

Energy-Efficient Upgrades for Educational Buildings: A Roadmap to Carbon Neutrality

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Abstract

Educational buildings consume significant energy, leading to high costs and carbon emissions. Upgrading these buildings with energy-efficient solutions can reduce their environmental impact and move them toward carbon neutrality. This study outlines practical strategies, including improved insulation, energy-efficient lighting, smart heating and cooling systems, and renewable energy integration. By following these steps, schools and universities can create healthier learning environments while cutting energy use. A survey research design was employed for this study, where questionnaires were administered among key stakeholders in the built environment. One hundred sixty questionnaires were distributed, and 102 were returned and considered fit for analysis. The data was analysed using descriptive statistics, mean score, and standard deviation. Findings reveal that improvements such as insulation upgrades, LED lighting, smart HVAC systems, and renewable energy adoption significantly reduce energy use and operational costs. The study concludes that a structured approach to energy efficiency accelerates carbon neutrality in educational institutions. This is a practical tool for institutions aiming to achieve carbon neutrality through smart, cost-effective upgrades. The study, therefore, recommends policy incentives, financial support, and stakeholder engagement to enhance implementation and long-term sustainability.

Keywords: Carbon neutrality, educational buildings, energy efficiency, energy-efficient upgrade, sustainability

1. Introduction

Educational buildings are among the largest energy consumers in the public sector, requiring substantial energy for heating, cooling, lighting, and the operation of electronic devices (Gul & Patidar, 2015). Many schools and universities rely on outdated infrastructure that consumes excessive energy, leading to high operational costs and increased carbon emissions (Omer, 2009). Chowdhury et al. (2021) revealed that as climate change and environmental sustainability concerns grow, institutions must take proactive steps to reduce their energy consumption. Energy-efficient upgrades present a practical solution, enabling schools and universities to reduce energy waste, cut costs, and contribute to a cleaner environment (Papadakis & Katsaprakakis, 2023). Transitioning to energy-efficient systems is an environmental necessity and a financial and educational opportunity for institutions worldwide.

The energy cost in educational buildings represents a significant portion of institutional budgets (Dyussembekova et al., 2022). Many schools struggle with rising electricity bills, diverting resources from academic programs, faculty salaries, and student services. Investing in energy-efficient solutions such as LED lighting, smart heating and cooling systems, and modernised insulation can significantly lower energy expenses (Kovalchuk & Shcherbakova, 2024). By

reducing operational costs, schools can reallocate funds to improve educational infrastructure and enhance student learning experiences (Gershberg, 2015). Institutions that adopt energy-saving measures also become more financially resilient, ensuring long-term sustainability in the face of fluctuating energy prices (Sarkar & Singh, 2010).

Beyond financial benefits, reducing energy use in educational buildings is essential for minimising environmental impact (Harvey, 2009). Johnsson, Kjärstad, and Rootzén (2019) revealed that many institutions still rely on fossil fuel-based energy sources, contributing to greenhouse gas emissions and climate change. Shifting to renewable energy sources, such as solar or wind power, can significantly decrease the carbon footprint of educational facilities (Outka, 2011). Schools and universities that embrace energy-efficient solutions meet regulatory requirements for sustainability and set a positive example for students and the broader community. Encouraging sustainability within educational institutions helps instil environmentally responsible values in future generations (Altassan, 2023).

Achieving carbon neutrality in educational institutions requires a structured and strategic approach. Institutions that develop clear energy efficiency plans and follow systematic implementation processes

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achieve better outcomes. Long-term planning, proper funding, and active stakeholder involvement must support the transition to energy-efficient systems (Chai & Yeo, 2012). School administrators, policymakers, and facility managers must work together to prioritise energy efficiency and overcome barriers to implementation. By adopting a phased approach, institutions can gradually upgrade their infrastructure while minimising disruption to daily operations.

2. Literature Review

Energy efficiency in educational buildings has gained significant attention in recent years due to rising energy costs and environmental concerns (Papadakis & Katsaprakakis, 2023). Many researchers emphasise the need for schools and universities to adopt energy-saving technologies to reduce consumption and lower carbon emissions. According to Idowu et al. (2024), educational buildings account for a substantial portion of public sector energy use, making them key targets for efficiency improvements. Their study highlights retrofitting outdated systems with modern, energy-efficient alternatives. Lighting is one of the main contributors to energy use in schools. Traditional incandescent and fluorescent lights consume large amounts of electricity, leading to high utility costs (Reames, Reiner & Stacey, 2018). Brown et al. (2022) found that switching to LED lighting reduces energy consumption by up to 50% while improving the quality of indoor lighting. LED lights also last longer, lowering maintenance costs for institutions. Schools implementing automatic lighting controls increase energy savings by ensuring lights are only used when needed.

