# Decarbonizing HVAC Systems in Educational Buildings: Challenges and Solutions

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## Abstract

The heating, ventilation, and air conditioning (HVAC) systems in educational buildings are significant contributors to energy consumption and greenhouse gas emissions. As the urgency to achieve carbon neutrality intensifies, decarbonizing HVAC systems has become a key priority in the retrofitting of educational infrastructure. This study aimed to investigate the challenges hindering the decarbonization of HVAC systems in educational buildings and to suggest viable solutions. A quantitative research approach was adopted, employing a structured questionnaire survey administered to professionals involved in HVAC operations across selected educational institutions in Gauteng province, South Africa. The findings reveal that the major challenges include high upfront costs of low-carbon HVAC technologies, limited technical expertise, and institutional inertia. However, respondents also highlighted opportunities such as government incentives, long-term energy savings, and growing support for climate action within the education sector. Solutions recommended include phased retrofitting strategies, capacity building for maintenance staff, and policy frameworks that support lifecycle costing and performance-based upgrades. Decarbonizing HVAC systems in educational buildings is both a necessity and an opportunity. A holistic and collaborative approach involving technical, financial, and policy interventions is essential. The study recommends targeted funding, awareness campaigns, and the integration of decarbonization goals into institutional infrastructure planning.

## Keywords

Decarbonization, Carbon neutrality, Educational buildings, Energy efficiency, Sustainable retrofitting.

## 1. Introduction

The global imperative to reduce greenhouse gas (GHG) emissions has placed considerable pressure on the built environment sector, which contributes nearly 40% of global energy-related carbon emissions (Min et al., 2022). Within this sector, HVAC (Heating, Ventilation, and Air Conditioning) systems represent a significant share of energy consumption and carbon output, especially in institutional buildings such as schools and universities (Almasri et al., 2024). These systems are essential for maintaining acceptable levels of indoor thermal comfort and air quality; however, their operation is often energy-intensive and heavily reliant on fossil fuels (Ali & Akkaş, 2023). As such, decarbonizing HVAC systems is a key strategy in achieving carbon neutrality in educational infrastructure.

Educational buildings, particularly in developing countries, are often characterized by outdated and inefficient HVAC technologies that were installed long before the advent of modern energy standards (Simpeh et al., 2022). Many of these facilities lack insulation, modern controls, and integrated energy systems, leading to excessive energy use and operational costs. This presents not only an environmental challenge but also a financial burden on public education systems (Kottara et al., 2025). Retrofitting HVAC systems, therefore, has become a central component of broader efforts to improve sustainability and resilience in the education sector.

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Decarbonizing HVAC systems involves a range of technological interventions, including the adoption of energy-efficient heat pumps, demand-controlled ventilation, and the integration of renewable energy sources such as solar and geothermal power (Olatunde et al., 2024). Additionally, building management systems and Internet of Things (IoT) technologies can play a vital role in optimizing HVAC operations and minimizing energy waste. While these technologies are available and increasingly cost-effective, their widespread adoption remains hindered by various challenges (Idowu et al., 2023).

Among the most significant barriers are high upfront investment costs, limited technical expertise among facilities managers, and a lack of supportive policies and incentives (Idowu et al., 2024; Amoah & Smith, 2024). In many studies, particularly in the Global South, retrofitting initiatives are further constrained by budgetary limitations and institutional inertia (Eames et al., 2013; Idowu et al., 2024). Moreover, the absence of robust data and performance benchmarks makes it difficult to evaluate the effectiveness of retrofitting interventions and scale them accordingly (Deb & Schlueter, 2021; Idowu & Aligamhe, 2016). Despite these challenges, a growing body of literature highlights numerous success stories and innovative strategies for HVAC decarbonization. The integration of passive design principles, such as natural ventilation and daylighting, can significantly reduce HVAC demand (Stephen et al., 2024). Similarly, performance contracting and energy service agreements offer financial models that reduce the initial burden on educational institutions (Ma et al., 2012; Adekunle et al., 2024). Effective stakeholder collaboration, government incentives, and regulatory reforms are also repeatedly identified as critical enablers of decarbonization efforts (Adeniyi et al., 2020).

