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Article

Integrating sustainable renewable energy systems into emerging construction projects in Ghana: Towards a low-carbon and climate-resilient future

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Abstract: Climate change mitigation increasingly hinges on decarbonising the built environment, yet renewable energy integration in building construction remains underexplored in many emerging economies in Africa, including Ghana. This study examined the enhanced deployment of renewable energy sources (RES) in real estate projects as a contribution to climate change mitigation using the IDT approach. Using quantitative design methodologies, data was collected from 400 professionals working in the real estate industry, receiving a response rate of 94 %. Descriptive statistics, relative Importance Index (RII) and Multiple Linear Regression analysis were the tools deployed in the analysis. The results of the multiple regression analysis show that the most statistically significant determinants for the deployment of RES in developing projects are efficiency in solar energy technologies ($\beta = 0.471$, $p = 0.000$) and smart energy management systems ($\beta = 0.247$, $p = 0.000$). Additionally, the major factors triggering the adoption include reduction of long-term operational costs (mean = 4.65), reduction of carbon emissions (mean = 4.59), and improvement of energy independence (mean = 4.54). On the other hand, the main barrier for integration is the inefficient governmental support and lack of RES equipment in Ghana and high initial investments. Framed through the Diffusion of Innovation Theory, adoption is still concentrated among early adopters and innovators; the early and late majority have not yet been brought along, largely because the institutional signals (policy certainty, financial incentives, technical capacity and codified standards) that typically accelerate that movement are still underdeveloped locally. The study recommends that government and industry stakeholders prioritise binding regulatory support, targeted financial incentives, and solar-led implementation strategies, sequenced ahead of demonstration and certification efforts, to move renewable energy adoption from isolated examples toward standard construction practice.

Keywords: construction, climate resilience; renewable energy; sustainable development; building-integrated photovoltaics

1. Introduction

The threat of the changing climate across the world is no longer a theoretical concern but a defining operational characteristic of modern engineering. The current disproportionate climatic vulnerabilities of changing rainfall patterns and increasing heatwaves in sub-Saharan Africa have necessitated decoupling economic growth from carbon emissions more [1]. Ghana, just like most sub-Saharan countries, is going through a period of tremendous urbanisation and industrial growth, which is resulting in a record number of civil and industrial engineering projects [2]. In the past, meeting

the energy requirements of such projects satisfactorily depended heavily on fossil fuels and hydro-baseloads, both of which were vulnerable to changing weather patterns. However, to achieve genuine climate change mitigation, Ghana will need to make a significant adjustment in the way it's built environment is designed, implemented and functions [1]. This research work aims at investigating the importance of the systematic integration of sustainable renewable energy sources in the lifespan of emerging engineering projects in Ghana. If the built environment in Ghana can incorporate clean energy directly into the design of new infrastructure, it can move from being a contributor to greenhouse gas emissions to being a forward-looking engine for climate resilience and sustainable socio-economic development.

To understand the importance of this integration, one has to look at the development of the energy landscape of Ghana. Until a recent shift from hydropower to fossil fuel, Ghana had relied heavily on the hydroelectric power generation from the Akosombo and Bui dams [1] with thermal (60.6 %), hydro (38.7 %), solar and renewable energy (0.7 %) as the most sustainable source. Currently, the 404 MW Bui Hydroelectric Station is a hybrid partner to the 5 MWp floating solar PV system of the Bui Power Authority (BPA) on the Black Volta River, currently the largest in West Africa. This technique provides a twofold benefit: the panels are naturally cooled by the water body, which allows for better photovoltaic efficiency to be maintained, and the physical shadowing of the panels lessens the rate at which the reservoir evaporates [3].

However, recurrent droughts due to climatic variability may sometimes lead to severe generation shortfalls and unstable sustainable power supply to communities, resulting in a common phrase, '*Dumsor'* (an Akan word meaning 'unstable power'). The above implies that Ghana now depends highly on thermal power, with less than 1 % energy generated from solar and renewable energy. This transition, however, increased the country's vulnerability to fluctuations in global fuel prices and raised the carbon footprint [3]. This puts engineering projects in a trilemma position: balancing energy security, financially affordable options and environmental sustainability [4]. Ghana currently has the potential capacity to increase the sustainable power generation to approximately 2.4 %, which may still seem very low [5]. There has, however, been a slow structural shift by government organisations towards envisioned solar integration and operationalisation of a Renewable Energy Authority (REA) to oversee and standardise green energy projects [6,7].

Even with these regulatory frameworks in place, there is still a gap between the implementation of projects at the micro level and the macro level national energy strategy. Ghanaian traditional engineering practices often see energy procurement as an afterthought and rely on conventional grid connections whilst using diesel generators as a backup energy source in the post-construction phase [8].

The integration of renewable energy sources directly into future projects represents a significant paradigm change [1]. This strategy necessitates that engineers, architects, and project managers utilise integrated project delivery (IPD) models [9]. These models include the integration of clean energy generation in the project from the feasibility stage through the design and implementation stage. Possibly, designers may consider the likes of building-integrated photovoltaics, local mini-grids and waste-to-energy systems on small scales in emerging engineering works as a necessity.

Ghana's expanding engineering projects cannot be built to be energy consumers anymore if we are to meet our climate commitments and, at the same time, support our industrial future. Instead, they need to be designed to generate, optimise and maintain clean energy as Ghana is preparing to achieve its target of net-zero energy by 2070. These initiatives would have a significant effect on both the micro- and macroeconomic indicators of the country and result in decreased importation of crude oil and help stabilise our local currency. Conversely, Ghana's national energy transition framework projects that a total of $560 billion would be required for the full transition of the economy [10]. That framework seeks to deliver 21 gigawatts of clean energy out of a diverse 83 gigawatts of national capacity by 2070. Already, local unique engineering prototypes are being developed, such as the thirty-megawatt floating solar plant developed at the Bui Hydropower Station [11]. The plant uses local manufacturing for its components to optimise space efficiency and reduce water evaporation.

1.1. Sustainable energy as a potential source of alternative power in Ghana

To successfully integrate sustainable technology in future engineering endeavours, the idea of renewable energy needs to be cleared of the fundamental global assumptions and firmly grounded in Ghana's specific techno-ecological zones [12]. The country is averagely characterised by an outstanding average daily solar radiation intensity that lies within the range of 4.4 to 5.6 kilowatt hours per square metre per day, and it also has yearly sunlight durations that range from 1800 to 3000 hours [13]. Therefore, in emerging civil engineering projects it is possible to employ photovoltaic materials to structurally or aesthetically replace conventional building elements, such as facades, roofs and windows, to exploit the geographical benefit of sustainable energy [14].

Again, to date, Ghana's biomass, biochemical and thermochemical energy sources represent a major energy potential, but they have been traditionally under-engineered [15]. Emerging engineering projects could potentially take advantage of new biochemical and thermochemical conversion pathways that utilise waste streams from agriculture and municipalities instead of the traditional combustion processes, such as charcoal or wood fuel, which release large quantities of atmospheric carbon [16]. For instance, Ghana's economy is dominated by a large agricultural sector that generates huge amounts of crop wastes, particularly cocoa husks, empty fruit bunches (EFBs) of oil palm and coconut shells. Gasification in engineering facilities is a thermochemical conversion process for the conversion of these solid wastes into syngas (synthetic gas). This creates a stable, localised thermal baseload for agro-processing businesses and rural manufacturing centres [17]. Most metropolitan areas in Ghana, such as Accra, are experiencing rapid growth. From the infrastructural point of view, municipal solid waste management is becoming a major challenge to manage. Anaerobic co-digestion systems can be incorporated in the plan of municipal waste management projects, which include civil and chemical engineering aspects. These facilities can extract biogenic methane (also called "CH") from organic waste to generate decentralised energy using combined heat and power (CHP) petrol engines [18]. This enables them to tackle the sanitation issues and minimise their reliance on

the grid.

Small-scale hydropower systems offer a more reliable and predictable alternative to large-scale hydroelectric dams such as Akosombo and Bui, which are more vulnerable to the effects of climate change that causes water levels to fluctuate. The technical term for systems of less than 10 megawatts (MW) in Ghana is 'small hydro', and 'mini/micro-hydro' for systems of less than 100 kilowatts (kW) to 1 MW. Unlike the macro-dams normally used, the run-of-river designs used by tiny and mini-hydro projects do not require large reservoirs or the ecological displacement that would be associated with their construction. Run-of-river technologies produce electricity by diverting a portion of a river's natural flow through a penstock into a turbine and then returning the water to the stream. Emerging infrastructural projects around the river networks in the southwestern region, especially the Pra, Tano and Ankobra basins, are well placed to incorporate mini hydropower. The Tsatsadu generating station in the Volta Region is an operating prototype of this type of power plant at 145 kW [19].

