

Energy management framework for low-income schools in developing regions

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ABSTRACT

This study presents a comprehensive framework designed to optimise energy management in low-income schools in developing regions, specifically aiming to address challenges such as limited resources, lack of technical skills, unreliable energy infrastructure, and low levels of energy literacy. Taking advantage of South Africa's unique energy landscape, the framework integrates renewable energy solutions, low-cost efficiency measures, and sociotechnical approaches to enhance energy efficiency while promoting sustainability. By combining global best practices with localised socio-economic insights, the study develops a flexible and scalable energy management strategy. This framework prioritises data-driven methods, stakeholder collaboration, and incremental implementation, ensuring contextual adaptability. The proposed model highlights cost reduction, energy efficiency, energy reliability, and behavioural optimisation, offering actionable pathways to empower educational institutions while addressing systemic energy inefficiencies. The framework is grounded in a mixed-methods approach and supported by empirical data from recent studies conducted in low-income South African schools, allowing schools to transition to sustainable energy practices, reduce dependency on fossil fuels, and foster energy literacy among students and staff. This proposed framework can significantly contribute to lower energy costs, reduced carbon emissions, and increased awareness and knowledge of sustainable energy practices in educational settings in developing regions.

1. Introduction

Considering the different challenges and unique socio-economic conditions of low-income developing countries, it is essential to establish a framework specifically tailored to their realities [1]. It must prioritise affordability, sustainability, and accessibility, ensuring that solutions can be easily implemented in resource-scarce settings, and recognise the vast potential for localised solutions. The Sustainable Development Goals 7 (SDG-7) progress review of the 2018 UN High-Level Political Forum revealed that outdated and ineffective policy frameworks are one of the main barriers to transforming cities into sustainable environments. These frameworks, in addition to market barriers, financing gaps and insufficient technical capacity, hinder the effective implementation of clean energy solutions and urban planning necessary to achieve the SDGs [2]. Beyond the critical role schools play in education and training, they can serve as powerful models for energy efficiency, instilling sustainable habits in students that extend far beyond the classroom, and influencing how learners interact with energy in their homes, communities, and future workplaces [3,

4]. In low-income regions, where access to reliable and affordable energy is often limited, the potential for schools to drive positive change is particularly significant. Schools can lead initiatives that teach the importance of resource conservation, integrate renewable energy technologies, and present practical energy-saving measures, contributing to a more energy-conscious generation and fostering resilience in communities facing energy challenges.

ISO 50001, an international standard for Energy Management Systems (EnMS), provides a structured framework for integrating energy management into organisational processes [5]. Although effective for formal organisations, these frameworks are often unsuitable for low-income schools in developing regions due to their unique operational challenges [6,7]. Many of these schools lack basic infrastructure and rely on intermittent energy sources, making the rigid framework of ISO 50001 difficult to implement. The standard's focus on stable energy systems fails to address the unreliable access and fluctuating needs common in such contexts. In addition, upfront costs, technical complexity, and resource demands can outweigh its benefits, particularly for

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schools with limited financial and human resources. Recent advances in energy management introduce a comprehensive energy management framework that underscores the transition from focusing solely on individual components to adopting a systems approach, optimising entire processes for more substantial energy efficiency improvements, and the importance of integrating technical and social strategies [8]. However, these frameworks are largely contextualised within developed nations and do not fully account for the socio-economic complexities and infrastructural limitations faced by schools in developing regions. This gap presents a critical opportunity to design energy management strategies that are locally adaptable, cost-sensitive, and capable of bridging the energy divide in under-resourced educational settings.

1.1. Global energy management in schools: Framework and strategies

The global energy landscape is undergoing a fundamental transformation driven by the need for sustainable and efficient energy management to address rising demands and environmental challenges [9,10]. This shift emphasises the integration of renewable energy, improving efficiency and reducing carbon footprints [11]. Climate change and the depletion of fossil fuels have made resilient and adaptable energy infrastructure a global priority. Innovative solutions leveraging the Internet of Things (IoT), data analytics, smart grids, and intelligent systems are revolutionising energy production, distribution, and use [10,12]. A framework piloted in 13 post-primary schools across six North-West European countries integrated technological, social, and behavioural components to tackle energy inefficiency. Using smart meters, digital platforms, and real-time indoor environmental quality (IEQ) monitoring, the framework adopted a data-driven approach to analyse energy use, environmental quality, and stakeholder actions [3].

Zhang and Bluysen [13] focused on the relationship between energy usage and how teachers and students perceived IEQ in schools in the Netherlands, highlighting the importance of understanding the behavioural and environmental factors that influence energy use. The study aligned teacher actions, student perceptions, and technical interventions, creating an approach that addresses energy usage and indoor environmental quality through real-time energy monitoring, energy audits, and behavioural insights. A major finding was that improving energy efficiency requires maintaining good IEQ without sacrificing comfort, and audits help identify areas where schools can reduce energy usage while maintaining comfortable learning environments.

Behavioural change and social participation, specifically, a ‘learning by doing’ method involving competition between schools, gamification, and web platforms for energy monitoring was used to reduce energy usage [14]. An important lesson was that behavioural changes at the individual and collective levels play a critical role in improving energy efficiency but should be combined with energy efficient measures [14, 15].

Educational modules and real-life data collection systems have been developed to engage students in learning about energy and how to manage it sustainably [16,17]. The focus was on promoting energy literacy among students, ensuring that energy literacy covers three dimensions: knowledge, attitude, and behaviour [17]. The critical importance of stakeholder collaboration and adaptable regulatory frameworks in the development of effective global energy strategies is reiterated [10].

1.2. Energy management for developing regions: Frameworks and strategies

Sabory et al. [1] proposed an administrative framework for the integration of smart and sustainable energy systems in urban planning in low-income developing countries, using Afghanistan as a case study. Although offering a hierarchical structure for integration, it lacked practical implementation guidelines. The Integrated Rural Energy Scheme (IRES) in Nigeria tackled the challenges of electrification in rural areas by integrating renewable resources such as solar, biomass, hydro and wind into decentralised systems such as mini-grids and

standalone units [18]. IRES addressed socioeconomic, technical and environmental barriers, focusing on local needs, geographic realities, and stakeholder participation, including policymakers, private players, and communities, to ensure sustainability. Its feasibility was demonstrated [19]. Moran et al. [20] introduced a convergence framework that highlights the collaborative and localised energy solutions that integrate social and environmental sciences. This approach demonstrated the success of context-specific strategies over generalised ones, emphasising adaptability and active stakeholder participation. Similarly, Chicombo and Musango [21] proposed a framework addressing gendered aspects of energy transitions in urban households in Mozambique, emphasising that integrating gender considerations is crucial for comprehensive energy transition strategies in developing economies. Colombo et al. [22] presented a Comprehensive Energy Solution Planning (CESP) framework, which offers a multi-criteria, evidence-based planning method for sustainable energy access projects. Their model integrated socio-economic, environmental, and technical variables to support national and regional decision-making in developing countries. However, the CESP framework is oriented towards macro-level planning and does not address operational challenges at the single-entity nor does it incorporate direct stakeholder engagement at the grassroots level. Similarly, Swarnakar and Singh [23] proposed a community-centric energy transition framework rooted in participatory governance and energy justice. While their model emphasises socio-political equity, it remains conceptual and lacks an implementable technical architecture for local energy management. In the investment domain, Abba et al. [24] introduced a holistic risk management framework for renewable energy projects, focusing on financial, technical, and environmental risks. This work is valuable for guiding developers and investors, but does not extend to deployment strategies for end-user-based systems. Furthermore, Lacey-Barnacle et al. [25] provided a critical review of energy justice literature in developing contexts, identifying a persistent gap in grounded, context-specific models that actively engage underserved communities. While their work strongly advocates for inclusive energy solutions, it falls short of offering operational mechanisms or governance structures. Together, these studies highlight the importance of inclusive, equitable, and well-planned energy strategies in developing regions; however, they reveal a lack of practical, mid-tier frameworks. The framework proposed in this study addresses this gap by offering a technically implementable, context-specific operable model.

Thollander et al. [8] introduced a transformative model that prioritises systems-level optimisation over isolated component-based improvements. Their framework emphasises the importance of holistic energy management, accounting for the interactions between different energy-consuming systems. A significant contribution of their study is the integration of socio-technical strategies, which include leadership commitment, employee engagement, and community-based participation, to enhance energy efficiency. They identify nine key social constructs necessary for sustainable energy optimisation, highlighting that technical solutions alone are insufficient without corresponding behavioural shifts. Integrating these socio-technical strategies into energy management in low-income schools in South Africa presents an opportunity to overcome typical barriers such as limited financial capacity and low energy awareness. Efficient energy management in developing regions should be built on socio-technical pillars shaped by the interplay of technology, user habits, social dynamics, and institutional practices [8,13,26]. A systemic approach that integrates technical infrastructure – such as energy-efficient appliances, renewable energy, community energy trading, and smart systems – with human factors like behaviour, awareness, and social engagement has the potential to be effective in the low-resource context.

1.3. South African energy context

Electricity was historically viewed as a public monopoly, with governments or single entities managing generation, transmission, and distribution to maximise efficiency [27]. In South Africa, post-apartheid electrification efforts relied on large state-controlled monopolies like Eskom. However, the 1998 White Paper on Energy Policy acknowledged the need for reform to ensure reliability, environmental sustainability, and a competitive electricity market [28]. Key proposals included unbundling Eskom into separate units (Generation, Transmission, and Distribution) and encouraging competition where feasible. Despite limited implementation, recent reforms have gained traction. The government has begun splitting Eskom into three units under the Eskom Holdings umbrella, supported by amendments to the Electricity Regulation Act (ERA). These changes allow independent power producers (IPPs) to enter the market, allow municipalities to purchase directly from IPPs, and reduce Eskom dependence [29,30]. In addition, Eskom's Just Energy Transition (JET) plan focuses on the repurposing of coal plants for renewable energy while promoting job creation and local manufacturing in the renewable sector. Simplified regulations, such as the elimination of approval requirements for small-scale power generation projects, further facilitate the development of renewable energy.