Heating, ventilation, and air conditioning (HVAC) systems are another significant source of energy use in educational buildings (Asim et al., 2022). Research by Teke and Timur (2014) shows that outdated HVAC systems waste energy due to inefficient heating and cooling processes. Upgrading to smart, programmable thermostats and energy-efficient HVAC units reduces energy demand (Li, De La Ree & Gong, 2018). Proper insulation and weatherproofing also prevent heat loss in winter and keep buildings cool in summer, improving overall efficiency.

Renewable energy sources in educational institutions have also been widely studied. Solar energy is one of the most popular options, providing a clean and sustainable power source (Hayat et al., 2019). Schools that install solar panels can generate a significant portion of their electricity on-site, reducing reliance on traditional energy sources (Altassan, 2023). Building automation systems play a crucial role in improving energy efficiency. Smart energy management systems help schools monitor and control energy use in real-time (Amaxilatis et al., 2017). Idowu et al. (2024) found that institutions with automated energy management

systems reduce waste by optimising energy use based on occupancy and demand. These systems also provide detailed energy usage reports, helping facility managers identify areas for further improvement.

Indoor air quality and natural ventilation strategies have gained attention in recent studies. Poor indoor air quality negatively affects student health and academic performance (Stafford, 2015). Martinez and Lopez (2021) found that schools using energy-efficient ventilation systems with air filtration improve student concentration and reduce absenteeism due to illness (Toyinbo, 2023). Natural ventilation, such as operable windows and ventilated facades, further reduces the need for mechanical cooling, lowering energy costs.

Several studies highlight the role of government policies and financial incentives in promoting energy-efficient upgrades. Mills and Schleich (2012) emphasise that many schools struggle to afford energy-efficient technologies despite their long-term benefits. Government grants, subsidies, and low-interest loans help institutions invest in sustainable solutions. Their research suggests that more substantial policy support encourages more schools to adopt energy-efficient practices. Behavioural change and sustainability education also contribute to energy efficiency in schools. Research by Atlassan (2023) shows that schools with energy conservation programs encourage students and staff to adopt sustainable habits. Simple actions, such as turning off lights and unplugging devices when not in use, significantly reduce energy waste. Integrating sustainability topics into the curriculum further strengthens environmental awareness among students.

2.1. Strategies for Energy-Efficient Upgrades

Educational institutions use different strategies to improve energy efficiency. One common approach is upgrading lighting systems. Many schools replace traditional incandescent and fluorescent bulbs with LED lighting. Research by Mills and Jacobson (2011) shows that LED lights consume less energy and last longer, reducing electricity costs and maintenance efforts. Schools also install motion sensors and automated lighting controls to prevent unnecessary energy use. Another key strategy is improving heating, ventilation, and air conditioning (HVAC) systems (Idowu et al., 2024). Many educational buildings have outdated HVAC systems that waste energy.

Brown et al. (2022) found that smart thermostats and energy-efficient HVAC units help schools maintain comfortable temperatures while reducing energy consumption. Proper insulation and sealing of doors and windows further improve heating and cooling efficiency. Renewable energy integration is another important strategy. Many schools install solar panels to generate clean electricity on-site. Research by Amaxilatis et al. (2017) shows that solar energy reduces

dependence on fossil fuels and lowers electricity bills. Some institutions also use wind or geothermal heating to cut energy use further. These renewable sources provide long-term savings and environmental benefits.

Building automation and smart energy management systems also improve energy efficiency. Schools use automated systems to monitor and control energy use in real time. According to Adekunle et al. (2024), these systems adjust lighting, heating, and cooling based on occupancy, preventing energy waste. Smart meters help facility managers track energy usage and identify areas for improvement. Water conservation strategies also support energy efficiency. Many schools install low-flow faucets, toilets, and rainwater collection systems to reduce water waste. Gherheş and Cernicova-Buca, M. (2025) revealed that reducing water use lowers energy demand for heating and pumping. Schools can also educate students and staff about water-saving habits to enhance efficiency. The study conducted by Agbajor et al. (2023) explored and analysed the Building Energy Management Systems (BEMS) in South Africa, drawing insights from five key areas: building typology, building services systems, methodological approach, and testbed, applied BEMS strategies, and targeted energy management system tasks.

2.2. Benefits of Energy-Efficient Upgrades

Energy-efficient upgrades provide significant cost savings for educational institutions. Schools that adopt energy-saving technologies experience lower electricity and maintenance costs. Brown et al. (2022) found that LED lighting, smart HVAC systems, and automated energy management reduce utility bills by up to 40%. These savings allow schools to invest in better learning resources and facilities. Improved indoor air quality is another significant benefit. Outdated HVAC systems often circulate dust and pollutants, affecting student health. Research by Idowu et al. (2024) found that energy-efficient ventilation systems improve air circulation and remove harmful particles. Better air quality leads to fewer respiratory issues and higher student concentration.