From the foregoing discussion, it can be deduced that a hybrid strategy is needed to realise the full potential of sustainable engineering in Ghana. This approach may be based on the integration of the daytime peak output of solar photovoltaics with the predictable baseloads of biomass or mini hydro to create self-sustaining energy ecosystems. By exploring the thermodynamic and chemical reality of carbon displacement, it is possible to understand the role of emerging engineering initiatives in the mitigation of climate change. The introduction of sustainable renewable energy sources into industrial, civil, and infrastructural systems directly modifies the mass balance of greenhouse gases (GHGs) in the atmosphere, which in turn results in changes in the fundamental dynamics of both global and local climatic trajectories [20].

1.2. Climate change as a necessity for sustainable energy

Ghana's vulnerabilities are the impetus for action within the ambit of the local climate mandate. Although mitigating the effects of climate change is a global commitment, climate change mitigation is an immediate infrastructural priority for Ghana. The geographical position of the nation between latitudes 4°N and 12°N places it immediately within a climate-sensitive tropical zone influenced by the Intertropical Discontinuity (ITD). Data from the Ghana Meteorological Agency (GNet) shows that localised models predict a further rise in temperature between 1.5 °C and 2.5 °C by the end of the century [21]. This suggests that the mean annual temperatures across all ecological zones have increased by more than 1◦ C over the last four decades. These environmental changes are not merely background conditions for new engineering projects; they are active hazards affecting material performance, energy consumption and durability of structures [22]. Globally there is a commitment to reduce the effects of climate change; therefore, in Ghana, climate change mitigation is a top priority on the infrastructural agenda [23]. These environmental changes are not only the background factors for new engineering projects, but they are the active dangers affecting the performance of materials, the amount of energy that is required and the lifespan of structures [24].

The compounded rise in the ambient temperature immediately triggers an

adversarial engineering feedback loop inside the constructed environment. This phenomenon, known as the Urban Heat Island (UHI) effect, is exposing metropolitan centres such as Accra, Kumasi and Takoradi to unprecedented levels of thermal stress on their civil structures following the rapid destruction of vegetation covers in these areas. Classic engineered materials experience high heat stress, which accelerates the chemical weathering process [25]. This results in premature spalling of concrete, failure of structural expansion joints and rapid deterioration of bituminous surfacing of roads. The heat entering a building from outside increases exponentially the microclimate of these environment [26]. Therefore, to provide an ambient internal temperature, a building is compelled to depend heavily on its heating, ventilation, and air conditioning (HVAC) systems, which significantly increase the amount of energy needed for its internal operations. Again, rising temperatures simultaneously cause an increase in the electrical resistance that exists inside grid transmission cables which results in higher thermal distribution losses on the GRIDCo network at a time of peak local electricity demand [27]. Besides the engineering impact and the greenhouse effect due to human activity, the primary driver of global climate change is an imbalance of thermal energy within the system of the earth and the atmosphere [28]. Under normal conditions, short-wave solar radiation, including ultraviolet and visible light, penetrates the atmosphere and warms the surface of the earth. This energy is then re-radiated by the planet back out to space as longwave infrared (IR) radiation for further exploration [29]. The engineering difficulty is obvious due to the chemical composition of the emissions produced by conventional thermal power plants. Ghana's thermal generation is largely reliant on the burning of natural gas and heavy fuel oil (HFO), which make up over 70 % of the country's overall power mix, based on the latest figures from the Energy Commission [14]. To get a chemical expression of the burning of these hydrocarbon chains, the usual oxidation process may be used as follows:

$$C_nH_{2n+2} + \left(\frac{3n+1}{2}\right) O_2 \xrightarrow{\Delta} nCO_2 + (n+1)H_2O \quad (1)$$

This reaction releases massive quantities of carbon dioxide (CO_2), alongside trace amounts of methane (CH_4) and nitrous oxide (N_2O). These gas molecules feature asymmetrical vibrational modes that allow them to absorb the escaping long-wave infrared radiation. Instead of escaping into space, this energy is trapped and re-radiated back to Earth, raising ambient temperatures [30]. This reaction produces large quantities of carbon dioxide and methane (CH_4) as well as a trace quantity of nitrous oxide (N_2O). These gas molecules have asymmetric vibrational modes, which allow them to soak up the long-wave infrared radiation that is leaking out from somewhere else. This energy does not leave space but is released back to earth, which increases the temperature of the surrounding environment. An engineering project based on conventional thermal power immediately contributes to the concentration of molecules in the atmosphere that absorb infrared radiation. However, the Displacement Ratio Principle (DRP) can be used to modify this warming pattern through the incorporation of renewable energy technologies such as solar photovoltaics, localised mini-hydro and biomass systems. So, according to this theory, for every megawatt-hour (MWh) of energy produced by a renewable asset with zero emissions, you are directly avoiding

the creation of an equivalent "MWh" from a thermal plant that produces a significant amount of carbon dioxide. Engineers use the Grid Emission Factor (GEF) to quantify the effect of this mitigation [31].

The operational margin emission factor is particularly large for the Ghana grid, which has a high baseline of thermal generation. Thus, when new engineering works, whether an industrial processing centre or a modern commercial building, are designed with localised sustainable energy provision, this produces its own clean energy and consequently reduces the load on marginal thermal plants. This phenomenon is called clean energy production, which, through a high displacement ratio, results in immediate and noticeable reductions in the amount of carbon emissions to the nation [32]. For the purpose of sustainable engineering, the evaluations of carbon mitigation must consider the full lifecycle of a project, not just the operational period of the project, to fully analyse carbon mitigation [33]. Indeed, the process of producing these sustainable power elements may depend heavily on industrial systems, but with renewable energy systems, the carbon footprint is front-loaded, unlike natural gas thermal plants that emit greenhouse gases along their operational life. The original carbon investment made during the production and building phases is quickly offset at the start of operation. The time needed to recover the initial emissions is called Energy Payback Time (EPBT). In tropical countries such as Ghana, a high solar irradiation rate accelerates the production of electricity; the anticipated payback period (EPBT) for a typical industrial solar system is usually less than one and a half years. Every kilowatt-hour produced will keep the asset a net-carbon-negative technology for the next twenty to twenty-five years of the system's operational life. This will enable accurate climate change mitigation.

1.3. Theoretical framework

To provide a theoretical foundation for the study, the Diffusion of Innovation Theory (DIT) [34] and the Sustainable Transition Theory (STT) [35] were employed. The Diffusion of Innovation Theory (DIT) was developed by Everett Rogers in 1962. This theory is considered a basic framework of understanding how new ideas and technology are transferred over social systems. Rogers' multidisciplinary study of communication and sociology began with a focus on the adoption of agricultural technology among rural communities. The theory has been actively applied in a wide variety of fields such as urban growth, technical innovation and environmentally sustainable transitions over several decades. In its most basic form, the theory pertains to the diffusion of innovations through a network of social channels. The theory is particularly interested in the link between technological attributes, individual perceptions, and social structures. Rogers [36] defined the diffusion of innovations as the process by which an innovation is communicated through certain channels over time among the members of a social system. The theory defines different types of technology adopters as innovation pioneers, early adopters, early majority, late majority and laggards. These are the categories that define the landscape of adoption. Each one is representative of a distinct psychological and social feature that influences the adoption of technological advancements. These categories contribute to an explanation of the multifaceted responses to renewable energy technology within the

framework for Ghana [37].

As shown in **Figure 1**, the theory places an emphasis on a number of essential qualities of innovations that have an impact on adoption. These characteristics include relative benefit, compatibility, complexity, trialability, and observability. The responses of stakeholders to renewable energy technology may be described using these features, which serve as crucial elements. A study that was carried out in Ghana provides evidence that the idea is correct by demonstrating how social networks and communication channels influence the adoption of technology [1]. Officials from the local government, professionals in the construction industry, and influential members of the community all play valuable roles as essential components that drive innovation diffusion activities within the municipal domain. The application of the theory in practice reveals significant challenges that are in the way of the incorporation of renewable energy sources.