South Africa's heavy dependence on coal for energy has serious environmental and public health consequences due to the high carbon emissions and pollution from coal-fired power plants. This dependency is exacerbated by the ageing of the energy infrastructure, the underinvestment in modern power plants, and the slow adoption of renewables, leading to significant energy capacity gaps. As a result, nationwide load shedding has persisted for more than 17 years [31]. The urgent need for a diversified energy mix and investments in renewable energy is clear to reduce coal dependency and ensure a sustainable and reliable energy future. Electricity tariffs in South Africa have increased sharply, increasing by 653% between 2007 and 2022, compared to an inflation rate of 129% [32,33]. In 2023, an additional 18.65% increase was approved to help Eskom address financial and operational challenges. Meanwhile, the effects of climate change, including record high temperatures of 42 °C in Cape Town in 2015 and the lowest annual rainfall since 1904, have worsened droughts, fires, and water insecurity. These challenges highlight the pressing need for climate action, yet research and solutions remain insufficient to address these issues comprehensively.

South Africa has established several standards to promote energy efficiency and safety in the built environment. Still, there remain gaps in the effective application of these standards within the education sector. Two key standards, South African Bureau of Standards [34] (SANS 1544) and South African Bureau of Standards [35] (SANS 10400-XA), are designed to guide energy performance and building efficiency. SANS 1544 outlines the process for generating Energy Performance Certificates (EPCs) for buildings, and SANS 10400-XA provides specific guidelines to optimise energy efficiency, classifying buildings based on occupancy, PSU (Primary Space Usage) and climatic zones.

1.3.1. Energy and education context in South African schools

In South Africa, electrified schools contribute 6 million kg of CO₂ daily due to high electricity usage and extensive infrastructure [36], making them an important factor in environmental protection [37]. The government mandated electricity for all public schools by November 2020 [38], resulting in more than 12,000 grid-connected and 3000 off-grid schools. Most schools are powered by Eskom's coal-based stations, increasing national carbon emissions. South Africa's quintile system (Q1 to Q5) categorises public schools into five groups according to the socioeconomic status of their communities and the quality of school infrastructure. Quintile 1 (Q1) schools serve the most economically disadvantaged areas and frequently struggle with limited resources and infrastructure, while quintile 5 (Q5) schools are in affluent communities

with more facilities. Low-income schools in this context are considered the Q1-Q4 schools, while Q5 schools are considered high-income schools [39]. This classification is intended to promote equitable financial allocation, and Q1 schools receive the highest level of funding to address disparities, support educational quality, and bridge resource gaps in the education system [40].

The poor energy performance of educational institutions arises from complex, interconnected factors that require a systemic approach – largely absent in current research. Studies in developing regions emphasise the need for energy management solutions tailored to local contexts [1,10,18,21]. The primary objectives of this study are to develop a scalable energy management framework tailored to the unique needs of low-income schools in developing regions. These objectives are directly linked to the gaps identified in the literature, specifically the lack of adaptable energy solutions for resource-constrained schools in developing regions. The proposed framework is designed not only to address current inefficiencies but also to provide a sustainable, long-term energy strategy that can be replicated across similar settings in the Global South. This study examines energy use patterns and management challenges, incorporating energy-efficient solutions, behavioural change strategies, and stakeholder engagement, while emphasising local adaptation to socio-economic and environmental conditions. Beyond optimising energy use, the framework provides a scalable, transferable model for other schools in similar contexts, providing lasting benefits to schools and their communities. To the authors' knowledge, no energy management framework specifically designed for low-income schools in developing regions currently exists. While studies like Brychkov et al. [3], Iljoianya et al. [10] and Thollander et al. [8] provide critical insights into energy management, their models lack scalability in severely resource-constrained environments. Table 1 offers a comparative overview of selected global frameworks and how they align or fall short in addressing the unique needs of low-resource educational institutions. The proposed framework builds upon these models, integrating their strengths while ensuring local adaptability and implementation feasibility. This study addresses this gap by proposing a novel, data-driven energy management framework that not only optimises energy consumption but also improves resilience and sustainability. Drawing from global best practices and local socio-economic insights, the framework prioritises low-cost efficiency measures, stakeholder collaboration, and scalable implementation strategies. The framework enables cohesive collaboration among policymakers, energy specialists, NGOs, and local communities, ensuring that solutions are technically sound and contextually relevant. The framework facilitates tailored, resilient, and sustainable energy strategies by integrating data analysis, participatory planning, and renewable energy systems. It is adaptable to local conditions and incorporates global best practices to enhance scalability and effectiveness in rural energy access.

2. Methodology

This study adopts a mixed-methods approach to develop a scalable, data-driven energy management framework tailored to low-income schools in South Africa. To develop a Scalable Energy Management Framework, a systematic literature review was conducted to identify existing energy management practices and frameworks. Key insights from global studies were analysed to understand the principles of scalability and adaptability in energy management for resource-constrained settings. Furthermore, South African-specific energy policies and infrastructure challenges were examined to contextualise the framework. A data-driven approach was employed, utilising a one-year dataset from 55 schools in South Africa. This approach combined theoretical insights with the socio-economic realities of these schools. The review focused on energy management in resource-constrained environments, sustainable energy solutions, and their integration into educational institutions. Keywords such as 'energy management', 'low-income schools', and 'renewable energy integration' guided the selection of studies,

Table 1
Comparison of selected energy management frameworks.

Framework/Source	Focus area	Limitations in low-income school contexts	Proposed framework
International Organization for Standardization [5] (International standard)	Industrial and commercial energy management systems.	High technical complexity, requires trained personnel, limited behavioural or institutional considerations.	Tailored to school-level implementation; integrates behavioural, technical, and stakeholder dimensions.
Thollander et al. [8]	Digitalised, stakeholder-driven, and sector-integrated energy management framework.	Designed for high-capacity industrial/commercial contexts; lacks granularity for low-resource public schools.	Builds on stakeholder feedback loops, but adapted to low-resource school realities with simple, scalable tools.
Brychkov et al. [3]	Systemic energy efficiency in European schools.	Context-specific to European settings, assumes reliable infrastructure and institutional capacity, limited financial flexibility.	Adaptable to infrastructural gaps, intermittent supply, and resource constraints in developing regions. Incorporates systemic approaches adaptable to various contexts.
Ilojanyia et al. [10]	Review of data-driven energy management in North America and Africa.	Highlights data centrality, but lacks a unified framework tailored to schools or phased low-cost deployment.	Builds a unified, education-specific, data-first model with scalable, context-sensitive implementation.
Ugwoke et al. [18]	Comprehensive review of Nigerian energy access studies.	Focuses on national-level energy access, lacks specific frameworks for school-level energy management.	Provides contextual insights that inform the development of school-specific energy management frameworks.
Sabory et al. [1]	Integration of smart and sustainable energy systems in urban planning for low-income developing countries.	Urban planning focus, does not address the specific needs of educational institutions.	Offers a macro-level perspective that complements school-level energy management strategies.
Chicombo and Musango [21]	Theoretical framework for gendered energy transition at the urban household level.	Concentrates on household energy use and lacks direct application to school settings.	Highlights the importance of inclusivity and stakeholder engagement in energy management frameworks.
Proposed framework	Low-income school energy management in resource-constrained settings	–	Integrates technical, behavioural, institutional, and financial strategies; designed for adaptability and scale

ensuring relevance to energy access, efficiency, and sustainability challenges. The study included an in-depth analysis of South Africa's energy challenges, highlighting disparities in access, dependency on fossil fuels, and the environmental impacts of current practices. Existing policy frameworks regulating energy management were also assessed, identifying gaps, strengths, and limitations in addressing the energy needs of low-income schools. Additionally, global best practices and case studies informed recommendations for adapting successful energy strategies to local contexts. Key stakeholders in sustainable energy management were mapped to understand their roles and interactions, which informed the framework design. The proposed framework integrates social, technical, financial, and institutional factors, addressing both energy needs and broader socio-economic challenges. To support adaptability, the study offers broad stakeholder recommendations for low-income countries alongside tailored policy guidance specific to South Africa. Finally, the methodology is visually presented as a step-by-step process, demonstrating the integration of global insights with localised policy analysis to create a robust, adaptable framework for sustainable energy management in low-income schools. Fig. 1 outlines the methodology.

2.1. Inputs

There were three main inputs for the methodology: the South African context, the global context, and the energy management strategies for developing regions.

2.1.1. The South African context

South Africa's specific data, including the education system, energy management policies, and energy challenges and issues, contained valuable insights. It helped to understand how South African schools operate, their infrastructure, strengths, weaknesses, and the resources available to them. The energy management policies in SA were examined; the current regulations and policies governing energy use and sustainability in South African schools. This includes policies related to energy efficiency, the adoption of renewable energy, and government

support for low-income institutions. In addition, identifying specific energy-related issues faced by schools was critical to developing the framework.

2.1.2. Case study

The study was conducted across 55 low-income schools in South Africa, comprising both primary and secondary schools, distributed between urban and rural areas, reflecting the diverse socio-economic and infrastructural challenges present in these settings. Students attending these schools range from 5 to 18 years of age, representing a mix of early learning and secondary education stages. Table 2 captures more details about the schools. This table presents key features, including school ID, quintile, school type, and the number of learners and educators. The dataset includes schools from quintiles 1 to 4, all reliant on the national grid with no renewable energy sources. All the schools are government-owned schools that follow the yearly calendar of the Department of Basic Education, spanning January to December and divided into four terms.

2.1.3. Global context

Global plans and strategies for energy management and global energy management challenges were reviewed to enable learning from global best practices, case studies, and successful frameworks implemented.

2.1.4. Energy management strategies for developing regions

Strategies, policy reviews, and case studies from countries with similar socio-economic conditions provide valuable insights into what has been successful and what challenges remain. These comparative examples offer lessons on both effective approaches and potential pitfalls, helping to inform and refine future decisions.

2.2. Contextual parameters

The inputs are processed through several contextual parameters that shape the development of the framework, influencing how they are analysed and adjusted to ensure local relevance.