This study is anchored in Sustainability Transition Theory (STT), Technology Acceptance Model (TAM), and Institutional Theory to explain the factors influencing HVAC decarbonization in educational buildings. STT frames the shift to low-carbon HVAC systems as a socio-technical transformation requiring the removal of cost, knowledge, and systemic barriers, while TAM highlights how perceptions of usefulness, ease of use, and institutional readiness affect adoption. Institutional Theory adds that regulatory frameworks, organizational norms, and societal pressures shape decision-making (Tolbert et al., 2019). The conceptual framework identifies three interconnected dimensions technical and economic barriers (e.g., high upfront costs, lack of skilled personnel), institutional and behavioral factors (e.g., organizational inertia, low awareness), and policy and market enablers (e.g., government incentives, lifecycle savings) and posits that integrated technical, financial, institutional, and policy interventions are essential for achieving effective HVAC decarbonization in educational institutions.

Given the complex interplay of technical, financial, and institutional factors, a comprehensive understanding of both the challenges and the solutions is essential for designing effective retrofitting strategies (Jagarajan et al., 2017). However, existing research on HVAC decarbonization in educational settings is fragmented, with limited synthesis of cross-cutting themes and practical recommendations. There is a need for a systematic approach that combines quantitative mapping of research trends with qualitative analysis of best practices. Therefore, the purpose of this study is to explore the challenges and potential solutions associated with decarbonizing HVAC systems in educational buildings. This approach aims to provide a structured understanding of the knowledge landscape, identify research gaps, and offer actionable insights to guide future retrofitting policies and practices.

## 2. Methods

This study adopted a quantitative research design to systematically investigate the challenges and potential solutions associated with decarbonizing HVAC (Heating, Ventilation, and Air Conditioning) systems in educational buildings. A structured questionnaire survey was employed as the primary data collection instrument to gather empirical insights from key stakeholders involved in the planning, operation, and maintenance of HVAC systems. The target population included facility managers, quantity surveyors, engineers, architects, and construction managers across selected higher educational institutions. A purposive sampling technique was used to ensure the inclusion of respondents with relevant experience and knowledge about HVAC systems and building operations. The sample frame consisted of three (3) selected higher educational institutions in Gauteng province, South Africa. A total of 267 questionnaires were distributed, and 207 valid responses were received, resulting in a response rate of 76.7%.

The questionnaire was designed to capture both closed-ended and Likert-scale responses and was divided into three key sections: demographic and institutional background, perceived challenges to HVAC decarbonization, and potential solutions. The instrument was pilot tested with six professionals to validate clarity, relevance, and reliability. Data collected were analyzed using descriptive statistics (mean, frequency, and percentage distribution) to identify

dominant trends. The findings provided a data-driven basis for formulating strategic recommendations to enhance the decarbonization of HVAC systems in educational settings.

## 3. Results

### 3. 1 Demographic Information and Reliability Test

The demographic breakdown of the survey participants shows a diverse mix of professionals involved in the built environment. Among the respondents, 20% are Quantity Surveyors, 25% are Architects, 24% are Engineers, 26% are Facility Managers, and 5% are Project Managers. Most of these professionals bring a wealth of experience, with a large number having worked in the field for over a decade. In terms of professional standing, 80% are fully registered (corporate) members of their respective professional bodies, while the remaining 20% are still in the early stages of their careers as probationer members. When it comes to post-qualification experience, half of the respondents have been practicing for 1 to 5 years, 25% have 6 to 10 years under their belt, and another 25% have 11 to 15 years of experience, bringing the average to about 6.67 years. The strong representation of seasoned professionals adds credibility to the findings and lends weight to the study's overall reliability.

The reliability of each of the two measurement sets used in the study was determined by calculating the Cronbach's alpha values. According to Yuksel et al. (2010), the closer the value is to 1.00, the more reliable a measurement is deemed to be.