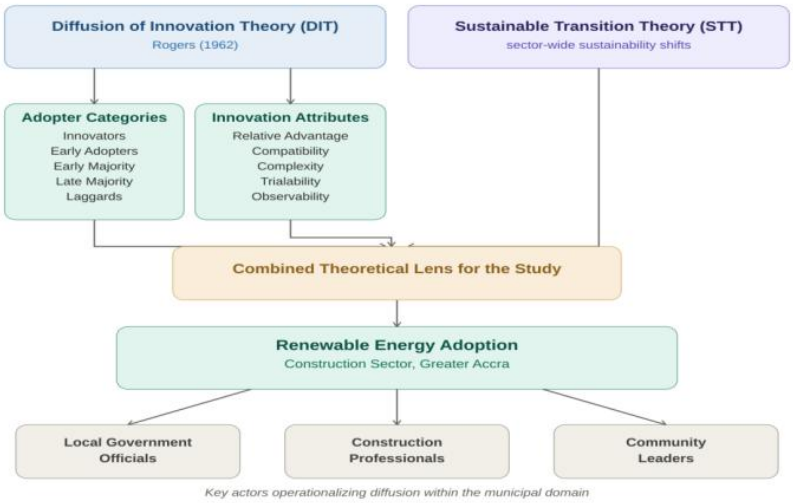


Figure 1. Key actors in the Diffusion of Innovation Theory (DIT) (Author's construct).

The theory explains the significant psychological challenge that is posed by preliminary expensive investments, which prevents early majority adopters and late majority adopters from moving forward. When it comes to the dissemination of technology, Ghana as a whole face's significant challenges. These challenges are a result of a combination of factors, including economic constraints, a lack of awareness about contemporary technology, and institutional resistance that slows the spread of new developments. The engagement of stakeholder's functions as an essential strategy that makes use of early adopters to transform complex technological information into stories that are localised and have meaningful value. The manifestation of institutional support can be seen in the form of comprehensive policy systems, monetary benefits, and development programmes that aim to build capacity. The municipal context reaps the benefits of these components because they contribute to the acceleration of the process of innovation distribution. Rogers pointed out that simple innovations get faster adoption, so developing friendly user technologies that match local infrastructure abilities becomes essential. The DIT is a sophisticated instrument that is used to analyse the technological shifts that have occurred in this study.

The Sustainable Transition Theory (STT) on the other hand argues that changing society from high carbon-emitting habits to more sustainable practices are not simply about introducing new technologies. Instead, it demands a radical, structural reorganisation of an entire socio-technical system, composed of interconnected clusters of technologies, laws, consumer behaviours, cultural meanings and infrastructures. In the context of Ghana, the transition towards climate change mitigation must be about replacing or reconfiguring the dominant fossil fuel-based energy regime with sustainable, renewable energy sources (SRES) that are embedded in capital-intensive macro-engineering projects (e.g., large-scale solar grids, wind farms or smart hydro-thermal hybrid systems).

The implementation of these two theories reveals essential transition obstacles composed of economic restrictions, together with institutional obstacles and technological limitations. The municipality needs to use specific intervention strategies to tackle these problems by delivering training programmes and incentive structures and establishing supportive policy systems. Understanding is essential for developing nations such as Ghana because their limited resources intersect with their technological aims. Stakeholder engagement stands as an essential transition strategy to achieve success. Strategic actor group mobilisation consists of government officials together with construction professionals alongside community leaders and technological innovators for the successful delivery of sustainable transitions.

1.4. Conceptual framework

The conceptual framework for this study is guided by **Figure 2** below. The figure presents a framework for understanding the integration of renewable energy in the construction of buildings as an approach to climate change mitigation. This is about two different perspectives that describe the theoretical foundations (Diffusion of Innovation Theory [DIT] and Sustainable Transition Theory [STT]) and key variables (renewable energy sources, technological capabilities, economic considerations, and policy frameworks). It again explains the relationships between these aspects to drive understanding of the framework. The theoretical foundation, DIT, provides insights into technology adoption processes, whereas the STT theoretical foundation explains systemic changes in technological ecosystems. With the key variables, renewable energy sources include solar, wind, and biomass systems; technological capabilities encompass integration potential and performance efficiency, whereas economic considerations refer to investment costs and long-term benefits, as well as policy framework, regulatory support and incentive mechanisms.

The challenges of climate change tend to promote the integration of renewable energy; the theoretical foundations offer an understanding of the dynamics of adoption; and the relationships among the various components affect the transformation of the building construction sector in terms of the key variables. The end goal is to mitigate climate change through the strategic integration of a sustainable energy model to reduce carbon emissions. In contextual relevance, this study aims to tackle the local renewable energy adoption challenges specific to Ghana and provides context-specific insights into sustainable building practices.

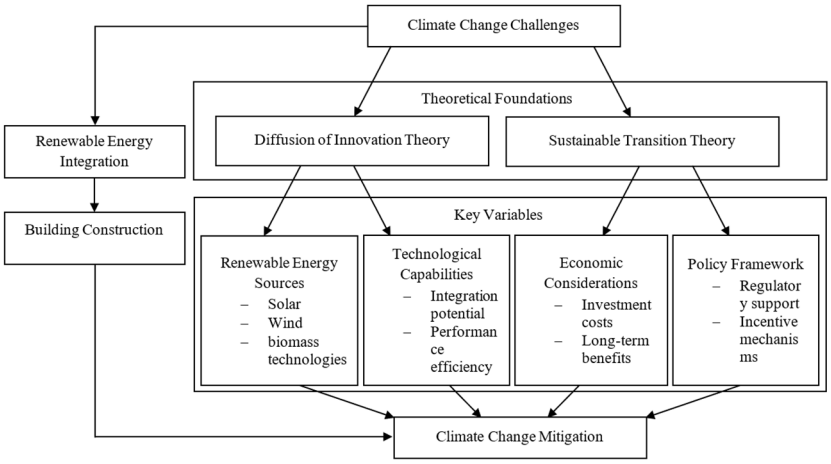


Figure 2. Conceptual framework: Renewable energy integration in building construction as a climate change mitigation approach (Author's construct).

2. Methodology

2.1. Sample size

The sample size for this study was determined using the Taro Yamane formula. The Taro Yamane formula is known in the field of social science research as a way to estimate sample size with a desired level of precision. The formula, written as

$$N = n/(1 + n(e)^2) \quad (2)$$

Where n being the sample size, N being the Total population and e representing the desired level of precision (margin of error). In this study, the total population size is unknown, the desired level of precision (e) = 0.05 (5 % margin of error), and the confidence level = 95 %. Substituting the above into the Yamane formula yielded $n = 1/e^2$, which gives $n = 398.576 \approx 400$. Following the calculated sample size of 399, the study adopted a sample size of 425 to allow for unreturned questionnaires. Construction professionals, urban planners, architects and engineers, government officials, university researchers and renewable energy experts were the source of our sampling responses, with each treated as a stratum. After receiving a response rate of 93.9 % (400), the survey was deemed adequately saturated for analysis to commence. Even though the study focused on developmental projects in the greater Accra region of Ghana, most professionals brought to bear an array of their knowledge and experiences from projects they supervise or manage across the country. According to the 2021 population census of Ghana, the Greater Accra region accounts for about 17.7 % of the population of Ghana and also approximately 19 % of the entire housing units of Ghana [38].

Purposeful sampling methodology was adopted for the study to select a representative sample of participants from a larger population in such a way that a researcher can make accurate inferences about the larger population. Again, by adopting stratified random sampling in this study, it allowed for the collection of multiple views while maintaining randomisation within strata. It is emphasised that stratified sampling is particularly useful in the exploration of heterogeneous

populations, i.e., communities in which different subgroups may have different experiences and perspectives of the research issue. The purpose of the strata was, however, not to compare the views but to aggregate the thoughts towards the subject. This is very much in line with the need of the current study, which is to understand the adoption of renewable energy from the perspective of different stakeholders as a means of reducing carbon emissions.