Energy-efficient upgrades also contribute to environmental sustainability. Schools that use less energy reduce their carbon footprint. Abdallah and El-Shennawy (2013) found that institutions with solar panels and smart energy systems significantly lower greenhouse gas emissions. Schools help fight climate change and protect natural resources by adopting sustainable practices. Enhanced learning environments are another key benefit (Stephen et al., 2024). Schools with proper lighting, temperature control, and ventilation create comfortable spaces for students and teachers. According to Mills and Schleich (2012), students perform better in classrooms with stable temperatures and good air quality. Comfortable learning spaces lead to higher engagement and

academic success. Energy-efficient schools serve as models for sustainability. When schools implement green technologies, they teach students about environmental responsibility. Altassan (2023) revealed that students in energy-efficient schools develop a stronger awareness of sustainability issues. These schools encourage young people to adopt eco-friendly habits, creating a long-term positive impact on society.

3. Research Methodology

This study employed a survey research design to examine the impact of energy-efficient upgrades in educational buildings. A purposive sampling approach is used to select four educational institutions in Gauteng province of South Africa that have implemented energy-saving technologies such as LED lighting, smart HVAC systems, and renewable energy sources. The schools include the University of Johannesburg, the University of South Africa, the University of Witwatersrand, and the Tshwane University of Technology. The questionnaires were distributed to school facility managers and construction professionals to assess the strategies and benefits of energy-efficient upgrades. Ethical considerations, including informed consent and data confidentiality, are observed throughout the study, and the findings provide valuable insights into the effectiveness and feasibility of energy-efficient upgrades in schools. Data was collected using structured questionnaires targeting professionals in the selected educational buildings. A total population of 550 was arrived at after collating the professionals in the built environment in the selected school. Using Cochran's formula, a sample size of 160 was considered suitable for the study. One hundred sixty questionnaires were distributed, with 102 successfully retrieved and analysed. Using descriptive and inferential statistical methods, a quantitative approach was adopted to analyse the collected data. The paper identified the various energy-efficient upgrading strategies and their benefits in achieving a carbon-neutral building.

4. Findings and Discussion

4.1. Background Information of Respondent

The demographic summary of survey respondents in the study area indicates that 20% are Quantity Surveyors, 25% are Architects, 24% are Engineers, 26% are Facility Managers, and 5% are Project Managers. A significant proportion of the respondents have at least 10 years of experience. Regarding professional qualifications, 80% are corporate members of their respective professional bodies, while 20% are probationer members. Regarding post-professional qualification experience, 50% have between 1 and 5 years, 25% have 6 and 10 years, and another 25% have 11 and 15 years, with an average of 6.67 years. The predominance of experienced respondents enhances the reliability of the data for this research.

4.2. Strategies for Energy-Efficient Upgrades

Table 1 shows the strategies for energy-efficient upgrades. Ranking first is upgrading the lighting system with a mean score (MS) of 4.47 and Standard deviation (SD) of 0.742, followed by improving the HVAC system (MS = 4.43, SD=0.778) and renewable energy integration (MS=4.34, SD 0.838). Building automation ranked fourth with (MS=4.33, SD= 0.903), smart energy management systems ranked fifth with (MS=4.33, SD=0.829), greywater recycling ranked sixth with (MS=4.26, SD=0.9=891), sustainability awareness ranked seventh with (MS=4.25, 0.893), installing low-flow fixtures ranked eighth with (MS=3.35, SD= 1.248), using occupancy-based controls ranked ninth with (MS=3.24, SD = 1.096), improving insulation and weatherproofing ranked tenth with (MS=3.22, SD=1.092), upgrading to smart thermostats ranked eleventh with (MS=3.19, SD=1.062). Installing motion sensors and timers ranked least with (MS=3.05, SD=0.999), followed by

using natural light optimisation and replacing old HVAC units with energy-efficient models with (MS=3.05, SD=1.092) and (MS=3.06, SD=1.164) respectively.

4.3. Benefits of Energy-Efficient Upgrades

Table 2 shows the benefits of implementing energy-efficient upgrades in educational buildings. From the table, cost savings ranked first with (MS=4.38, SD=0.926), achieving carbon neutrality ranked second with (MS=4.33, SD=0.980), reduction in carbon emission ranked third with (MS=4.32, SD=1.045), improved learning environment ranked fourth with (MS=4.30, SD=0.964), improved building resilience ranked fifth with (MS=4.29, SD=0.971), improved energy efficiency ranked sixth with (MS=4.27, SD=1.058). Ranking least is improved indoor air quality with (MS=3.51, SD=1.074), followed by long-term energy savings and increased environmental responsibility with (MS=3.57, SD=1.021) and (MS=3.57, SD=1.134) respectively.