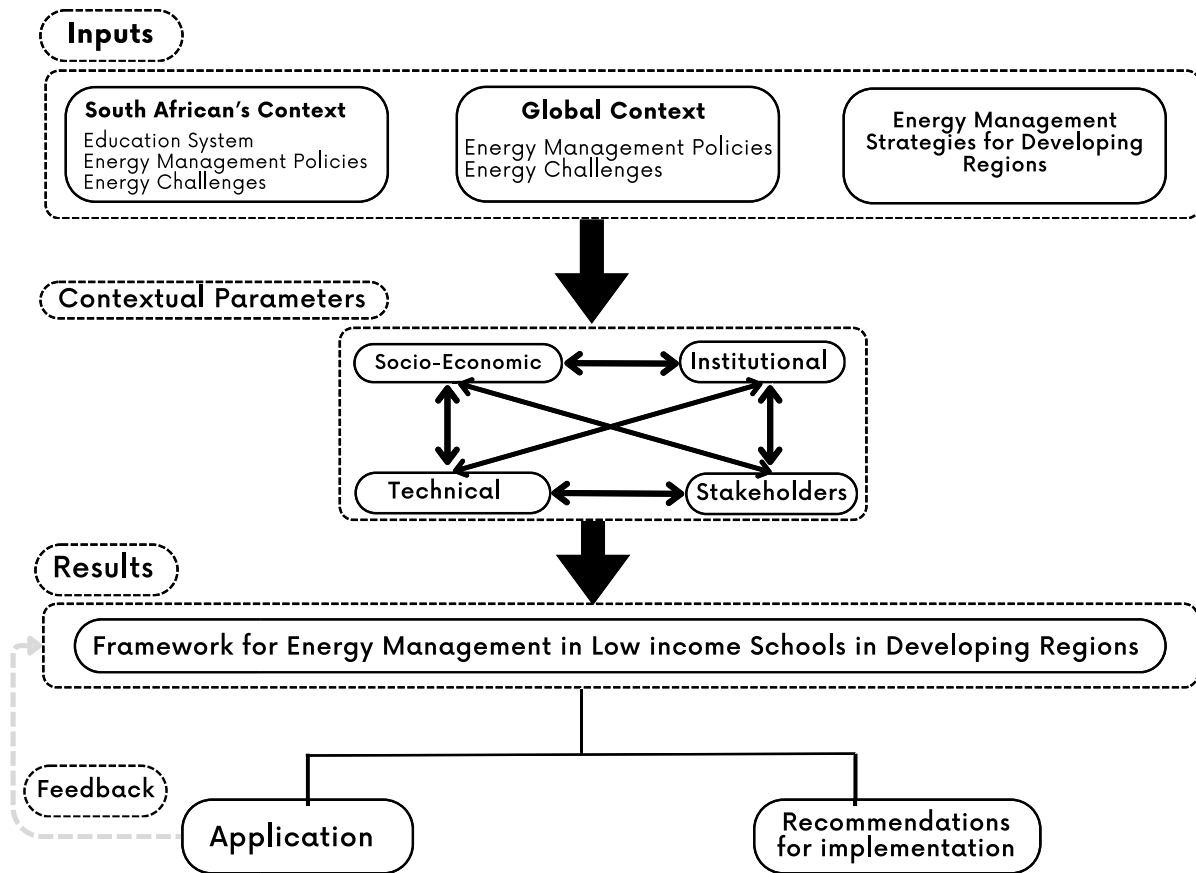


Fig. 1. Methodology for developing an energy management framework for low-income schools in developing regions.

2.2.1. Socio-economic context

The socio-economic context encompasses financial, social, and cultural factors that influence the perception, adoption, and implementation of energy management solutions in low-income schools. This context is vital in developing regions, where resource limitations, cultural practices, and community involvement shape energy outcomes. Socio-economic factors such as income levels, education, and energy habits significantly impact the adoption of renewable energy. In poorer communities, renewable solutions may be perceived as expensive or unfamiliar, necessitating careful consideration of cost-benefit and long-term sustainability. Beyond installation costs, schools must account for operational and maintenance expenses, as budget constraints are a common barrier. Access to funding – whether through government, non-profits, or community initiatives – is critical to enabling investment in new energy technologies.

2.2.2. Technical context

This parameter assesses the existing technological infrastructure in schools and the feasibility of implementing new energy solutions. It considers energy usage patterns, the availability of renewable resources, and the technical capacity for system maintenance. The technical context ensures that proposed solutions are practical and compatible with current infrastructure limitations.

2.2.3. Institutional context

This encompasses governance, policy frameworks, and regulations shaping energy management in schools. It includes operational boundaries, funding mechanisms, policy enforcement, institutional leadership, and decision-making processes.

2.2.4. Stakeholders context

This parameter highlights the role of stakeholders: government agencies, school administrators, students, teachers, parents, and energy

providers, in shaping and implementing energy management strategies. Engaging these stakeholders ensures solutions are relevant, supported, and sustainable by fostering consensus, securing funding, aligning with operational needs, and addressing community preferences for long-term success.

2.3. Framework for energy management in low-income schools development

Processing inputs through contextual parameters generates an adaptive energy management framework tailored to low-income schools in developing regions. The framework combines local (South African) and global insights to address specific challenges while remaining flexible for localisation and universally applicable.

2.4. Outputs of the framework: Applications and recommendations

The framework is then applied to produce results in two key areas; **applications** and **recommendations for framework implementation**. The application phase transitions the framework from theory to practice, translating contextual insights into actionable strategies tailored to low-income schools' unique needs. recommendations proffer specific guidelines for implementing the framework in South Africa and other low-income regions. The guidelines provide scalable, adaptable strategies for implementing the framework in South Africa and other low-income regions. They ensure alignment with policies, support capacity-building, and facilitate the integration of sustainable energy solutions tailored to each school's needs, delivering long-term benefits to the education sector.

2.5. Feedback loop

The methodology incorporates a feedback loop to ensure that the energy management framework remains practical, relevant, and

Table 2
General features of the schools in the case study.

School ID	Quintile	Type	Learners	Educators
S1	2	Primary	1431	38
S2	1	Primary	605	21
S3	1	Primary	1405	43
S4	4	Primary	579	19
S5	2	Primary	794	24
S6	3	Primary	1075	34
S7	2	Secondary	1053	29
S8	3	Primary	1439	44
S9	1	Primary	773	22
S10	1	Primary	678	20
S11	3	Combined	1159	38
S12	3	Secondary	610	19
S13	2	Primary	1341	41
S14	4	Secondary	1619	46
S15	1	Primary	905	28
S16	1	Secondary	1123	35
S17	2	Secondary	1730	58
S18	1	Secondary	1319	29
S19	1	Secondary	1015	25
S20	1	Primary	356	11
S21	3	Primary	1630	52
S22	2	Secondary	958	31
S23	4	Secondary	545	14
S24	3	Secondary	1758	46
S25	2	Primary	1894	52
S26	3	Primary	434	17
S27	2	Primary	515	15
S28	3	Primary	1233	34
S29	3	Secondary	1266	38
S30	3	Primary	534	20
S31	2	Primary	759	27
S32	3	Intermediate	525	18
S33	3	Combined	590	17
S34	1	Primary	435	12
S35	3	Primary	1110	34
S36	2	Primary	1236	38
S37	2	Intermediate	620	21
S38	2	Primary	447	16
S39	3	Primary	1397	41
S40	1	Primary	1502	40
S41	1	Primary	778	31
S42	3	Combined	930	28
S43	1	Secondary	1861	47
S44	2	Primary	1495	40
S45	1	Primary	502	18
S46	3	Secondary	840	27
S47	1	Secondary	1276	37
S48	2	Secondary	1334	40
S49	3	Primary	1728	42
S50	1	Primary	553	18
S51	2	Primary	562	22
S52	1	Primary	458	17
S53	1	Secondary	742	27
S54	1	Primary	1400	35
S55	3	Secondary	1704	68

adaptable over time. Although primarily theoretical, parts of the framework have been implemented in select schools, providing scenario-based insights that refine and improve the framework. This iterative process combines empirical data with conceptual feedback from stakeholders such as administrators, policymakers, and energy experts, offering valuable perspectives on feasibility and applicability. By integrating real-world experiences and theoretical insights, the framework evolves dynamically to address emerging challenges and changing conditions, ensuring its effectiveness in diverse educational contexts.

3. Results and discussion

This study examined South Africa's energy management landscape, identifying key policy gaps and implementation challenges through national and international perspectives. This section highlights key gaps,

explores successful global strategies, and emphasises their relevance to South Africa's energy and education sectors.

3.1. Energy challenges and policy gaps in South Africa

Energy efficiency in low-income schools in developing regions faces several challenges requiring attention for sustainable improvements. A key gap is the lack of energy literacy among students, teachers, and staff, limiting awareness of energy conservation, renewable options, and the benefits of sustainable practices [41,42]. Similar issues have been observed globally [3,8,16], reducing user contributions to energy-saving efforts. South African low-income schools also suffer from energy access issues, including insufficient real-time monitoring, poor management of peak-hour energy costs [41], and outdated energy-intensive infrastructure like inefficient lighting systems [42]. Administrators often lack the knowledge to make informed decisions about energy efficiency, utility management, and cost-saving measures [39, 41,43].

Sustainable financing for energy efficiency projects is another critical barrier, disrupting the implementation and longevity of energy-saving initiatives. Additionally, these schools lack structured stakeholder networks essential for resource sharing, knowledge transfer, and coordinated action. South Africa's energy policies promote renewable energy but fail to address behavioural interventions or provide adequate funding and infrastructural support [39,44]. The disparity between affluent and low-income schools further compounds the issue. While well-resourced schools benefit from advanced energy-efficient technologies, low-income schools rely on outdated, energy-intensive systems, leading to higher costs and environmental impact [39].

According to SANS 10400-XA, all primary and secondary schools in the Western Cape fall into the category – 'Places of Instruction' (A3) in energy zone 4, with a reference benchmark of 60 kWh/m²/year. However, this benchmark does not adequately reflect the diversity among schools. Although well-resourced schools (Q5) consume 25–55 kWh/m²/year, low-income schools (Q1–Q4) exhibit much lower energy use, typically 8–20 kWh/m²/year, due to resource constraints and differing usage patterns. The difference between standardised benchmarks and actual energy consumption in low-income schools highlights a critical flaw in energy policy: the lack of customised metrics suited to diverse school profiles. Furthermore, the current system overlooks seasonal and termly variations in energy use, which is critical for schools with irregular schedules. Low occupancy periods, such as holidays, present significant yet underutilised energy-saving opportunities. Globally, energy benchmarking has gone beyond the primary use of space alone, incorporating load profiles and other influencing factors to provide more accurate assessments [45–47].

3.2. Global energy management insights

Globally, successful energy management strategies have leveraged technologies such as smart grids and advanced metering infrastructures (AMI) for real-time energy monitoring and dynamic load balancing. The transition to energy-efficient lighting remains one of the most cost-effective strategies for schools, with widespread success [48–51]. Energy efficiency programmes offering incentives for upgrades and demand response initiatives to reduce peak period energy usage have also been proven effective [52].

The adoption and expansion of renewable energy sources, such as solar, wind and hydropower, and the adoption of off-grid solutions have helped reduce the dependence on fossil fuels in developed regions [10, 20]. Predictive analytics and machine learning are increasingly used to forecast energy demand and optimise grid efficiency [53–55]. However, while decentralised energy systems offer energy independence, their high upfront costs and complexity make them less viable for low-income schools operating under severe budget constraints.