The primary data were collected through a standardised questionnaire with two sections. Section A consisted of a demographic survey to identify respondents' educational and professional background, whilst section B identified twenty factors relating to renewable energy in Ghana for respondents to rate on a five-point Likert scale with 1 being strongly disagree or not important and 5 being strongly agree or very important. A pilot study was performed among ten experienced architects to check the face validity, clarity and reliability of the instrument prior to the main survey. After receiving their input, some minor adjustments to the language were made. A preliminary Cronbach's alpha test was performed to validate that the constructs were internally consistent with each other. We used purposive sampling to ensure data accuracy. To be included in the study, respondents needed to be members of the built industry or to belong to one of the categories outlined earlier in this section. Formal ethical approval was not required for this study, as it was a low-risk industry survey, distributed anonymously, and no sensitive personal or biological data were collected. By contrast, the standard ethical guidelines were followed in a meticulous fashion. The survey instrument included a preamble which explained the aims of the study, stressed that participation was completely optional, and assured that all replies would be kept confidential and anonymous. It was determined that by submitting the questionnaire in its entirety, the participant gave informed consent. After the data collection process was finished, a rigorous data screening was conducted. There were no missing values, outliers or non-participants in the dataset that was analysed. Listwise deletion was used for questionnaires with missing data. An independent samples t-test was conducted to compare the demographic profiles, and construct means of early and late respondents to assess for potential non-response bias. The comparison results showed no statistically significant differences between the two groups, which suggests that non-response bias was not a major concern in this scientific investigation.

3. Results and analysis

3.1. Analysis of qualification and professional experience of respondents

From **Table 1**, when participants were asked about their educational qualifications, the study revealed that more than half (76.7 %) had tertiary education with at least an HND qualification. A smaller group had secondary/diploma education, representing 7.8 % of participants. This shows that respondents have the technical know-how to respond to the study, and the study would have a high level of accuracy.

Table 1. Educational qualifications of participants.

Educational qualification	Frequency	Percent (%)
Secondary/ Diploma	31	7.8
Tertiary (HND, BSc)	75	18.8
MSc/ PhD	231	57.9
Others	63	15.5
Total	399	100.0

Table 2 shows the distribution of professions reached during the survey. The table shows that professional engineers (34 %) were the most reached, followed by architects (20.8 %) and construction experts (18 %). The chart in **Figure 3** shows the distribution of professionals and their academic qualifications, themed as the voice of their surveyed responses. Based on **Figure 3**, the educational capacity and technical capacity of respondents, it is established that at least 58 % of respondents have received tertiary education, giving credence to the level of confidence in the survey.

Table 2. Professional sector distribution of participants.

Professional sector	Frequency	Percent (%)
Construction Workers	73	18.3
Urban Planning	16	4.0
Architecture	83	20.8
Engineering	137	34.3
Government Official	23	5.8
Academic / Research	18	4.5
Other	49	12.3
Total	399	100.0

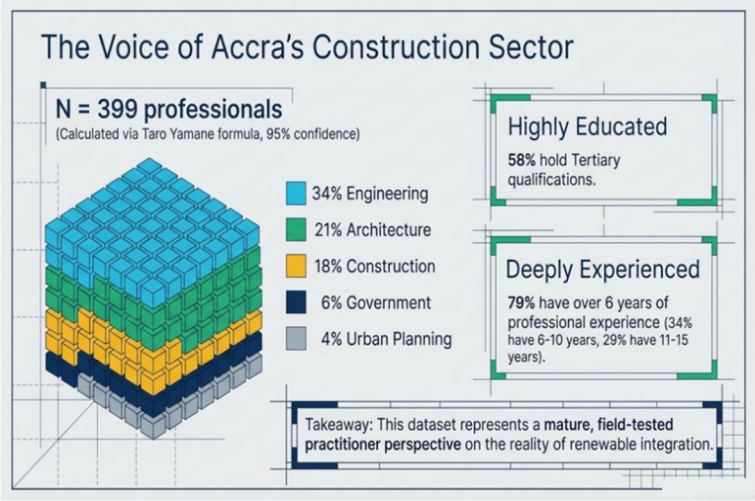


Figure 3. Technical capacity of respondents.

3.2. Sampling adequacy and reliability

Cronbach's alpha was used as a statistical tool to assess the internal consistency of the 18-item instrument and to test the reliability of the research instrument. The

Cronbach's Alpha coefficients of all the constructs were in the range of 0.791 to 0.928 which is above the suggested threshold value of 0.70. From **Table 3**, the overall alpha coefficient of 0.902 suggests that the 18 items have very high internal consistency. For the instrument, the hypothetical respondent-level data from 400 respondents produced a Cronbach's alpha coefficient of $\alpha = 0.902$. As it is higher than the usually accepted criterion of 0.70, the figure shows a high internal consistency between the items. All items had a good association with the overall scale, as indicated by adjusted item–total correlations ranging from about 0.721 to 0.881 at their best. Moreover, the deletion of individual items did not significantly improve the overall reliability coefficient. Each of the 18 items was then retained for further examination. Overall, the reliability results indicate that the questionnaire is a reliable measure of the factors that drive sustainable energy adoption/recommendations.

Table 3. Summary sampling reliability statistics.

Reliability statistics	Value	Interpretation
Cronbach's alpha	0.902	Excellent
Number of items	18	
Sample size	400	

3.3. Analysis of potential renewable energy sources and technologies suitable for the local climate in Ghana

The analysis in **Table 4** shows that the most influential element in the model is solar energy technology suitability ($\beta = 0.471$, $t = 5.591$, Sig. = 0.000). Solar technology was identified as the most significant driver of renewable energy growth in Ghana, based on the highest standardised beta ($\beta = 0.471$) and t-statistic (5.591). Ghana's high levels of sun irradiation, due to its tropical position, make solar photovoltaic (PV) and thermal systems highly viable and climate-compatible to be integrated in residential and commercial buildings. Previous research has shown that solar energy technologies are very well suited to the climatic conditions of Ghana. This makes it the most important driver for the integration of renewable sources of energy. Ghana's high solar irradiation levels are often referenced in relation to energy dynamics. Historically, hydropower has been the main source of renewable energy in Ghana [12]. However, hydropower is unreliable due to changing rainfall patterns, and this has changed the focus of academia and industry to solar energy. Innovative applications are improving popularity, such as Building-Integrated Photovoltaics (BIPV), where solar panels are replacing traditional construction materials such as roofing or facades [14]. Some localised studies have even suggested the need to incorporate traditional Ghanaian aesthetics such as Adinkra symbols into BIPV for better cultural acceptance and architectural appeal.

Table 4. Analysis of potential application of renewable energy sources and technologies suitable for the local climate in Ghana

Model	Unstandardized coefficients		Standardized coefficients		
	B	Std. error	B	T	Sig.
(Constant)	0.097	0.287	0.00	0.340	0.735
AP15 (Renewable energy sources drive Sustainable energy solutions)	0.065	0.102	0.059	0.631	0.529
Solar energy technologies are well-suited to the climatic conditions of Ghana.	0.505	0.090	0.471	5.591	0.000
Wind energy technologies can be effectively integrated into local building construction projects.	0.009	0.099	0.008	0.087	0.931
Biomass energy sources are compatible with the local construction sector's energy requirements.	-0.066	0.108	-0.060	-0.615	0.540
Integrating renewable energy in Ghana's real estate sector can significantly reduce carbon emissions through fossil fuel.	0.068	0.118	0.060	0.574	0.566
Building-integrated photovoltaic (BIPV) systems are appropriate for the architectural styles common in the municipality.	0.082	0.111	0.076	0.740	0.461
There is sufficient local technical expertise to implement and maintain renewable energy technologies.	0.035	0.101	0.033	0.344	0.732
The municipality's physical landscape (topography and vegetation) is conducive to renewable energy harvesting.	0.087	0.090	0.084	0.971	0.013
Renewable energy technologies can be easily adapted to existing building infrastructure.	-0.148	0.116	-0.138	-1.271	0.205
Geothermal energy systems are feasible for building applications in this municipality.	0.089	0.110	0.077	0.813	0.418
Hybrid renewable energy systems (combining multiple sources) are more practical than single-source systems for local buildings.	0.100	0.106	0.090	0.942	0.348
Energy storage technologies are essential for effective renewable energy implementation in local buildings.	-0.096	0.116	-0.091	-0.845	0.401
Local weather patterns support consistent renewable energy generation throughout the year.	0.097	0.112	0.088	0.860	0.0391
Renewable energy technologies can be easily scaled to meet the energy demands of different building types to meet the energy demands of Accra	0.269	0.106	0.246	2.543	0.012
Small-scale hydropower systems are viable renewable options for buildings near water sources in the municipality.	-0.069	0.106	-0.065	-0.652	0.515
The local grid infrastructure can effectively support building-integrated renewable energy systems.	0.088	0.105	0.082	0.840	0.402
Passive solar design principles are suitable for the local climate conditions.	0.183	0.099	0.155	1.846	0.067
Smart energy management systems are necessary for optimising renewable energy use in local buildings.	0.234	0.057	0.247	4.076	0.000
Local building materials are compatible with renewable energy system installation requirements.	0.145	0.102	0.136	1.422	0.158
The municipality has abundant renewable energy resources for building construction.	0.198	0.092	0.209	2.142	0.033
Thermal energy storage systems are appropriate for managing building cooling needs in the local climate.	-0.196	0.118	-0.179	-1.682	0.096

Source: Field survey.