**Table 1.** Reliability Test

| Measurement Sets | No of Items | Cronbach |
|---|---|---|
| Challenges of HVAC decarbonization | 16 | 0.854 |
| Measures of Addressing HVAC Decarbonization Challenges | 16 | 0.920 |

### 3. 2 Challenges of HVAC Decarbonization

Table 2 below highlights the challenges in decarbonizing HVAC systems in educational buildings, ranked by mean score and standard deviation (SD). Ranking first is the high initial cost of low-carbon HVAC systems, with the highest mean score (MS) of 4.56 and a low standard deviation (SD) of 0.61, indicating strong agreement among respondents. This is followed by the complexity of retrofitting old buildings (MS = 4.33, SD = 0.67) and low prioritization of sustainability in budgeting (MS = 4.28, SD = 0.68). Limited availability of technical expertise ranked fourth with (MS = 4.21, SD = 0.73), limited access to green financing mechanisms ranked fifth with (MS = 4.15, SD = 0.69), high maintenance costs for advanced HVAC systems ranked sixth with (MS = 4.12, SD = 0.71), lack of integration with Building Energy Management Systems (BEMS) ranked seventh with (MS = 4.08, SD = 0.70), slow approval processes ranked eighth with (MS = 4.05, SD = 0.76), the lack of institutional policies supporting decarbonization ranked ninth with (MS = 4.02, SD = 0.79). Insufficient post-installation performance tracking ranked tenth with (MS = 3.95, SD = 0.75), limited options for green HVAC technologies ranked eleventh with (MS = 3.91, SD = 0.79), lack of collaboration between departments ranked twelfth with (Mean = 3.89, SD = 0.80), lack of awareness among decision-makers ranked thirteenth with (Mean = 3.87, SD = 0.82), and resistance to change from facility managers ranked fourteenth with (MS = 3.78, SD = 0.86). Lower-priority challenges, though still relevant, include poor indoor air quality monitoring practices (MS = 3.66, SD = 0.84) and disruption to learning during retrofitting projects (MS = 3.48, SD = 0.88), which ranks the lowest. The data suggests that cost, technical complexity, and institutional gaps are the most pressing concerns, while operational and awareness-related issues, though less critical, still require attention.

**Table 2.** Challenges of HVAC decarbonization

| Identified challenges | Mean Score | SD | Rank |
|---|---|---|---|
| High initial cost of low-carbon HVAC systems | 4.56 | 0.61 | 1 |
| Complexity of retrofitting old buildings | 4.33 | 0.67 | 2 |
| Low prioritization of sustainability in budgeting | 4.28 | 0.68 | 3 |
| Limited availability of technical expertise | 4.21 | 0.73 | 4 |
| Limited access to green financing mechanisms | 4.15 | 0.69 | 5 |
| High maintenance costs for advanced HVAC systems | 4.12 | 0.71 | 6 |
| Lack of integration with building energy management systems (BEMS) | 4.08 | 0.70 | 7 |

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| Slow approval processes | 4.05 | 0.76 | 8 |
| Lack of institutional policies supporting decarbonization | 4.02 | 0.79 | 9 |
| Insufficient post-installation performance tracking | 3.95 | 0.75 | 10 |
| Limited options for green HVAC technologies | 3.91 | 0.79 | 11 |
| Lack of collaboration between departments | 3.89 | 0.80 | 12 |
| Lack of awareness among decision-makers | 3.87 | 0.82 | 13 |
| Resistance to change from facility managers | 3.78 | 0.86 | 14 |
| Poor indoor air quality monitoring practices | 3.66 | 0.84 | 15 |
| Disruption to learning during retrofitting projects | 3.48 | 0.88 | 16 |