3.3. Evolution of global energy management frameworks

Energy management frameworks have evolved significantly over the past few decades, driven by global energy challenges, technological advancements, and heightened environmental awareness. Historically, energy management focused predominantly on component-level optimisation, targeting individual systems such as HVAC units, electric motors, and lighting [26,39,56]. While these approaches delivered incremental improvements, they fell short of addressing the systemic inefficiencies inherent in broader energy consumption patterns and the interconnected nature of energy use [7,8]. A systems-level optimisation, which considers the complex interactions between equipment, user behaviours, and energy policies, is the current direction for energy management [8]. This holistic approach enables energy efficiency improvements across entire operations, optimising not only isolated components but also the synergy between them [8]. Parekh et al. [57] advances this concept by applying an Energy Management Maturity Matrix (EMMM) specifically tailored to chemical process industries in India, with a focus on small and medium enterprises (SMEs), proposing a strategic assessment tool that not only identifies gaps but also guides firms towards progressive energy optimisation. Their framework enables organisations to evaluate current energy practices across multiple dimensions, including technology, policy, and behaviour, and prioritise improvements. This aligns with the systems-level and socio-technical principles advanced by Thollander et al. [8]. In contrast, frameworks designed for low-income settings in Africa and Southeast Asia have focused primarily on decentralisation, emphasising microgrids and off-grid solar systems to mitigate unreliable grid access [9]. Studies by Brychkov et al. [3] and Samuels and Booyesen [41] show that educational institutions are typically underserved in energy policy planning, despite their substantial energy footprints and role in community development. The transition towards systems thinking has been demonstrated in global pilot projects; the North-West European School Energy Framework piloted in 13 post-primary schools emphasised smart meters, digital platforms, and real-time IEQ monitoring to optimise energy usage holistically [3]. This data-driven, systems-level perspective led to significant reductions in energy consumption while maintaining optimal learning environments. In addition, the role of digitalisation (IoT, smart grids, and real-time monitoring) in achieving sustainable energy management was demonstrated in [8]. Advances in energy management also include national change and stakeholder engagement [14,16]. This socio-technical perspective is particularly relevant for low-income schools in developing regions, where community involvement and stakeholder alignment are crucial for successful energy management. Finally, the global evolution of energy management has also been driven by policy. The establishment of ISO 50001 provided a standardised approach for organisations to implement energy management systems. This standard encourages continual improvement in energy performance, emphasising monitoring, reporting, and policy integration [5]. These lessons are crucial for the design of the proposed framework in this study, which aims to adapt advances in global best practices to the unique context of low-income schools in developing regions.

3.4. Application to South African low-income schools

The proposed framework adapts these global best practices to South African schools' unique socio-economic and infrastructural constraints. By combining data-driven energy monitoring, community-based energy trading, and renewable integration, it provides a scalable solution that addresses both energy efficiency and sustainability. Unlike ISO 50001, which presupposes stable infrastructure and significant financial investment, this framework is designed for modular deployment, allowing low-income schools to progressively adopt energy-saving measures. Furthermore, community-based energy trading introduces a novel opportunity for schools to generate revenue from excess renewable energy production, potentially offsetting operational costs and reducing dependency on fossil fuels. This aligns with global energy transitions that emphasise local energy resilience and sustainable development.

3.5. Framework scalability and policy implications

A key strength of the proposed energy management framework lies in its inherent scalability and adaptability across diverse educational contexts. Designed with flexibility in mind, the framework leverages low-cost, modular technologies, such as smart meters, behavioural strategies, and phased renewable energy integration, making it both financially accessible and technically feasible for schools in low-income and under-resourced regions. For example, the framework is empirically supported by energy usage data from 55 South African schools, where energy use intensity (EUI) benchmarks were found to range between 12 and 37 kWh/m²/year, significantly below the prevailing national benchmark of 60 kWh/m²/year. These values align with international findings from other low- to middle-income or mild-temperate regions, reinforcing the framework's transferability. For instance, public primary schools in Australia (many of which lacked energy-intensive amenities such as HVAC systems, computer labs, and sports facilities), reported a mean EUI of 33.1 kWh/m²/year when using electricity only [58], while schools in Taiwan exhibited EUIs ranging from 20.1 to 22.5 kWh/m²/year depending on level and infrastructure [59]. In Brazil, a large-scale study of school facilities revealed an estimated average EUI of 27 kWh/m²/year [60]. These benchmarks provide strong comparative validation, indicating that the proposed framework, originally contextualised for South Africa, can be feasibly adapted to similar socioeconomic and climatic settings globally. Furthermore, the use of behaviourally-driven optimisation, stakeholder co-creation, and continuous feedback loops enhances the framework's resilience and relevance across regions with varying institutional capacities. From a policy perspective, the framework aligns with Sustainable Development Goal 7 (SDG 7) by promoting affordable, reliable, and modern energy services for schools. Its modular structure allows for phased integration into education and energy policy at local, provincial, or national levels. By standardising data collection, promoting energy awareness, and supporting renewable energy adoption in schools, the framework serves as a replicable model for sustainable energy transformation in the education sector.

3.6. Developing regions energy management insights

Other developing regions have implemented innovative energy strategies tailored to their unique challenges. Sub-Saharan Africa and parts of Southeast Asia have adopted decentralised solutions like microgrids and off-grid solar systems to address unreliable grid access, focusing on cost-effectiveness, local engagement, and integration of renewable energy. These approaches offer insights into South Africa's similar challenges. For under-resourced schools, a simplified model for forecasting energy needs to size grid-tied PV systems was proposed, aiding schools without the technical capacity for complex audits [61]. Anber [62] explored the potential of retrofitting school buildings to improve thermal comfort and energy efficiency in Egypt's hot climate and found that implementing cost-effective insulation, natural ventilation, and shading strategies can significantly reduce energy consumption while improving student learning environments and comfort levels. Strategies for designing energy-efficient green schools using Indian Green Building Council (IGBC) standards achieved 12% energy savings in school buildings in Gurgaon, addressing energy efficiency in composite climates [63]. Although effective, these solutions are cost-intensive and rely on advanced infrastructure, making them less feasible for resource-constrained schools. In addition, the energy management convergence framework used in the Brazilian Amazon emphasises the importance of inclusive policies and community-based governance to ensure sustained access and reliability of energy systems [20]. It highlighted the lack of reliable infrastructure and governance mechanisms in remote areas. Similar governance challenges in South Africa, particularly with the ageing coal-based infrastructure, highlight the potential of community-led energy solutions to improve sustainability

through inclusive decision-making adopted in Moran et al. [20], can be adopted in other developing regions. Empowering local stakeholders to manage renewable energy systems and building local capacity could address socio-technical challenges in low-income schools. Renewable energy solutions in developing regions often focus on low-cost, modular technologies, such as small-scale solar installations, which are financially viable and scalable. While decentralised systems like microgrids offer increased access, their high costs and complexity make them less suitable for low-income schools.

3.7. Contextual parameters and their impact

Low-income schools face significant challenges in implementing advanced energy systems due to limited funding [42]. Financial restrictions and a lack of technical skills hinder schools from benefiting from modern energy-saving technologies, such as smart meters and efficient HVAC systems [39]. These technical and financial disparities perpetuate inefficiencies and hinder energy management adoption. In addition, inadequate energy education and stakeholder participation contribute to unsustainable energy practices. Many staff members are unaware of the time-of-use tariff structures, leading to poor energy management decisions. Institutional priorities are not focused on energy strategies, as administrative workloads often take precedence [41]. Combined with load-shedding and high energy costs, these challenges underscore the need for targeted interventions to bridge the energy efficiency gap in low-income schools. A study in South African schools found that staff training and smart meter data visualisation improved energy-saving behaviours, but these declined without ongoing feedback [41]. Sustained stakeholder engagement, including administrators and policymakers, is essential to monitor, refine, and adapt strategies for long-term success. Continuous feedback loops ensure interventions remain effective, highlighting the critical role of stakeholders in sustaining energy efficiency measures.

3.8. Solutions for low-income schools in developing regions

Data Availability

Global energy strategies often prioritise technical solutions but frequently neglect the collection of localised energy and stakeholder data. Although effective in developed regions, these approaches do not address the socioeconomic factors, institutional setup, and community behaviours that shape energy use in developing regions. Prioritising comprehensive data collection – both quantitative (energy usage patterns) and qualitative (user, institutional, and stakeholder perspectives) – is crucial in these contexts. This foundational step enables policymakers to design energy strategies rooted in local realities, fostering more resilient, inclusive, and efficient energy management solutions.

Prioritising Low-Cost Interventions

Low-cost strategies, for example, LED replacements, should be a priority for low-income schools due to their cost-effectiveness, ease of implementation, and immediate energy savings. These upgrades lower energy bills, offering short-term financial relief while enabling schools to adopt more sustainable energy practices without the need for complex systems. Schools can achieve short-term financial relief, which enables them to reinvest savings into more sustainable energy management practices.

Simple monitoring systems are an affordable and scalable solution for low-income schools in developing regions. They enable real-time energy tracking to identify inefficiencies and savings opportunities without costly infrastructure. With limited budgets, these systems offer a practical and cost-effective way to improve energy management and can be easily scaled across multiple schools to improve regional energy efficiency.

Renewable Energy Integration and Microgrids

Renewable energy offers reliable and sustainable alternatives to fossil fuel-based systems, reducing the dependence on costly grids and

providing long-term financial and environmental benefits. These systems, suited to the climates of many developing regions, are affordable and require low maintenance. Microgrids further enhance energy management for remote schools by creating localised systems that operate independently or alongside the main grid. This ensures a consistent energy supply, particularly in areas with limited access to centralised power or frequent grid outages. It should be noted that tailored control mechanisms are crucial for effective energy management in schools in developing regions. Integrating renewable energy with unreliable grids requires advanced control and scheduling systems to manage grid power, solar energy, and battery storage. These systems dynamically optimise energy reliability and cost efficiency based on availability and demand. Unlike developed regions with stable energy infrastructures, developing regions require custom algorithms to adapt to fluctuating grid conditions. By addressing operational, financial, and infrastructural constraints, these customised systems improve energy reliability and resilience, ensuring minimal disruptions during load shedding and outages while supporting sustainable energy management.

