful for student communities.

Cluster 5: Climate-responsive housing and emissions mitigation

Cluster 5's theme emphasizes the urgent need to align housing development with climate action which addresses carbon emissions, energy use, and planning strategies. The cluster of keywords indicates the climate imperative that underpins all discussions of smart and sustainable student housing. The repeated focus on carbon, greenhouse gases, gas emissions, and climate change situates housing within the broader challenge of global warming and environmental degradation [1]. In South Africa, where coal remains a dominant energy source, student housing developments can either exacerbate or help mitigate climate risks [70], [71]. The term energy utilization reflects the critical link between how buildings are operated and their emissions footprint [72]. Student housing mostly densely populated has high per-square-meter energy demands (lighting, heating, cooking), making it essential to optimize heating systems, insulation, and appliance efficiency to minimize environmental impacts [73], [74]. Other keywords are planning and surveys suggesting the importance of data-driven decision-making and urban policy. A holistic planning ensures that sustainable housing is not treated in isolation but is integrated within larger climate-resilient urban frameworks [75], [76]. Surveys are instrumental in understanding occupant behaviours, housing needs, and energy consumption patterns, which can inform more precise, user-centred design and climate-responsive planning. For student housing, this means adopting low-carbon materials, energy-efficient systems, and climate-adaptive designs to minimize both operational and embodied carbon which has been earlier emphasized. Reinforcing that smart and sustainable student housing must be deeply attuned to climate science, policy commitments (like South Africa's Nationally Determined Contributions (NDCs) under the Paris Agreement), and the global push for net-zero carbon buildings.

Cluster 6 Retrofitting and material strategies for low-energy housing

This theme captures the focus on improving energy performance through both new construction and retrofitting, using sustainable materials and renewable energy. Finally, cluster 6 addresses a practical challenge in sustainable housing that is how to achieve low energy demand not just through new builds but also by retrofitting existing structures. Given the vast number of existing student residences, historical retrofitting and sustainable material adoption are critical strategies for achieving low-energy housing [3], [77]. In South Africa, many student accommodations are older buildings that were not designed with energy efficiency in mind, making historical retrofitting essential for meeting sustainability targets [78]–[80]. The term heating demand reflects the need to optimize thermal performance, ensuring that buildings require minimal energy for comfort. This is especially relevant in regions with cooler winters, where poor insulation can lead to high heating costs and energy waste [30], [81]. Low energy buildings conform to broader goals of reducing operational energy use through passive design, efficient systems, and smart controls [82]. For student housing, which typically sees intensive daily use, achieving low-energy status can have a huge cumulative impact on campus-wide sustainability. The cluster's emphasis on sustainable materials and its importance of not only reducing operational carbon but also addressing embodied carbon [3], [40]. Using locally sourced, low-impact materials reduces the environmental footprint of both new builds and retrofits. For student housing, this might involve materials like compressed earth blocks, recycled content, and modern insulation materials that enhance both sustainability and performance. In essence there is a focus to improve the performance of existing buildings (retrofitting) and set high standards for new constructions, all grounded in renewable energy use and sustainable material choices.

VI. Toward an integrated framework for smart and sustainable student housing in South Africa

The bibliometric analysis revealed six interlinked thematic clusters that, together, shape a holistic understanding of sustainable student housing models and how it can be implemented in the South African context. Each cluster provided an in-depth insight into critical dimensions technological, economic, social, environmental, and educational that must converge to realize housing solutions that are both smart and sustainable. Cluster 1 focused on renewable energy technologies, energy management systems, and carbon reduction strategies. Solar energy, energy-efficient cooling systems, and battery storage emerge as pivotal in mitigating carbon emissions and ensuring resilience against energy insecurity. Cluster 2 brought attention to the financial, policy, and urban development landscapes. Sustainable housing models must navigate costs, investment challenges, and social housing imperatives, requiring policies that incentivize green construction and ensure equitable access, especially in a socially diverse and economically stratified country like South Africa. Thereafter, Cluster 3 emphasized the architectural and material innovations essential for sustainability. The integration of building-integrated photovoltaics (BIPV), ecodesign, and local materials (e.g., compressed earth blocks) points to context-sensitive strategies that enhance energy performance and thermal comfort while aligning with local climatic and socio-economic realities.