### 3.3 Measures of Mitigating HVAC Decarbonization Challenges

The table outlines various strategies for advancing HVAC system decarbonization in educational buildings, The most highly rated strategy is phased retrofitting and system upgrades (Mean = 4.41, SD = 0.66), followed by government subsidies and green financing schemes (Mean = 4.36, SD = 0.71), and the integration of passive design to reduce HVAC load (Mean = 4.33, SD = 0.65). This indicates strong agreement on the importance of financial, technical, and design interventions. Creation of pilot projects to demonstrate benefits ranked fourth with (Mean = 4.30, SD = 0.68), development of clear HVAC decarbonization policy frameworks ranked fifth with (Mean = 4.28, SD = 0.67), stakeholder engagement and awareness campaigns ranked sixth with (Mean = 4.25, SD = 0.69), periodic HVAC energy audits ranked seventh with (Mean = 4.20, SD = 0.70), capacity-building programs for technical staff ranked eighth with (Mean = 4.18, SD = 0.72), incentives for early adopters ranked ninth with (Mean = 4.16, SD = 0.73), inclusion of HVAC energy goals in institutional plans ranked tenth with (Mean = 4.12, SD = 0.71), use of digital tools for real-time monitoring ranked eleventh with (Mean = 4.07, SD = 0.74), the implementation of BEMS ranked twelfth with (Mean = 4.02, SD = 0.78), establishment of a dedicated HVAC sustainability task force ranked thirteenth with (Mean = 4.00, SD = 0.80), adoption of performance-based procurement models ranked fourteenth with (Mean = 3.95, SD = 0.76). The lowest ranking solutions are the use of modular HVAC systems with (Mean = 3.92, SD = 0.78) and collaboration with energy service companies with (Mean = 3.89, SD = 0.77). The responses highlight a strong preference for a blend of financial, technical, policy-driven, and capacity-enhancing strategies to enable effective HVAC decarbonization.

**Table 3.** Measures of Addressing HVAC Decarbonization Challenges

| Identified challenges | Mean Score | SD | Rank |
|---|---|---|---|
| Phased retrofitting and system upgrades | 4.41 | 0.66 | 1 |
| Government subsidies and green financing schemes | 4.36 | 0.71 | 2 |
| Integration of passive design to reduce HVAC load | 4.33 | 0.65 | 3 |
| Creation of pilot projects to demonstrate the benefits of decarbonized systems | 4.30 | 0.68 | 4 |
| Development of clear HVAC decarbonization policy frameworks | 4.28 | 0.67 | 5 |
| Stakeholder engagement and awareness campaigns | 4.25 | 0.69 | 6 |
| Conducting periodic HVAC energy audits | 4.20 | 0.70 | 7 |
| Capacity-building programs for technical staff | 4.18 | 0.72 | 8 |
| Incentives for early adopters within the education sector | 4.16 | 0.73 | 9 |
| Inclusion of HVAC energy goals in institutional plans | 4.12 | 0.71 | 10 |
| Use of digital tools for real-time energy monitoring | 4.07 | 0.74 | 11 |
| Implementation of building energy management systems (BEMS) | 4.02 | 0.78 | 12 |
| Establishment of a dedicated HVAC sustainability task force | 4.00 | 0.80 | 13 |
| Adoption of performance-based procurement models | 3.95 | 0.76 | 14 |
| Use of modular HVAC systems for easier upgrades | 3.92 | 0.78 | 15 |
| Collaboration with energy service companies | 3.89 | 0.77 | 16 |

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## 4. Discussion

The findings of this study provide a comprehensive understanding of the challenges and potential solutions related to decarbonizing HVAC systems in educational buildings. The high mean scores associated with several key variables underscore a strong consensus among stakeholders on the urgency of transitioning to low-carbon systems and the barriers that must be overcome. The findings from the survey reveal a strong consensus among professionals on the major challenges impeding HVAC system decarbonization in educational buildings. The high initial cost of low-carbon HVAC systems emerged as the most critical barrier, corroborating earlier studies such as that of Idowu et al. (2024) and Zuo & Zhao (2014), which highlighted cost-related constraints as primary deterrents to sustainable building technology adoption. This is particularly pronounced in public educational institutions that operate under limited capital budgets. Similarly, the complexity of retrofitting old buildings aligns with research by Ma et al. (2012) and Amoah and Smith (2018), who argue that legacy infrastructure in schools often lacks structural and spatial flexibility to support modern energy-efficient HVAC systems.