Renewable Energy Trading

Energy trading of surplus renewable energy enables low-income schools to achieve financial sustainability. By selling surplus renewable energy to the grid or nearby communities, schools gain additional revenue while fostering a community-based clean energy model [64]. This approach optimises renewable resource use and promotes economic empowerment in under-resourced regions.

Redefining Energy Performance Metrics

Redefining energy performance metrics is essential, as existing standards often fail to address the unique challenges faced by low-income schools, such as energy poverty. Current metrics, typically based on well-resourced institutions, make it difficult for under-resourced schools to accurately evaluate their energy performance. Developing context-specific metrics that also account for termly and seasonal variations in energy demand allows schools to gain a clearer understanding of their energy usage, identify areas for improvement, and set realistic efficiency goals. Tailored metrics enable better tracking of progress and informed decision-making for sustainable energy management.

Technical Skilling and Systematic Knowledge Transfer

Lacking technical expertise, low-income schools benefit greatly from training programs for staff, students, and local communities. Hands-on skills in operating and maintaining energy systems ensure the longevity and efficiency of these technologies. Systematic knowledge transfer from experts to local stakeholders builds capacity, fosters system ownership, and reduces reliance on external contractors. Structured training and continuous knowledge sharing empower schools to adapt to new technologies, troubleshoot issues, and optimise energy use, creating a sustainable energy management solution for resource-limited settings.

Energy Literacy and Engagement: Users and Stakeholders

Energy literacy and stakeholder participation are crucial to the promotion of sustainable energy practices. Educating students, teachers, administrators, and local communities on energy usage, efficiency, and renewable benefits drives behavioural change and promotes responsibility. Regular workshops, training, and collaborative planning enhance stakeholder alignment with energy goals, fostering ownership and ensuring long-term success.

Energy Financing

With limited financial resources, innovative financing models are essential for implementing energy solutions in low-income schools. Community-based mechanisms such as crowdfunding and energy co-operatives can pool local resources, while grants, loans, public-private partnerships, and energy contracts offer additional support. Flexible and inclusive financing options are the key to overcoming financial barriers.

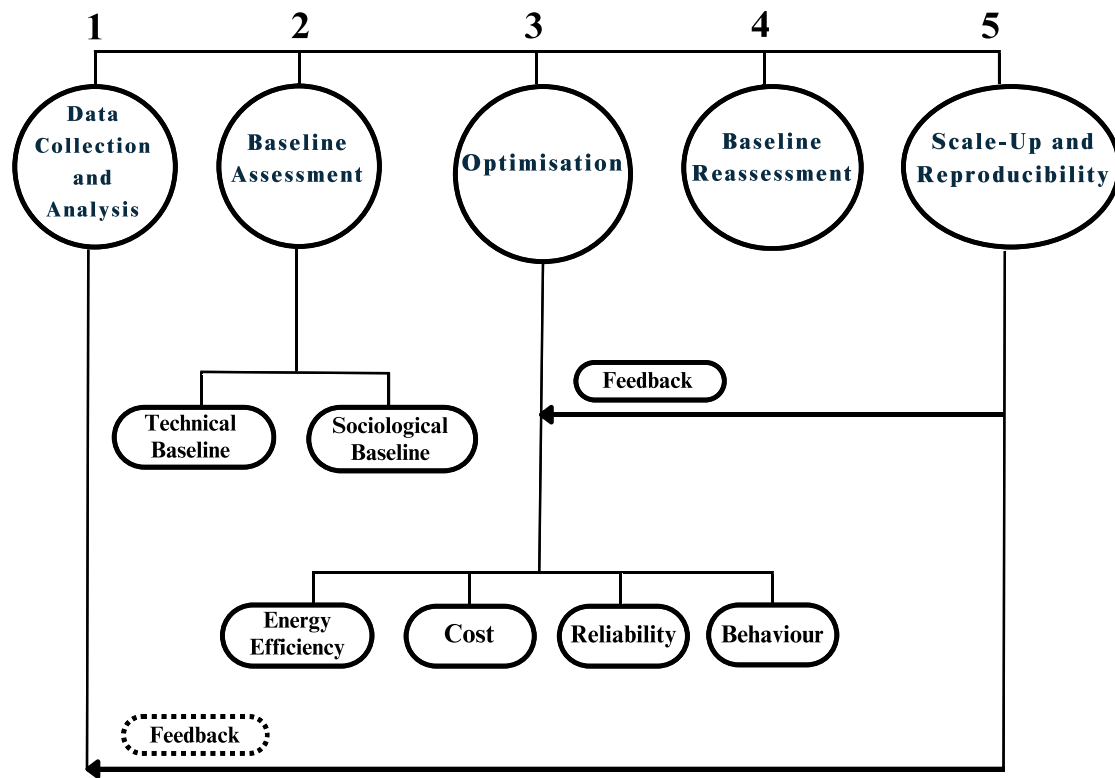


Fig. 2. Proposed energy management framework for low-income schools in developing regions.

Demand-Side Programmes

Demand-side programs encourage energy-efficient practices and off-peak energy use, helping schools lower costs and consumption. Combined with other solutions, these initiatives deliver immediate energy savings while promoting long-term energy awareness in school communities.

3.9. Proposed framework

This energy management framework offers a structured, context-specific approach tailored to low-income schools. It comprises five phases: data collection and analysis, baseline analysis, optimisation, baseline reassessment, and scale-up and reproducibility. The framework is illustrated in Fig. 2.

3.9.1. Energy data collection and analysis

The framework begins with systematic energy data collection and analysis, which forms the basis for identifying usage patterns, inefficiencies, and targeted management strategies. In addition, insights into behavioural patterns, external infrastructure, and stakeholder perspectives are essential for a holistic understanding of the energy landscape in low-income schools. Accurate data are crucial, as interventions based on assumptions risk being ineffective. Key data points to collect include the following.

- **Energy Usage Profiles** - Gather detailed data on energy usage in hourly, daily, seasonal, and yearly time frames to identify peak and low demand periods, allowing optimal resource allocation.
- **Appliance Load Profiles** - Analyse energy demand from appliances (e.g., lighting, HVAC) to pinpoint systems and periods of high consumption, ensuring targeted energy management.
- **Energy Costs** - Assess the financial impacts of energy use to identify cost-saving opportunities and design budget-friendly interventions.

- **Environmental Data** - Collect solar irradiance, temperature, and humidity data to evaluate the potential of renewable energy and adapt solutions to local climates.
- **Behavioural Data** - Examine energy usage habits, appliance timing, and cultural norms to address inefficiencies and design behaviour-focused interventions aligned with school practices.
- **External Energy Infrastructure** - Evaluate external energy supply reliability to better integrate renewable energy and manage grid dependencies.
- **Stakeholder Surveys** - Understand stakeholder priorities and perspectives to ensure that the strategy is widely supported and actionable.

To optimise data collection within resource-constrained environments such as low-income schools, Table 3 recommends data collection prioritisation based on three levels: critical, important, and optional, in line with their impact on energy optimisation, cost efficiency, and strategic decision-making. This prioritisation is intended to streamline the data-gathering process, focusing first on high-impact metrics that drive energy savings and improve operational efficiency.

Tools and Methods for Data Collection Effective energy management in low-income schools requires robust data collection tools and methods to monitor, analyse, and optimise energy consumption. The proposed framework proposes a combination of real-time monitoring, historical analysis, and environmental assessment to ensure data-driven decision-making. This section details the primary tools and methods employed for comprehensive energy data collection and analysis.

- **Smart Meters** - Enable real-time energy monitoring, providing insight into usage patterns and identifying inefficiencies cumulatively or across different areas of the school, including classrooms, administrative offices, and common areas. These devices capture granular data on electricity usage, providing insights into consumption patterns and identifying peak load periods. Some smart meter integrations also facilitate load disaggregation, allowing the system to differentiate between energy consumed by HVAC

Table 3
Data prioritisation for energy management framework.

Data point	Description	Priority level
Energy usage profiles	Detailed data on energy consumption patterns (hourly, daily, seasonal, yearly) to identify peak and low demand periods.	Critical
Appliance load profiles	Analysis of major appliances like lighting, HVAC, and IT equipment to identify high consumption periods.	Critical
Energy costs	Financial analysis of energy consumption to identify cost-saving opportunities and optimise resource allocation.	Critical
Environmental data	Solar irradiance, temperature, and humidity to evaluate renewable energy potential and climate adaptation.	Important
External energy infrastructure	Assessment of grid reliability and the potential for renewable integration to manage dependencies.	Important
Behavioural data	Analysis of usage habits, timing of appliance operation, and cultural norms impacting energy consumption.	Important
Stakeholder surveys	Feedback from teachers, students, and administrators to align the framework with community needs.	Optional

systems, lighting, and electronic devices. This level of monitoring helps identify specific points of inefficiency, enabling targeted interventions.

- **Energy Management Systems (EMS)** – Offer historical data to analyse past usage patterns and forecast future needs. EMSs provide a centralised platform for analysing historical energy usage and forecasting future consumption trends. The EMS aggregates data and enhances the tracking of energy usage patterns over daily, weekly, and monthly intervals, identification of long-term trends, and prediction of high-demand periods. It also allows the monitoring of the impact of energy-saving interventions in real-time.
- **Secondary Data Sources** – Supplement primary data collection. Some notable sources are national energy databases (government and utility-provided datasets on average consumption rates and tariff structures), weather services (which access to solar irradiance, temperature fluctuations, and seasonal weather patterns to optimise renewable energy planning), and utility company reports containing information on grid stability, energy outages, and scheduled maintenance. These external data sources provide contextual information that enhances predictive modelling and improves the accuracy of energy optimisation strategies.
- **Sensors** – Play a crucial role in environmental monitoring and energy optimisation. Temperature, humidity, and motion sensors collect environmental and operational data, optimising energy use by reducing wastage in unoccupied areas. Temperature sensors monitor indoor and outdoor temperatures to optimise heating and cooling loads, humidity sensors track humidity levels, and motion sensors detect occupancy in classrooms and common areas, triggering lights and HVAC systems only when spaces are occupied. Integrating sensor data allows for automated control mechanisms, reducing unnecessary energy consumption during non-operational hours.
- **Energy Audits** – Evaluate infrastructure efficiency, such as lighting, heating, and cooling systems, identifying areas for energy savings, inefficient systems with high energy consumption, and potential areas for retrofitting. The findings from energy audits are used to influence and prioritise future interventions.
- **Surveys and Interviews** – Gather insights from staff, administrators, and stakeholders on energy use and management priorities, and complement quantitative data. This qualitative data can be collected from staff and administrators to understand the perceived energy challenges and areas for improvement, students to assess energy awareness and identify behavioural patterns that contribute to energy consumption, and community members to evaluate support for community-based energy initiatives and renewable energy projects. These interactions provide valuable insights into energy usage behaviours and stakeholder priorities, ensuring that the proposed framework is both contextually relevant and community-supported.