The fourth cluster also provided highlights into the aspiration for zero-energy buildings (ZEBs), positioning student housing not only as a site of residence but also as a learning environment. The synergy between engineering education, architectural design, and renewable energy systems creates opportunities for living labs, where students engage with real-world sustainability challenges and innovations. Cluster 5 further situated student housing within the global climate crisis, emphasizing the need for planning frameworks and emissions monitoring. Surveys, data-driven planning, and policy integration are key to ensuring that student housing contributes to national and international climate goals by minimizing carbon emissions through optimized energy utilization and low-carbon construction. Then lastly, Cluster 6 gave the importance of retrofitting existing housing stock a practical and often overlooked aspect of sustainability. Combining historical retrofitting, sustainable materials, and renewable energy integration is vital for reducing heating demands and achieving low-energy status in both new and old student accommodations.

All together these thematic clusters collectively highlight that smart and sustainable student housing in South Africa requires:

Technological Innovation: Renewable energy, smart systems, and material advancements.

Policy and Economic Support: Incentives, social equity, and financial viability.

Architectural and Urban Design Excellence: Passive design, local materials, and urban integration.

Educational Synergy: Embedding sustainability into curricula and student engagement.

Climate and Environmental Alignment: Targeting net-zero and resilient infrastructure.

Upgrading Existing Infrastructure: Systematic retrofitting and performance enhancement.

The bibliometric review suggests that successful models will not depend on a single solution but on the intersection of these strategies, tailored to South Africa's unique socio-economic and environmental context.

Figure 5 provides a pictorial framework of the interlinkages between the themes and recommends it as a foundational conceptual framework for implementing smart and sustainable student housing model in South Africa which can be adopted by other developing and developed countries.

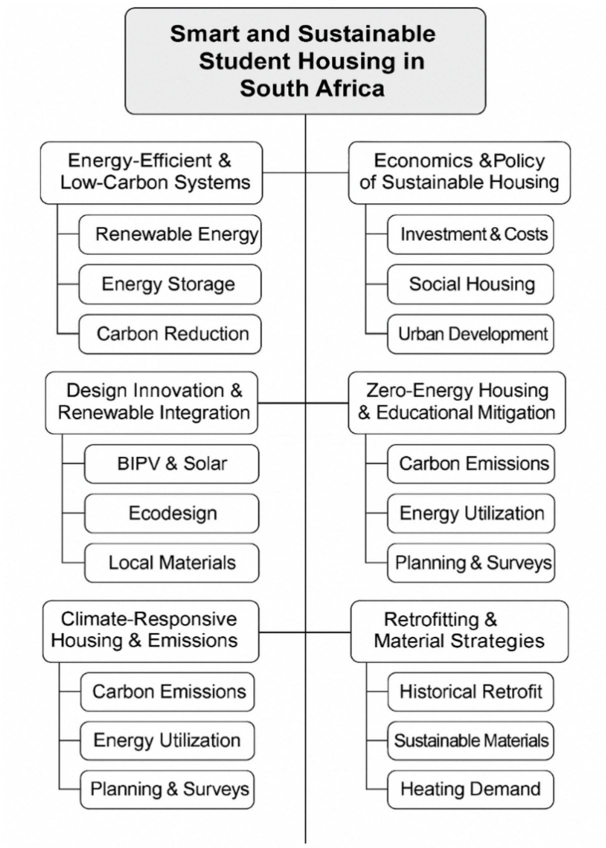

Figure 5: Integrated implementation framework

VII. Conclusion

To fully realize the potential of smart and sustainable student housing in South Africa, there is a need for policy-driven implementation, financial incentives, and institutional collaboration. The government must develop regulatory frameworks that support the integration of renewable energy, energy-efficient materials, and smart housing technologies into student residences.

Furthermore, public-private partnerships and sustainable financing models should be promoted to overcome financial constraints in deploying smart housing solutions. Universities must also incorporate nature-based solutions and climate-responsive design principles into their housing policies to ensure long-term sustainability. Despite significant advancements, several gaps remain in the research and implementation of smart and sustainable student housing: Limited empirical data on the long-term performance of smart energy systems in student housing. Lack of policy alignment between urban planning regulations, energy efficiency standards, and student housing guidelines. Need for more interdisciplinary collaboration between academics, policymakers, and industry practitioners to develop cost-effective, climate-resilient student housing solutions.

Future research should focus on scaling innovative solutions, integrating AI-driven energy systems, and analysing the socio-economic benefits of sustainable student housing models. By addressing these gaps, South Africa can develop a more resilient, energy-efficient, and student-centred housing infrastructure that aligns with global sustainability targets.

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