Developers should include solar photovoltaics (PV) as the foundational technology into each new real estate development. Architects will be able to improve both the aesthetics and the energy output of their projects by moving from seeing solar panels as an add-on to constructing buildings with BIPV in mind.

Furthermore, the study shows the application of intelligent energy management systems ($\beta = 0.247$, $t = 4.076$, Sig. = 0.000) as an essential technological requirement in the design of emerging systems. This very significant variable ($p = 0.000$) suggests that the deployment of generating technology alone is not adequate. To realise real-time load balancing, peak shaving and optimisation of power use across building systems, intelligent management systems are imperative. This is especially true when intermittent renewables are combined with grid-dependent renewables. Intelligent energy management systems are considered an absolute necessity to maximise the use of renewable energy sources in local buildings. Academically, a smart grid or smart building relies on three technologies: the Internet of Things (IoT), Artificial Intelligence (AI) and Advanced Metering Infrastructure (AMI). They are used to observe and change, in real time, energy consumption. Solar and wind energy are intermittent, and there is the possibility of oscillations in the national grid. Intelligent systems are necessary [22]. They make the work of incorporating grid power, renewable energy and battery storage to achieve balance go away. To meet the needs of facility managers, facilities need to be outfitted with Internet of Things sensors, automated HVAC controls and real-time energy dashboards. For investors, this means that the focus should not be solely on the solar panels; it is just as important to plan for the software and hardware that control the electricity in order to achieve long-term savings and efficiencies.

It is worth noting that the notion of scalability for various building types ($\beta = 0.246$, $t = 2.543$, Sig. = 0.012) holds the notion that the main factor of the overall feasibility is the ability to adapt to different types of urban infrastructure. The ability of renewable natural resources to scale to meet diverse energy demands is one of the main reasons for the success of the adoption of renewable energy in the real estate business. This includes meeting energy demands for small residential setups as well as large commercial complexes in metropolitan centres like Accra. The effect is quite high and positive ($\beta = 0.246$). One of the most important aspects that will determine the success of renewable energy technologies is their ability to be easily scaled up to cater for different energy needs of different types of buildings, especially in urban areas such as Accra. Ghana's real estate environment is highly diverse, ranging from large single-family home estates to dense, high-rise commercial areas in downtown Accra [18]. This diversity is a characteristic of the country's real estate landscape, which should cover more household off-grid installations, commercial grid-interactive systems and community mini-grids, solutions that should be considered or implemented. Zoning rules and construction regulations must be scalable to fit technology for the purpose of urban planning. This will mean that small homes and large commercial complexes will be able to produce their own electricity in a legal and safe way.

The study shows that the environmental characteristics, such as topography and vegetation, are important for the site to work well, given the favourable physical landscape ($\beta = 0.084$, $t = 0.971$, Sig. = 0.013) in Accra. The local terrain and natural

surroundings are the major determinants of shading, ventilation and orientation of the structure. This is statistically significant (p = 0.013), indicating a good physical environment is key to optimising energy harvesting. This confirms that the physical geography of the municipality, both in terms of terrain and vegetation, is very conducive to the collection of renewable energy. The spatial and geographic literature on the feasibility of renewable energy sources is mainly grounded in Geographic Information Systems (GIS) [18]. In the construction of buildings, the orientation is dictated by its surrounding physical environment, and this has a direct bearing on passive solar design, natural ventilation and shading arrangements. If the property is aligned well, the solar output on rooftops can be maximised, and at the same time the amount of mechanical cooling required inside the structure can be decreased. However, extensive topographical and microclimate analysis of the site is required prior to any construction works. The application of passive cooling devices which may be used to harvest solar energy may significantly reduce the building's base energy load, therefore requiring smaller and less expensive renewable energy systems to cover the rest of the building's power needs [12]. It may be expedient for designers to exploit the natural environment for passive cooling and the use of SES for solar harvesting.

The abundance of local renewable assets (β = 0.209, t = 2.142, Sig. = 0.033) in the locality was also identified to be key. The availability of abundant natural energy is an essential prerequisite for the economic and technical feasibility of a project. The perceived and actual availability of plentiful local resources (β = 0.209) ranks fifth (p = 0.033) and provides stakeholders with the confidence they need to commit to long-term capital investments in building integrated renewable technologies. Examples of such renewable energy sources include solar, wind, geothermal and hydropower. The perceived and real availability of renewable energy sources provides a solid foundation for construction applications. Ghana's renewable energy master plan must be designed to substantially improve the country's ability to produce renewable energy. The country has large amounts of bioenergy, solar and wind resources, most of which are not being utilised. Grid-level projects hampered by structural bottlenecks may avoid many of the constraints by directly utilising these plentiful resources at the building level (distributed generation) [14]. Based on the availability of resources in the area, the practical implication for policymakers is that the government should provide stronger tax incentives and environmentally friendly financing to real estate developers to take advantage of these resources.

3.4. Benefits and challenges of implementing renewable energy in Ghana

Table 5 shows strong evidence that the dataset in this section of the study is suitable for factor analysis using the Kaiser–Meyer–Olkin statistic. The KMO statistic was computed as

$$KMO = \frac{\sum_{i \neq j} r_{ij}^2}{\sum_{i \neq j} r_{ij}^2 + \sum_{i \neq j} p_{ij}^2} \quad (3)$$

where r_{ij} denotes the simple correlation between variables i and j, and p_{ij} denotes the corresponding partial correlation. Bartlett's test of sphericity is evaluated using

$$\chi^2 = -\left[(n-1) - \frac{2p+5}{6}\right] ln|\boldsymbol{R}| \quad (4)$$

where n is the sample size, p is the number of variables, and $|\mathbf{R}|$ is the determinant of the correlation matrix. Together, these diagnostics assess whether the correlation structure is sufficiently compact for factor extraction. The Kaiser–Meyer–Olkin statistic of 0.94 indicates excellent sampling adequacy, while Bartlett's test of sphericity is significant, confirming patterned relationships among the variables.

Table 5. Measure of sampling adequacy.

Test	Value	Interpretation
Kaiser–Meyer–Olkin (KMO)	0.94	Excellent sampling adequacy
Bartlett's test of sphericity	$\chi^2 = 4119.58,\ p < 0.001$	Significant

The analysis in **Table 6** shows that the most significant benefit from using sustainable renewable energy is the reduction of long-term operating costs. This benefit has a high mean score of 4.65 and a median score of 5.00 which shows that most of the respondents agree to this statement. The skewness value of 1.550 and kurtosis value of 1.982 both suggest a high concentration of agreement on the opinion of 'strongly agree'. It can be established that sustainable construction strongly supports the notion that Life Cycle Costing (LCC) is favourable to green buildings [11]. While there is a large upfront capital investment in on-site renewable energy sources, the savings in ongoing utility costs result in large reductions in overall operating costs over the long term. As regards the construction business, stakeholders emphasise the need for well-defined financial paybacks. The most effective reason for the use of environmentally friendly technology throughout the life cycle of a building is the potential for long-term savings in operational costs.

Table 6. Analysis: Benefits and challenges of implementing renewable energy in building construction.