- **Observational Studies** - Examine energy use in classrooms, offices, and common areas to identify inefficiencies. Observational studies are important in identifying energy wastage during unoccupied periods and monitoring energy usage patterns relative to occupancy or schedule. These observations, in turn, allow for practical adjustments.

3.9.2. Baseline analysis

Once data are collected, they are analysed to establish a baseline for school energy usage, tailoring strategies to their specific needs. The analysis identifies inefficiencies, DSM opportunities, benchmarking gaps, and customised solutions. This step ensures that strategies are grounded in a clear understanding of usage patterns and challenges. It includes evaluating both technical and sociological baselines. The technical baseline explores current and potential efficiency gains, while the sociological baseline covers the behavioural analysis to understand users and the stakeholder analysis to understand the roles and influences of key actors.

Technical Baseline: Assesses technical efficiency of the school. Covers both the current and potential status of efficiency. The current efficiency status refers to the current state of the energy systems and infrastructure of the school. This includes an analysis of how efficiently existing systems operate, the condition of energy-related equipment, and the overall energy performance of the school. Potential efficiency gains refer to improvements that can be made in energy usage by upgrading existing systems, optimising usage, or implementing better practices. These gains represent the difference between the current performance of a system and the optimal performance under ideal conditions. By incorporating potential efficiency gains, the baseline provides a roadmap for energy improvements, allowing schools to set realistic efficiency goals. It also supports long-term planning for gradual upgrades, offering insight into the maximum achievable energy savings under ideal conditions.

Sociological Baseline: Assesses the human factors of energy management through behavioural and stakeholder analysis. The behavioural baseline focuses on how users (staff, students, and administrators) influence energy use through daily habits, awareness, and training. The stakeholder analysis seeks to understand the roles, priorities, and influence of key stakeholders in the energy management process. This is essential to ensure that all relevant parties are aligned and supportive of the goals of the framework. An important component of the stakeholder analysis is the stakeholder influence matrix, which maps the level of influence and interest each stakeholder has in the energy management process, helping to prioritise engagements and identify potential champions or blockers in the energy management process.

The baseline analysis phase is crucial, as its accuracy directly influences monitoring and evaluation. By assessing technical efficiency, user behaviour, and stakeholder influences, the framework ensures that subsequent strategies are well-informed and tailored to the unique needs of each school.

3.9.3. Optimisation

The optimisation phase is applied across four key paths - Energy Efficiency, Cost, Reliability, and Behaviour. The goal of this phase is to implement targeted strategies that improve energy performance in each of these areas based on the findings of the baseline analysis.

Optimise Energy Efficiency: Energy efficiency optimisation involves improving the performance of existing systems, upgrading to more efficient technologies, and reducing energy waste. This path focuses on ensuring that the school uses the minimum amount of energy necessary to maintain its operations without compromising comfort or functionality. Some strategies include equipment upgrades, building upgrades, energy management systems, and renewable energy integration. Optimising energy efficiency will lead to a reduction in overall energy usage, allowing schools to use fewer resources while maintaining the same level of service. This also leads to cost savings and a smaller carbon footprint, contributing to environmental sustainability.

Optimise Cost Savings: This focuses on reducing the financial burden of energy use in schools, which is especially important for low-income schools operating on limited budgets. The strategies in this path aim to reduce energy costs without sacrificing energy quality or availability. Some strategies include the integration of renewable energy, demand-side management, and energy financing options. Demand-side management (DSM) strategies, such as load shifting, present a practical solution. Aligning school schedules with peak solar generation reduces reliance on grid energy during high-demand periods, ensuring maximum use of clean energy without costly infrastructure Michael-Ahile et al. [65]. DSM provides a cost-effective, sustainable solution within the constraints of low-income schools. Optimising cost allows resources to be allocated to other essential school functions. Over time, savings from reduced energy costs could be reinvested in additional energy efficiency measures.

Optimise Reliability: For schools in developing regions, energy reliability is a critical issue, especially when grid power is unreliable or when schools face frequent outages. Optimising energy reliability ensures that the school has access to consistent and uninterrupted power, which is vital for maintaining a productive and stable learning environment, reducing the risk of disruption to critical activities. Some strategies include power backup systems, microgrid solutions, renewable energy generation, energy management systems, and load prioritisation.

Optimise Behaviour (Energy Users and Stakeholders): While technological solutions can significantly reduce energy use, behavioural changes can further amplify these savings by reducing energy waste and encouraging conscious energy use. The framework acknowledges that technology alone is insufficient for achieving sustainable energy savings; behavioural optimisation is equally critical. To this end, the study recommends three key strategies: energy literacy programs, gamification competitions, and IoT-based automated reminders. Energy literacy programs aim to equip staff and students with practical knowledge on energy conservation, fostering a culture of conscious energy use through workshops and hands-on activities. Gamification strategies, such as energy-saving competitions between classes and schools, incentivise collective action by rewarding measurable reductions in energy consumption. To complement these efforts, the framework integrates IoT-based automated reminders that optimise real-time energy usage. Smart sensors monitor occupancy in classrooms and common areas, triggering alerts to switch off unused lights and appliances automatically. Additionally, interactive digital dashboards display live energy usage data, providing instant feedback to students and staff. This data-driven feedback loop not only reinforces energy-conscious behaviour but also aligns with performance-based incentives, encouraging sustainable practices. The combination of energy literacy, gamification, and IoT automation transforms energy-saving measures from isolated actions into consistent habits, fully integrated with the framework's monitoring and optimisation strategies. This holistic approach ensures that

behavioural improvements are continuous, measurable, and adapted to the specific energy demands of low-income schools.

This optimisation path focuses on reducing energy use by promoting energy-efficient habits among all users, as well as engaging key stakeholders to promote energy-efficient habits and practices. Behavioural changes, when reinforced by stakeholders, have a long-lasting impact on energy use, as they create a culture of sustainability and shared responsibility to reduce energy waste, without requiring large capital investments. Some strategies include collaborative energy awareness campaigns, the inclusion of energy education in the curriculum, recognition and awards, energy use automation, the creation of energy working groups, and energy-saving competitions. Additionally, involving stakeholders provides valuable feedback and insights that can be used to continuously refine energy-saving strategies and ensure they align with the community's unique needs and values. A collaborative environment where everyone is responsible for energy efficiency is created and embedded in the school's culture and sustained over the long term.

It is important to note that some solutions might combine two or more of the optimisation paths. By addressing technical and financial aspects alongside human behaviour, this phase ensures that energy systems are operating optimally, costs are minimised, energy supply is reliable, and everyone in the school is engaged in energy conservation efforts. Implementing these strategies in a coordinated way leads to a comprehensive approach to energy management that aligns with the school's goals for sustainability, cost-effectiveness, and operational efficiency.

3.9.4. Baseline reassessment: Monitoring, evaluation, realignment, and adaptability

This phase creates a cohesive, cyclical, and dynamic process for continuous improvement and ensures that the energy management strategy is adaptive and responsive to ongoing changes. It involves monitoring energy performance over time, evaluating progress relative to baseline targets, and realigning strategies to maintain or improve efficiency. Reassessment is both technical and sociological, while evaluation compares this data against the initial baseline to assess progress towards energy-saving goals and efficiency targets. It also examines whether users maintain energy-conscious behaviours and evaluates the effectiveness of optimisation strategies. Feedback from stakeholders informs realignment and adaptability, ensuring that strategies remain relevant. Schools can use this data to adjust to changes such as budgets, stakeholder priorities, new technologies, energy costs, or user behaviours. The baseline is periodically reassessed, establishing a new reference point to measure future improvements. Empirical evidence from developing country contexts underscores the importance of structured baseline assessments [44,60]. For instance, the reported EUI values in Michael-Ahile et al. [44] for under-resourced South African schools were significantly lower than the national benchmark. This data can be used not only to benchmark energy performance, but also to guide the identification of optimisation targets during reassessment. These studies demonstrate how baseline performance can inform progressive, data-driven realignment in low- to middle-income contexts. Thus, reassessment is not simply a verification stage but an opportunity to refine the energy management process based on emerging data, shifting school needs, or changes in stakeholder priorities.

3.9.5. Scale-up and reproducibility

The final phase focuses on scaling up successful energy management strategies for broader application across schools or regions with similar challenges. This transition aims to create a scalable, adaptable model that retains core principles of energy efficiency, cost-effectiveness, reliability, and behavioural optimisation. This phase is crucial for transitioning from a single-school implementation to a broader and impactful approach that benefits multiple institutions in developing regions. Formal documentation, including guidelines, best practices, toolkits, and

training materials, ensures reproducibility and supports schools with varying resources and technical expertise. Some important components of this phase include;

1. **Policy Integration and Advocacy:** Scaling the framework requires integration into national education and energy policies to ensure long-term commitment and institutionalisation. Advocacy efforts should promote energy efficiency mandates, incentives for the adoption of renewable energy, and national benchmarks for school energy use. Collaboration with national or regional education departments is critical for success.
2. **Standardisation of Key Phases:** To enable broader adoption, processes such as energy audits, data collection, monitoring, and evaluation should be standardised while allowing flexibility for local conditions. Tools such as templates, dashboards, and checklists can simplify implementation for schools with limited energy management experience.
3. **Leveraging Technology for Scalability:** Technology can streamline data collection, monitoring, and evaluation across multiple schools. A centralised energy management platform, such as a cloud-based or mobile system, can improve usability and track energy performance consistently in schools.
4. **Knowledge Sharing:** Establishing peer-to-peer networks where experienced schools mentor others can support the scale-up phase. Sharing lessons learnt, challenges, and implementation experience through workshops, webinars, and online platforms fosters knowledge dissemination and continuous support for new adopters.
5. **External Funding and Partnerships:** Partnerships with government agencies, NGOs, and donors are essential to secure funding for scaling. Innovative models, such as grants, microloans, or energy performance contracts in which savings are repaid for investments, can accelerate adoption in low-income regions.

The final phase focuses on extending the benefits of energy efficiency, cost savings, and sustainable energy practices to multiple schools in developing regions. By ensuring scalability, flexibility, and adaptability, the framework can significantly enhance energy performance across educational institutions, creating better environments for students and staff.