Low prioritization of sustainability in budgeting and limited access to green financing indicate systemic issues in policy and funding frameworks. These findings echo the work of Unruh et al. (2016), which emphasizes that sustainability investments are often sidelined in favor of immediate operational needs. Moreover, the limited availability of technical expertise and the lack of integration with Building Energy Management Systems (BEMS) support findings by Kozlovska et al. (2023), which stress the need for upskilling technical staff and investing in digital infrastructure for optimized building performance. The study also identified softer but still significant barriers such as lack of institutional policies, poor post-installation tracking, and resistance to change. These align with Choi et al. (2016), who emphasized that organizational inertia and weak governance structures slow the transition to energy-efficient solutions in public sector buildings. Notably, disruption to learning during retrofitting, though ranked lowest, is supported by Fawcett and Killip (2019), who observed that operational disruptions can delay or even derail sustainability upgrades in active learning environments.

The study also identified strategic responses to address these challenges, with phased retrofitting and system upgrades ranked highest. This reflects best practices noted by Kwak et al. (2020) and Ürge-Vorsatz et al. (2015), who advocated for staged interventions to minimize operational disruptions and manage cost over time. Government subsidies and green financing schemes and integration of passive design to reduce HVAC loads were also highly ranked, echoing the recommendations of Garde et al. (2017), who found that financial support mechanisms and passive cooling strategies are essential enablers for low-carbon transitions. Furthermore, pilot projects, clear policy frameworks, and stakeholder engagement campaigns reflect the need for demonstration, policy alignment, and institutional elements highlighted in the works of Ahn et al. (2016) and Lützkendorf et al. (2015). Mid-ranking strategies such as capacity-building programs, digital monitoring tools, and implementation of BEMS reinforce the argument of Britton et al. (2021) that decarbonization success relies on both technological innovation and human capital development. Lower-ranked strategies like performance-based procurement, modular HVAC systems, and collaboration with energy service companies suggest that while these options are beneficial, they may face practical or institutional limitations. However, studies by Ali et al. (2023) and Simpeh et al. (2022) advocate for their adoption as complementary measures when well-structured contracts and partnerships are in place.

## 5. Conclusions

This study examined the critical challenges and enabling strategies for decarbonizing HVAC systems in educational buildings, drawing on expert perspectives from built environment professionals. The findings reveal that high initial costs, technical complexity, limited access to green financing, and weak institutional frameworks are among the most significant barriers hindering progress. Despite these challenges, there is a strong consensus on practical and policy-driven strategies that can support the transition to low-carbon HVAC systems. Strategies such as phased retrofitting, government subsidies, integration of passive design principles, and the development of clear policy frameworks received high levels of support. The involvement of skilled personnel, stakeholder awareness, and digital monitoring tools also emerged as important facilitators. These results emphasize that effective HVAC decarbonization in the education sector requires not only financial investment and technical solutions but also robust institutional support, continuous capacity development, and integrated policy alignment. Based on the findings, the following recommendations are proposed:

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i. Government agencies and financial institutions should provide subsidies, grants, or low-interest loans specifically aimed at decarbonizing HVAC systems in schools and universities.
ii. Educational institutions should integrate HVAC decarbonization targets into broader sustainability or infrastructure development plans, supported by measurable goals and performance tracking.
iii. Schools should adopt a step-by-step HVAC upgrade strategy that minimizes disruption to learning while spreading costs over time.
iv. Collaboration with energy service companies (ESCOs) and the Private Sector should be encouraged.
v. Integrate passive cooling and ventilation strategies in building design to reduce HVAC loads and use digital tools such as Building Energy Management Systems (BEMS) for real-time performance.

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