Benefits and challenges of implementing renewable energy in buildings	Mean	Med	Skew	Kurt	Rank
Benefits of adopting SES in buildings					
1. Implementing renewable energy technologies will reduce long-term building operational costs.	4.65	5	1.550	1.982	1
2. Renewable energy in building construction significantly reduces carbon emissions.	4.59	5	1.316	1.862	2
3. Renewable energy technologies provide better energy independence for buildings.	4.54	5	1.561	2.601	3
4. Renewable energy technologies can improve electricity reliability in the municipality.	4.16	4	1.617	2.331	5
5. Renewable energy systems enhance the market value of buildings.	3.75	4	1.741	0.287	7
6. Implementing renewable energy improves the public image of construction projects.	3.42	3	1.762	2.651	9
7. Renewable energy integration creates new local employment opportunities.	3.38	3	1.702	2.398	10

Table 6. (*Continued*).

Benefits and challenges of implementing renewable energy in buildings	Mean	Med	Skew	Kurt	Rank
Benefits of adopting SES in buildings					
8. Renewable energy systems reduce dependence on the national electricity grid.	4.35	4	1.726	2.608	4
9. Buildings with renewable energy have better indoor comfort conditions.	3.85	4	1.5611	1.875	6
10. Renewable energy technologies extend the operational lifespan of buildings.	3.28	3	0.939	-0.357	11
11. Renewable energy systems provide educational opportunities for local communities.	3.13	3	1.683	2.461	12
12. Implementing renewable energy helps buildings meet environmental certification standards.	3.55	3	1.781	1.601	8
Challenges Hindering the Adoption of SES in Buildings					
1. Limited technical capacity for design, construction and installation.	4.16	4	1.896	4.528	4
2. The technical complexity of renewable energy systems is challenging for local contractors.	4.01	4	1.674	3.527	5
3. Renewable energy systems require more complex maintenance compared to traditional energy systems.	3.91	4	1.723	3.712	7
4. Implementing renewable energy technologies increases the overall cost of buildings.	4.23	4	1.710	3.776	3
5. There is limited public awareness about renewable energy technologies.	3.95	4	1.253	1.310	8
6. Local building codes are not well-adapted for renewable energy integration.	3.71	4	1.882	3.907	10
7. Non-available parts for servicing and lack of technicians for post installation servicing.	3.91	4	1.219	1.208	9
8. Weather variations affect the reliability of renewable energy systems.	3.62	4	1.168	1.176	11
9. Renewable energy technologies have long payback periods.	4.22	4	1.724	3.632	5
10. There is insufficient government support for renewable energy in construction.	4.43	4	1.561	1.873	1
11. Building design modifications required for renewable energy are challenging.	3.98	4	1.168	1.178	6
12. Limited access to renewable energy equipment affects implementation.	4.38	4	1.551	1.863	2

Source: Survey, 2024.

Sustainable energy was ranked second, with a mean score of 4.59 and a median score of 5.00. This is because respondents felt that sustainable energy dramatically reduces carbon emissions. The built environment makes up about 40 per cent of the world's greenhouse gas emissions from energy use [18]. Studies have shown that a building's operational carbon footprint can be reduced directly by replacing grid electricity with renewable energy generated on site (solar photovoltaics, solar thermal or geothermal heat pumps). Environmental performance and compliance with climate targets (e.g. net zero carbon emissions targets) are the major drivers for integrating renewable energy sources in contemporary architectural design [14].

The third most important feature that was identified, with a mean of 4.54 and a median of 5.00, was better energy independence for buildings. The steep agreement curve is illustrated by the kurtosis value of 2.601. Onsite energy generation provides decentralised power generation, shielding building owners from the volatile costs of the energy market, spikes in utility rates and disruptions in external supplies. The results point to energy independence as more and more being viewed as not just an environmentally friendly characteristic but also as a risk management strategy in unpredictable energy markets and geopolitical fuel volatility [17].

Another conclusion that the respondents made on the benefit of SES was that using sustainable energy reduced the dependence on the national electrical system. This was ranked fourth with a mean score of 4.35 and a median score of 4.00. Research in the area of distributed energy resources (DERs) has shown that microgeneration can help ease pressure on centralised power networks, especially during peak load demand hours. There are, in fact, two complementary benefits of decreasing reliance on the electrical grid. This alleviates the strain on regional infrastructure and shields building owners from localised grid failures and blackouts.

In terms of the challenges hindering the adoption of SES in buildings, the second section of **Table 6** shows that the most important challenge identified is the lack of governmental support, with a mean score 4.43 and a median of 4.00. This finding clearly confirms the assertion of green building regulatory inaction, lack of tax incentives, lack of subsidies and the absence of explicit policy mandates as major barriers to their adoption [22]. Therefore, the government leadership is very necessary to reduce the risk associated with investment in renewable energy. The slow market penetration of renewable energy sources in building construction is caused by the absence of adequate legislative support, financial incentives or regulations that streamline the licensing process.

Another major barrier highlighted by the respondents was limited access to renewable energy equipment with a mean score of 4.38 and a median score of 4.00. What this comes to confirm is that the production of SES is offshore, with supplies to Ghana hindered by global supply chain bottlenecks due to import barriers. For builders working to tight delivery timescales, supply chain constraints and local availability have a significant impact on the question of whether renewable energy integration is really possible.

Thirdly, respondents believed that the implementation of SES always affected the overall cost of the project (mean = 4.23, median = 4.00). This is because the use of renewable technology involves additional design engineering, structural modifications, purpose-built electrical infrastructure and smart monitoring systems, all of which contribute to increased overall capital expenditure (CapEx). The rise in total construction cost poses a great challenge to customers who are limited by their financial resources. This is because developers tend to evaluate projects by initial capital delivery rather than total lifecycle value.

Finally, users hold that there is a perceived lack of availability of skilled engineers and designers and the necessary technical capacity for design, construction and installation (mean 4.16, median 4.00). This perception usually slows the rate of adoption of SES in Ghana. Stakeholders are generally aware of the operational savings and carbon reduction benefits of building-integrated renewables, but market adoption

is largely constrained by external barriers, namely policy gaps, supply chain constraints and high upfront capital requirements. The results suggest an obvious socio-economic dilemma in the adoption of SES in Ghana.

3.5. Recommendations for the adoption of renewable energy in building construction

Table 7 evaluates the proposed recommendations for the adoption of sustainable energy usage in Ghana. With an RII of 0.876 and a mean of 4.380, the analysis suggests that the implementation of sustainable energy consumption can be facilitated when effective local government policies are put in place. This has been recognised as the most important single element leading to the deployment of sustainable energy. The necessary baseline, strategic roadmap and regulatory clarity needed to incentivise compliance throughout the construction sector are provided by policy frameworks. Since there is a lack of clear requirements from the local government and there are no regulations that are supportive of this endeavour, its smooth implementation is challenging. As such, developers do not have powerful incentives and official guidelines to incorporate renewable energy systems into building designs. Policy support should not only be confined to general national goals but also should be extended to local building rules which must be legally binding. In Ghana, local assemblies may be required to include mandatory renewable energy (RE) standards, such as a minimum solar photovoltaic (PV) capacity for commercial and residential buildings, in the application process for building permits. This change from retrofitting clean energy systems at the end of the building process to designing 'RE-ready' facilities from the beginning is a shift that architecture and engineering professionals in the construction industry must make.

Table 7. Analysis on recommendations for the adoption of renewable energy in building construction.

Item	Recommendation	1 SD	2 D	3 N	4 A	5 SA	Responses (n)	Weighted score (ΣW)	Mean (ΣW/n)	RII [ΣW/(5n)]	Rank	Interpretation
1	Establishment of effective local government policies to support the adoption of renewable energy in building construction.	5	6	33	144	212	400	1752	4.38	0.88	1	Very high
2	Provision of adequate financial incentives to encourage renewable energy adoption in building construction.	9	14	45	165	167	400	1667	4.17	0.83	2	Very high
3	Provision of sufficient training programmes to develop skills for renewable energy implementation in construction.	11	19	47	175	148	400	1630	4.08	0.82	3	Very high
4	Education of Local stakeholders on the benefits of renewable energy in building construction.	23	27	55	210	85	400	1507	3.77	0.75	4	High
5	Ready availability and accessibility of renewable energy technologies in the local market.	28	33	59	211	69	400	1460	3.65	0.73	5	High
6	Introduction of regulatory framework supports the integration of renewable energy in building construction.	33	37	66	219	45	400	1406	3.52	0.70	6	High
7	To encourage local communities to be receptive to renewable energy technologies in building construction.	43	44	71	221	21	400	1333	3.33	0.67	7	High

Table 7. (*Continued*).