3.9.6. Feedback loops

Feedback loops ensure that the framework is not a one-time implementation, but a continuously evolving system that improves as more data and experience are collected. As the framework scales, new challenges and successes emerge that can be used to make smarter, more informed decisions.

Scale-Up and Reproducibility → Optimisation: As the framework is scaled to other schools or regions, different challenges and varying levels of success with certain strategies may emerge. In this feedback loop, the insights and lessons learned during the Scale-Up and Reproducibility phase are fed back into the Optimisation phase, allowing for continuous improvement of the energy management strategies. This process helps identify which optimisation strategies are universally effective and which need to be adapted to specific contexts. By refining these strategies based on real-world applications, the framework becomes more flexible and responsive to local conditions. Additionally, best practices and toolkits are updated, ensuring that new schools adopting the framework benefit from the experiences and insights gained during the scaling process. This dynamic feedback loop ensures the optimisation process remains context-sensitive and adaptable to different environments.

Scale-Up and Reproducibility → Data Collection and Analysis: Data is the foundation of this energy management framework. By ensuring that insights from the final phase inform the data collection phase, each new implementation is built on a stronger, more refined, and

relevant foundation, leading to better decision-making throughout the framework. In this feedback loop, data and insights gathered during the Scale-Up and Reproducibility phase are fed back into Data Collection and Analysis to improve the accuracy, scope, and relevance of future data collection efforts. As new schools adopt the framework, regional variations, local conditions, and specific challenges are revealed. These insights highlight what worked well during data collection and expose any gaps or inefficiencies that occurred. By incorporating this feedback into the data collection process, future implementations benefit from improved tools, better-targeted methodologies, and a more comprehensive understanding of which factors to prioritise. This loop ensures the framework is continuously improving by using real-world data from diverse school environments to refine the data collection process. Each time the framework is scaled to new schools, the insights gained help enhance the focus areas, tools, and methods used in future data collection efforts, making them more relevant to the unique conditions of each school. By feeding these lessons back into the first phase, the data collection process becomes increasingly customised and adaptable to different regional contexts, ensuring it remains effective and context-sensitive. This feedback loop also prevents redundant data collection and avoids overlooking critical factors, allowing you to focus on the most impactful areas. Ultimately, the loop ensures that each new iteration of the framework is more data-driven, targeted, and responsive to real-world feedback, increasing the success of energy management strategies.

By creating feedback loops, a self-improving adaptive framework is built, ensuring that the framework learns from several implementation phases. By continuously feeding lessons and new data back into earlier phases, schools can optimise energy use more effectively, leading to more sustainable long-term improvements in energy management in diverse educational settings.

3.10. Practical application of the proposed framework in low-income schools

The design of the proposed energy management framework is supported by empirical evidence from existing studies focused on low-income schools in resource-constrained settings. Table 4 highlights this and quantitative metrics from the literature.

3.10.1. Framework phase mapping

The Framework Phase Mapping, Table 5 organises the five core phases of the framework, aligning them with their corresponding activities, data requirements, tools and methods, and expected outputs. This structured view enables school administrators, energy practitioners, researchers, and policymakers to understand at a glance how each phase unfolds and reinforces the iterative and integrated nature of the framework, where each phase builds on data and insights from the previous steps.

3.10.2. Stakeholder Influence/Interest Grid

The Stakeholder Influence/Interest Grid, as captured in Fig. 3, provides a strategic lens for managing the engagement of different actors involved in school energy projects. Recognising that stakeholder participation varies in influence and interest, the grid categorises groups accordingly and suggests appropriate engagement strategies for each quadrant. This helps ensure that energy initiatives are not only technically sound but also socially inclusive and contextually grounded.

3.11. Implementation recommendation for South Africa and developing regions

The success of the framework is largely due to its adaptability to local environmental, social, and economic conditions. South African schools could benefit from tailored energy management systems that account for local climatic conditions, energy needs, and the specific

Table 4
Framework application in low-income schools.

Framework component	Key findings and application	Source(s)
Data collection and Analysis	Provided a robust dataset for understanding electricity usage behaviours in schools. Collected 30-min interval electricity usage data from 53 lower-to middle-income schools in South Africa, highlighting usage patterns, the impact of academic schedules, and load shedding effects. Provided foundation for advanced analysis of usage trends and informed strategies for energy efficiency and cost reduction.	Samuels et al. [66]
Technical baseline assessment	The study used smart meter data to introduce a nuanced benchmarking approach tailored to the unique energy consumption patterns of schools in developing regions. By analysing data from 31 less affluent schools in South Africa, the researchers established Energy Use intensity (EUI) benchmarks ranging from 12 to 37 kWh/m ² /year, significantly lower than the existing 60 kWh/m ² /year standard. These findings underscore the importance of context-specific baseline assessments. Incorporating such tailored benchmarks into the framework ensures more accurate evaluations of a school's energy performance, facilitating targeted interventions and realistic goal setting.	Michael-Ahile et al. [44]
Technical baseline assessment	Analysed energy usage across 16 schools representing different affluence levels in South Africa. Found that poorer schools used only 40% of the energy compared to affluent ones, primarily due to infrastructure disparities. Identified lighting as a significant energy consumer, accounting for up to 40% of usage in poorer schools.	Samuels et al. [39]
Technical baseline assessment and Energy efficiency and Cost optimisation	Conducted a techno-economic analysis of integrating solar PV and battery storage systems in schools affected by load-shedding. Optimal PV-battery configurations ranging from 15–3 to 30–8 kWp–kWh were found for low-demand to high-demand low-income schools, respectively. Results showed potential grid independence of up to 47%, a 63% reduction in peak demand, and 98% coverage of energy needs during load-shedding, ensuring uninterrupted learning. Highlighted the importance of tailoring energy solutions to the specific needs and constraints of lower-to-middle-income educational institutions. Provided empirical data supporting the feasibility and benefits of renewable energy integration in schools.	Michael-Ahile et al. [67]
Energy efficiency and Cost optimisation	Proposed shifting school start times from 7 a.m. to 9 a.m. to align with peak solar energy generation. Found that this adjustment, combined with solar integration, could reduce peak demand by up to 60% and lower energy costs by 28%. Emphasised the role of operational changes in enhancing energy efficiency without significant infrastructural investments. Encourages schools in low-resource contexts to consider non-technical interventions as part of a holistic energy management strategy.	Michael-Ahile et al. [65]
Technical baseline assessment and Energy efficiency and Cost optimisation	Assessed existing lighting systems in South African schools, identifying inefficiencies associated with traditional fluorescent lighting. It established a performance baseline by quantifying energy consumption before interventions. By replacing fluorescent lights with LED alternatives, the study demonstrated significant energy reductions ranging between 20% and 40% across various schools. These findings support the framework's component on optimising energy efficiency through targeted retrofitting measures.	Booyesen et al. [42]
Energy efficiency and Behavioural optimisation	Explored a community-based energy trading (CBET) model where schools with surplus solar energy share with neighbouring households. Demonstrated that CBET can reduce grid dependency by 16% and lower household energy costs by up to 6%. Highlighted the potential of schools to act as energy hubs, fostering community resilience and engagement. Provides a model for schools to extend their energy management practices beyond institutional boundaries, promoting broader energy literacy and societal benefits.	Michael-Ahile et al. [64]
Behavioural optimisation	Demonstrated the effectiveness of behavioural interventions by presenting tangible energy savings through staff engagement and data visualisation. Implemented a behavioural intervention in five South African schools using staff training and smart meter data visualisation. Achieved a 15% reduction in electricity consumption through enhanced energy awareness and behavioural changes.	Samuels and Booyesen [41]

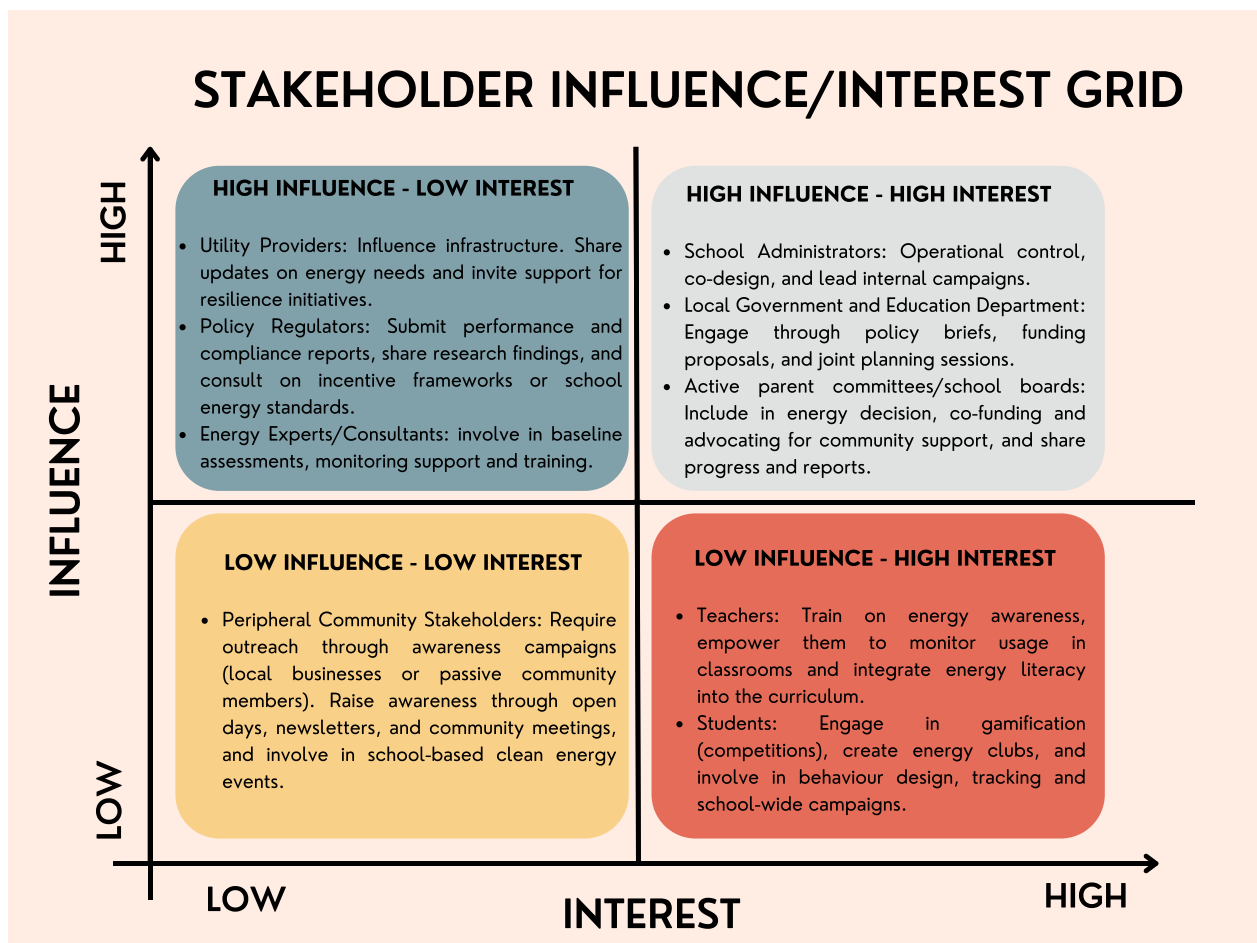
challenges of unreliable electricity grids. In addition, the focus on long-term sustainability, through capacity building and the development of local expertise, is crucial. Ensuring that energy solutions are not only implemented but also maintained and governed locally would contribute to the long-term success of energy management frameworks in low-income schools. In developing regions, energy projects that integrate with local economic structures and consider social dynamics tend to perform better. Projects that benefit the community and continue to generate local employment have been more successful. Therefore, integrating energy projects with the local educational curriculum or offering job creation through maintenance roles could improve project sustainability and community involvement. Regular evaluation of energy performance, stakeholder feedback, and adaptability to new challenges is crucial. As schools implement energy solutions, regular monitoring and feedback collection can help optimise performance, making the system more effective over time. A key recommendation to ensure the success of energy management strategies in low-income schools is to start with small-scale interventions or implement solutions in phases rather than introducing the entire system at once. This incremental approach allows users to gradually adapt