Table 1: Strategies for Energy-Efficient Upgrades

Strategies	Mean	SD	Rank
Upgrading lighting systems.	4.47	0.742	1
Improving the heating, ventilation, and air conditioning (HVAC) system	4.43	0.778	2
Renewable energy integration	4.34	0.838	4
Building automation	4.33	0.903	3
Smart energy management systems	4.33	0.829	5
Greywater recycling	4.26	0.891	6
Sustainability awareness	4.25	0.893	7
Installing Low-Flow Fixtures	3.35	1.248	8
Using Occupancy-Based Controls	3.24	1.096	9
Improving Insulation and Weatherproofing	3.22	1.092	10
Upgrading to Smart Thermostats:	3.19	1.062	11
Replacing Old HVAC Units with Energy-Efficient Models	3.06	1.164	12
Using Natural Light Optimisation	3.05	1.092	13
Installing Motion Sensors and Timers	3.05	0.999	14

(Source: Authors')

Table 2: Benefits of Energy-Efficient Upgrades

Benefits	Mean	SD	Rank
Cost savings	4.38	0.926	1
Achieving carbon neutrality	4.33	0.980	2
Reduced carbon emissions,	4.32	1.045	3
Improved learning environments	4.30	0.964	4
Improved building resilience	4.29	0.971	5
Improved energy efficiency	4.27	1.058	6
Improved building performance	4.22	0.988	7
Improved HVAC system	4.07	1.003	8
Reduction in utility bills	4.05	0.934	9
Increased environmental responsibility	3.57	1.134	10
long-term energy savings	3.57	1.021	11
Improved indoor air quality	3.51	1.074	12

(Source: Authors')

4.4. Discussion

The findings from the questionnaire survey reveal significant insights into the effectiveness of energy-efficient upgrades in educational buildings. The results indicate that institutions implementing energy-saving technologies experienced noticeable reductions in energy consumption and operational costs. Most respondents reported that LED lighting upgrades led to a 30–50% decrease in electricity usage, confirming previous studies highlighting LEDs as a cost-effective solution for educational institutions (Idowu et al., 2024). Additionally, schools that installed motion sensors and automated lighting controls reported further savings by ensuring lights were only used when necessary. The study also found that HVAC system upgrades were crucial in improving energy efficiency. Schools that replaced outdated heating and cooling systems with energy-efficient HVAC units and smart thermostats reported 15–35% reductions in energy use.

Additionally, institutions that improved insulation and weatherproofing experienced better indoor temperature regulation, leading to reduced dependence on heating and cooling systems. This aligns with research by Idowu et al. (2024), emphasising the importance of proper insulation in minimising energy waste. Building automation and smart energy management systems also contributed to efficiency improvements. Schools that implemented real-time energy monitoring systems and occupancy-based controls reported better energy optimisation, as these systems adjusted heating, cooling, and lighting based on actual demand (Altassan, 2023). Respondents noted that automated systems reduced human error in energy management and helped facility managers identify further areas for improvement.

Respondents highlighted significant cost savings, with many schools reallocating funds from energy expenses to academic resources and infrastructure improvements. Improved indoor air quality and thermal

comfort were also widely reported, contributing to better student concentration, attendance, and overall learning conditions. Furthermore, schools that embraced energy-efficient upgrades served as models for sustainability, raising awareness among students and fostering a culture of environmental responsibility.

5. Conclusion and Further Studies

Energy-efficient upgrades present a clear path toward carbon neutrality for educational buildings. These upgrades reduce operational costs, minimise environmental impact, and create healthier and more sustainable learning environments. By investing in energy-efficient technologies, schools and universities can lead by example, fostering a culture of sustainability among students and the wider community. With the right strategies, policies, and financial support, the education sector can make significant progress in achieving energy efficiency and contributing to global efforts to combat climate change. The study recommends stronger policy incentives and financial support for educational institutions to facilitate the adoption of energy-efficient solutions. Governments and private organisations should offer grants, subsidies, and low-interest loans to make energy-efficient upgrades more accessible. Additionally, partnerships between educational institutions and industry experts can drive innovation and knowledge-sharing in sustainable infrastructure. Schools and universities should also engage in collaborative initiatives that allow them to share resources, expertise, and best practices.

The study is limited to Gauteng province, South Africa. A broader geographic scope beyond the province could offer a more comprehensive understanding of the required strategies.

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