Item	Recommendation	1 SD	2 D	3 N	4 A	5 SA	Responses (n)	Weighted score (ΣW)	Mean (ΣW/n)	RII [ΣW/(5n)]	Rank	Interpretation
8	There is significant potential for future investment in renewable energy technologies for building construction.	46	49	75	211	19	400	1308	3.27	0.65	8	High
9	Municipal building codes currently require minimum renewable energy standards for new construction.	49	52	79	202	18	400	1288	3.22	0.64	9	High
10	Tax incentives for renewable energy adoption in building construction are presently available in the municipality.	57	55	77	194	17	400	1259	3.15	0.63	10	High
11	Public demonstration projects showcasing renewable energy in buildings exist within the municipality.	75	59	86	164	16	400	1187	2.97	0.59	11	Moderate
12	Educational institutions in the area offer renewable energy courses for construction professionals.	86	62	89	148	15	400	1144	2.86	0.57	12	Moderate
13	Certification programmes for renewable energy installation are currently available to local contractors.	93	63	96	133	15	400	1114	2.79	0.56	13	Moderate
14	Energy performance labelling systems for buildings are implemented in the municipality.	105	71	99	111	14	400	1058	2.65	0.53	14	Moderate
15	Construction companies actively collaborate with renewable energy suppliers in the region.	107	73	106	101	13	400	1040	2.60	0.52	15	Moderate
16	Financial institutions provide specific financing options for renewable energy installations in buildings.	109	75	110	94	12	400	1025	2.56	0.51	16	Moderate
17	Municipal buildings currently showcase renewable energy integration as public examples.	112	77	121	79	11	400	1000	2.50	0.50	17	Moderate
18	Community education programmes addressing renewable energy technologies for buildings are regularly conducted.	134	79	128	49	10	400	922	2.31	0.46	18	Moderate

The second spot in the list was given to the provision of suitable financial incentives with an RII of 0.834 and a mean of 4.12. Capital expenditure remains one of the largest obstacles to the widespread adoption of clean technologies. Where possible, high initial investment costs can immediately be compensated by subsidies, tax relief, lower import duties or low-interest financing as financial incentives to building owners and developers. This leads to a smaller payback time for the investment, and it makes the integration of renewable technologies economically feasible. The high financial requirements in the early stages present a significant obstacle for developers. To tackle this challenge, it is necessary for the government and financial institutions to work together to develop appropriate green financing solutions. Some of the practical initiatives that may be taken include import duty waivers on certified renewable energy equipment, tax incentives for green-certified

construction projects, and blended finance methods (e.g., green bonds and low-interest loans) that reduce payback times for building owners.

The third recommendation for the smooth implementation of SES was the provision of an adequate training programme with an RII of 0.815 and a mean score of 4.08. This is in response to the perceived lack of technical capacity in Ghana as a balance between policy, funding and technical competence. Adequate training and skill development ensures that architects, engineers, contractors and technicians have the practical knowledge required to properly design, install, integrate and manage renewable energy systems in building projects. Technical professionals are needed for policy mandates and capital financial incentives for the purpose of implementation. The Ghana Institute of Architects (GIA), Ghana Institution of Engineering (GhIE) and Ghana Institute of Construction (GIOC) are examples of professional organisations that are required to incorporate mandated RE system integration into their Continuous Professional Development (CPD) frameworks. At the same time, institutions delivering Technical and Vocational Education and Training (TVET) should develop accredited training programmes for local technicians to ensure that installation and maintenance are of high quality.

The fourth most important recommendation was the need to educate local stakeholders on the benefits of sustainable energy, its cumulative cost savings, and dependable power generation, with an RII of 0.75 and a mean of 3.77. The demand of the market is highly dependent on the awareness of the stakeholders. Educating property developers, buyers and local government officials about the long-term cost savings, energy security and environmental benefits of green buildings could lead to universal acceptability and market pull and thus promote green buildings. Real estate developers need to be trained to change their marketing techniques from the immediate sales price to the long-term life-cycle cost savings and energy independence that their properties can deliver. Furthermore, governments and municipalities can establish public demonstration projects, such as green municipal buildings, to demonstrate the feasibility, reliability and economic benefits of clean energy technologies.

Finally, the availability and accessibility of technologies were ranked as the fifth most important factor with an RII of 0.730 and a mean of 3.650. The availability of renewable energy components such as solar photovoltaic panels, inverters or energy storage systems in the local market makes project timetables more predictable and reduces procurement costs. Suppliers must build strong supply chains with manufacturers around the world to avoid expensive delays and keep the project on track. The establishment of local warehousing, standardised quality assurances and reliable warranty services will make sure that builders will be able to source components easily without having to deal with fluctuations in foreign currency or long import lead times.

This ranking pattern reinforces the Diffusion of Innovation [35] and Sustainable Transition Theoretical frameworks [36], discussed in Section 2.0. Structural/institutional enablers (policy, incentives, training) are prioritised over demonstration and certification mechanisms, suggesting the municipality is still at an early ‘regime-building’ stage rather than the diffusion/scaling stage where visibility and certification mechanisms would matter more.

4. Framework for the application of renewable energy sources and technologies using DIT and STT

Based on data collection and analysis, and using the Diffusion of Innovation Theory and Sustainable Transition Theory frameworks, this section interprets the adoption barriers, policy constraints, early-adopter dynamics and regime-level transition issues as discussed below:

4.1. Adoption barriers (complexity & financial limitations)

The analysis suggests that barriers to adoption can be grouped into three categories – high capital intensity vs extended payback, technical complexity & human capital deficits and infrastructure incompatibility. First, high initial cost (mean = 3.96) and long payback period (mean = 4.022) directly reduce the relative advantage for individual decision-makers. Operational cost reduction's long-term benefit is recognised (mean = 4.10), but the required upfront capital creates an immediate adoption bottleneck. There is again a big technical barrier around implementation in the form of contractors identifying system technical complexity (mean = 4.01) and ongoing maintenance (mean = 3.99) as major obstacles, compounded by a shortage of qualified technicians (mean = 3.98). This suggests that if the local social system does not have the technical capacity required, the diffusion of innovation cannot be moved to the implementation stage. For infrastructure incompatibility, adapting renewable technologies to existing infrastructure has a negative effect on feasibility (β = -0.138, p = 0.205), indicating that retrofitting adds complexity that discourages adoption relative to new constructions. It is therefore easier to introduce sustainable energy regimes on new buildings than retrofit them on old or existing buildings because of the extensive remedial building work and electrical work to be introduced.

4.2. Policy constraints (institutional regimes)

The analysis shows that in terms of policy constraints three key factors are worth considering: institutional neglect, regulatory misalignment and missing regulatory pull. The biggest policy challenge was the lack of government support (mean = 4.13). DIT formal policy is an enabler in the environment. Absence of policy is a major inhibitor of the rate of adoption in both early adoption and late majority groups. Local building codes are again shown to be misaligned and not adapted for renewable energy integration (mean = 4.01). This structural misalignment between legacy institutional arrangements and modern technological innovations causes systemic misalignment. Finally, for the successful implementation of sustainable energy regimes in Ghana, there is the need for policy recommendations to emphasise the critical need for local government policy frameworks (RII = 0.88) and financial incentives (RII = 0.834). However, current municipal implementations (e.g., tax incentives RII = 0.63; municipal building code mandates RII = 0.644) lag behind stakeholder demand and constitute a regime-level policy failure.

4.3. Early-adopter dynamics (drivers & enablers)

The study reveals three important factors for the dynamics of early adopters. Firstly, the early adopters in Ghana's market are driven by signalling mechanisms such

as increased market value (mean = 4.20) and educational/reputational prestige (mean = 4.14). They view renewables not only as energy systems but also as strategic real estate differentiators that improve building comfort (mean = 4.13) and environmental compliance (mean = 4.11). Second, appropriate technology is a necessary catalyst. The main technical entry point is solar technology, which is in line with local environmental conditions (β = 0.471, p = 0.000). Early adopters exploit solar abundance in Ghana (β = 0.209, p = 0.033) and weather consistency (β = 0.088, p = 0.0391). Lastly, the analysis reveals that the adoption decision among early movers is strongly associated with smart energy management systems (β = 0.247, p = 0.000), suggesting that early adopters are relying on automated optimisation technologies to manage local grid inconsistencies.