to the new systems, experience the tangible benefits of each step, and build trust and buy-in over time. This visibility is essential to foster engagement, as stakeholders are more likely to support a project when they can see the positive impact of their actions. Additionally, starting small prevents users from feeling overwhelmed by the complexity of new energy systems, particularly in environments where technical expertise may be lacking. A phased rollout also offers schools the opportunity to build capacity as the project progresses. As each phase is completed, users will have time to gain technical knowledge and develop skills necessary for the operation and maintenance of more complex systems, ensuring that schools are better prepared for subsequent, more advanced phases of implementation, minimising the risk of project failure due to technical barriers or lack of understanding. Furthermore, phased implementation allows for continuous feedback and adjustments. As each phase is implemented, schools can assess the effectiveness of the solutions, make the necessary modifications, and ensure that each step is aligned with the energy goals and resource capacity of the school. This adaptive approach also mitigates financial risks by spreading the cost over time, making it easier for schools to secure funding for each phase rather than investing a large sum in

Table 5

Framework phase mapping: Activities, Data, Tools, and Expected outputs.

Phase	Key activities	Data required	Expected outputs
Data collection	Deploy smart meters and sensors; conduct energy audits, stakeholder surveys, and observational studies, and gather secondary data.	Real-time energy usage, appliance load profiles, cost data, environmental data, behavioural patterns, users and stakeholder perceptions.	Baseline consumption trends, peak demand periods, usage by end-use costs, retrofit needs, and user and stakeholders' behavioural insights.
Baseline assessment	Analyse collected data (technical and sociological), assess stakeholder influence and priorities, benchmark against similar schools, identify inefficiencies and opportunities.	Historical and real-time energy data, infrastructure and appliance efficiency data, and behavioural and stakeholder survey results	Context-specific EUI benchmarks, retrofit targets and priorities, behavioural profiles and targets, stakeholder influence grid, and tailored intervention roadmap.
Optimisation	Design and implement energy efficiency, cost, reliability, behavioural strategies, optimise schedules and operations, and build partnerships	Real-time monitoring, usage profiles, cost constraints and financing readiness, system design parameters, behavioural analysis, stakeholders' influence grid, and infrastructure constraints.	Efficient energy systems, improved energy reliability, improved energy literacy, reduced energy poverty, reduced grid dependency, phased rollout plan, users and stakeholders' participation, and cost savings.
Baseline Reassessment	Track and assess energy use and stakeholder behaviour post-implementation, evaluate strategy effectiveness, and adjust based on new data.	Post-intervention energy and behavioural data, updated stakeholder input, contextual changes (e.g., costs, priorities).	Updated performance metrics; new efficiency targets; revised strategies; refreshed baseline for future evaluation.
Scale-up and Reproducibility	Package and document successful strategies; develop toolkits; establish partnerships; advocate for policy integration.	Best practice case studies; standardised templates; regional data and feedback, funding models.	Adaptable toolkits, policy briefs, national/regional adoption, expanded school network participation.
Feedback loops	Feed scale-up insights into earlier phases, refine data collection tools and optimisation strategies for future implementations.	Implementation insights, regional variations, stakeholder feedback from scaled schools.	Improved framework tools and processes, greater adaptability, evidence-informed optimisation and data strategies.

**Fig. 3.** Stakeholder Influence/Interest Grid.

advance. Moreover, to support the capital requirements of each phase, some funding mechanisms can be explored. Community co-financing where local communities can contribute to energy projects through

cooperative models, where small financial contributions from parents and local businesses are pooled to fund installations, government grants that allow schools apply for subsidies to reduce the costs of solar

installations and energy efficiency upgrades, partnership with energy service providers that allow schools to implement energy upgrades with no upfront cost, among others. In addition, community-based energy trading can be used as a revenue model [64]. This model allows schools to trade surplus energy generated from solar PV installations with nearby community centres, small businesses, and local households. This can also strengthen community ties, increase energy literacy, foster collaboration with local stakeholders, and increase community support for school-based energy projects. These funding mechanisms not only alleviate the financial burden on schools but also enable scalable implementation over time.

4. Conclusion and future work

The interdisciplinary complexity of energy management in low-income schools in developing regions calls for an integrated approach that addresses technological, social, economic, and policy dimensions. Although partial solutions exist, there is no standardised framework that effectively combines these perspectives. This study proposes a holistic, modular framework tailored to the unique energy needs of low-income primary and secondary schools, accounting for financial constraints, infrastructure limitations, and the demand for localised, sustainable interventions. While designed for broad applicability, the framework allows for contextual adaptation, recognising that variations in infrastructure, school size, stakeholder capacity, and geographic conditions may require phased or region-specific implementation. Its flexible structure supports scaling or simplification, making it suitable for both rural and urban schools with diverse resource profiles.

The findings of this study reveal significant gaps in energy literacy, outdated infrastructure, and insufficient policy support in these schools, leading to inefficiencies and high operational costs. Limited awareness of energy efficiency practices and the absence of real-time energy monitoring systems further hinder the adoption of sustainable energy solutions. The proposed framework integrates global best practices with local socio-economic and institutional contexts to address these challenges, ensuring its applicability to schools in sub-Saharan Africa, developing Asia, and other regions facing similar energy access issues. This framework emphasises the critical role of behavioural change, focusing on interventions such as energy literacy programmes and active stakeholder engagement to drive energy efficiency. Incorporating renewable energy solutions, including photovoltaic systems and microgrids, as reliable and cost-effective means to improve energy resilience in resource-constrained settings. In line with international standards such as ISO 50001, the framework promotes energy conservation, waste reduction, and resource management, fostering sustainable development and reducing dependence on traditional energy sources. Combining low-cost efficiency measures, renewable energy integration, and continuous energy monitoring ensures a sustainable and scalable solution for low-income schools. Moreover, this structured approach not only optimises energy use but also contributes to broader socio-economic development by cultivating a culture of sustainability and resilience among school communities.

Although this study is primarily conceptual, it is strongly supported by empirical insights drawn from recent pilot projects and data-driven studies in similar contexts. For example, behavioural interventions in South African schools have demonstrated up to 15% electricity savings, and energy usage benchmarking has revealed significantly lower EUI values in under-resourced schools (12–37 kWh/m²/year) compared to the national standard of 60 kWh/m²/year. These quantitative findings, though not derived directly from this study, provide a robust foundation for validating the framework.

In addition, over 70 public schools have undergone energy audits as part of recent provincial efforts to improve energy efficiency in the education sector. Energy audits are essential diagnostic tools that provide a data-driven foundation for targeted interventions, enabling schools to prioritise the most impactful and cost-effective efficiency measures.

This includes a focused dataset of 53 lower- to middle-income public schools in the Western Cape, where 100% of the schools had undergone energy audits in the past five years, yet none had implemented formal energy management policies. Leveraging audit results can drive evidence-based policy and budgetary decisions, ensuring that strategic operational changes complement infrastructure upgrades. While all 53 schools were equipped with smart meters and dashboards, only 8% were actively using them for energy monitoring. Furthermore, 100% had completed lighting retrofits, 13% had adopted solar energy installations, and none had been issued Energy Performance Certificates, which aligns with current regulatory exemptions. These insights underscore the gap between infrastructural improvements and institutional practices, highlighting the critical need for behavioural, managerial, and policy-level interventions. A key component of such interventions is the presence of trained personnel in energy management, as many of these schools lack staff with the technical knowledge and skills. Capacity-building and professional development programmes are therefore critical to empowering school administrators and facility managers to effectively manage energy use and drive continuous improvement.

Advancing energy efficiency in the education sector also requires that decision-making authorities and policymakers are equipped with adequate knowledge of energy management, renewable energy technologies, and sustainability principles. Informed leadership is essential to create supportive regulatory frameworks, allocate funding effectively, and champion long-term sustainable energy goals. At this stage, the focus is on building a robust context-applicable theoretical model that aligns with global best practices, and where the framework is conceptualised before pilot implementation. Several limitations must be acknowledged. First, the framework is primarily conceptual and supported by secondary empirical insights, rather than direct field experiments or pilot implementations by the authors. Second, challenges such as stakeholder resistance, varying institutional capacities, and financial constraints may hinder the standardised deployment of the framework. Future work will draw on these models to validate the proposed framework's effectiveness through a comprehensive and structured pilot testing and statistical analysis, including measures of energy efficiency, cost-effectiveness, and community impact, validating the feasibility of this framework in diverse schools and regions, refining the framework components, and supporting large-scale adoption. This structured approach ensures that the framework is both conceptually robust and empirically validated, paving the way for sustainable energy solutions in low-income educational settings.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Jason Avron Samuels reports a relationship with Green X Engineering that includes: employment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that support the findings of this study are available in Mendeley Data at <https://doi.org/10.17632/nm2vc4v2br.1>. [68] The data set is openly accessible under the CC BY 4.0 license.

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