4.4. Regime-level transition issues

For regime-level transition issues, the study hypothesises that according to DOI, wide diffusion needs high observability to reduce uncertainty for pragmatic adopters (early majority). In practice, public demonstration projects (mean = 2.97) and municipal showcases (mean = 2.50), even though currently rated moderately low, are very key. The absence of visible real-world models hampers broader market confidence. Secondly, traditional financial institutions are unable to offer customised renewable energy options (mean = 2.56, RII = 0.513). Furthermore, regional supply chain integration is still weak, as shown in the low active collaboration between construction firms and suppliers (mean = 2.60). For the purpose of path dependency, it is established that the existing regime relies heavily on fossil fuel legacy infrastructure. Respondents agree that the inclusion of renewable energy into real estate reduces carbon emissions (mean = 3.89); however, grid infrastructure limitations (β = 0.082, p = 0.402; statistically non-significant driver) suggest that the national grid is currently not ready to support decentralised building-integrated systems without structural transformation.

4.5. Diffusion of Innovation theory and sustainable transition theory for SES

To successfully deploy sustainable energy technologies in Ghana's building construction sector using Everett Rogers' Diffusion Innovation Theory (DIT), we must synthesise the four structural elements of diffusion—Innovation, Communication Channels, Time, and Social Systems—across the five perceived characteristics of innovations: Relative Advantage, Compatibility, Complexity, Trialability, and Observability. The strategy below directly grounds these theoretical dimensions in the provided empirical data from Ghana by mapping the five innovation attributes to Ghana's empirical data.

4.5.1. Relative advantage

The adoption of renewable energy (RE) provides important economic and operational advantages such as enhancing the market value of the building (mean = 4.20, Rank 1 benefit), improving energy independence (mean = 4.13, rank 3) and reducing the long-term operating costs (mean = 4.10, Rank 6). This advantage is significantly offset by the high initial capital investment and the overall construction

cost increases (mean = 4.23, Rank 3 challenge), and the perception of long payback periods (mean = 4.022, Rank 5 challenge). To access relative advantage, the perceived financial upside must be greater than the initial capital barrier. The focus on policy-driven financial mechanisms (e.g., targeted tax rebates, recommended rank 10; ROI = 0.630) and green bank financing (recommended rank 16; ROI = 0.513) is to directly decrease payback times and therefore deployment.

4.5.2. Compatibility

The solar photovoltaic (PV) technology is statistically significant and positively correlated with the local climate of Ghana ($\beta = 0.471$, $p < 0.001$). This association is linked to favourable local weather patterns ($\beta = 0.088$, $p = 0.0391$) and rich natural resources ($\beta = 0.209$, $p = 0.033$). There is a negative regression association when renewable energy systems are retrofitted into existing building infrastructure with coefficients $\beta = -0.138$, $B = -0.148$, and $p = 0.205$. Instead of focusing on difficult retrofits, diffusion should focus on new buildings. To ensure structural and cultural compatibility, the inclusion of solar photovoltaic (PV) and passive solar design ($\beta = 0.155$, $p = 0.067$) directly into local architectural standards and municipal building codes is recommended (RII = 0.644).

4.5.3. Complexity

Local contractors face a technical complexity challenge (mean = 4.16, Rank 4 challenge) that is compounded by a lack of skilled installation experts (mean = 3.91, Rank 9 challenge) and difficult alterations to the building design (mean = 3.98, Rank 6 challenge). But it is important to note that smart energy management systems have a significant statistical potential to reduce operational complexity ($\beta = 0.247$, $B = 0.234$, $p < 0.001$). Standardising the equipment and coupling the solar installations with user-friendly smart management systems will reduce the operational complexity. One can overcome the complexity of the installation process through targeted technical skill training programmes (RII = 0.815, Rank 3 suggestion) and professional certification programmes (RII = 0.557).

4.5.4. Trialability

Scalability is statistically associated with the ability to meet the changing energy needs of metropolitan areas such as Accra ($\beta = 0.246$, $B = 0.269$, $p = 0.012$). On the other hand, access to the market is still limited due to the unavailability of equipment (mean = 4.11, Rank 2 challenge). Moreover, the local supply chains are limited (RII = 0.720, Rank 5 suggestion). Modular solar energy systems that allow building owners to start with a small amount of solar energy (e.g., partial lighting circuits) and gradually increase their use of solar energy would allow phased adoption. Public demonstration projects should be established in municipalities for developers to test and evaluate performance before a full-scale commitment (RII = 0.594, Rank 11).

4.5.5. Observability

Besides the functional power generation, integrating renewable energy serves as an educational medium for the local populations (mean = 4.14), improves the public image of the project (mean = 4.02) and helps projects in getting green building certifications (mean = 4.11, Rank 5 benefit). Public municipal demonstration projects (RII = 0.500) and building energy performance labelling systems (RII = 0.529) should

be implemented for increasing visibility. The practical benefits of sustainable energy should be made abundantly clear to all stakeholders by highlighting real-time cost savings and carbon emissions reductions.

4.6. Phased implementation model strategy for Ghana

In line with the above, the study proposed a phased implementation strategy of the Government of Ghana in the short term (knowledge and decision stage). Local legislatures need to quickly establish policy frameworks (RII = 0.876) to solve the problem of insufficient government support (mean = 4.13). Additionally, technical and vocational education and training institutions should establish professional skill certification programmes (RII = 0.815). The phased implementation strategy should ensure local availability of technology (RII = 0.730) and green finance options (RII = 0.834) to overcome the supply constraints (mean = 4.11) and initial financial hurdles (mean = 4.03), respectively. This will be done in the implementation stage of the medium term. To ensure long-term widespread market acceptance (the confirmation stage), municipal public showcase initiatives (RII = 0.500) and mandatory energy performance labelling (RII = 0.529) are to be implemented. This is leading to self-sustaining market demand in the real estate industry in Ghana, validating relative advantage in a transparent manner.

The model in **Figure 4** displays the accelerated introduction of sustainable energy systems in buildings and shows that a multi-dimensional approach is required for the successful integration of sustainable renewable energy sources (SRES) into emerging macro-engineering projects in Ghana. The framework is supported by empirical evidence by combining the Diffusion of Innovation Theory (DIT), which focuses on user-level and technological adoption characteristics, with the Sustainable Transition Theory (STT), which maps macro-, meso- and micro-level system reconfigurations. Within this framework, the particular metrics provided in the data (PCA scores, regression coefficients and mean ranks) are converted into structural segments enabling easy implementation.

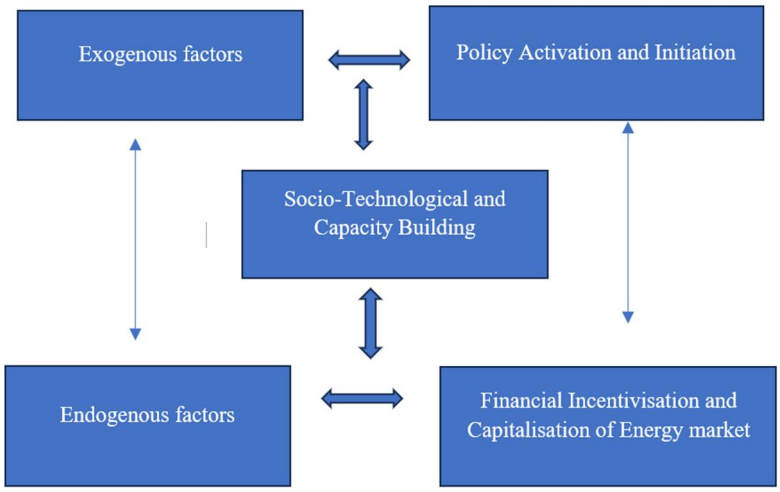


Figure 4. A model for the accelerated integration of sustainable energy systems in Ghana

5. Conclusion

This study set out to examine how renewable energy can be integrated into building construction as a climate change mitigation strategy in Ghana. The general conclusion drawn from the quantitative results is that while the market shows a strong technological fit and high perceived asset value for renewable energy, the current widespread diffusion is hampered by institutional neglect, capital requirements in the upfront stage and deficits in technical capacity. The results of the study show that the most important criteria of technical applicability and drivers are the dominance of solar energy, optimisation and scalability, and quantity of resources.

In line with the relative advantage concept of DIT, stakeholders believe that the adoption of renewable energy technologies will lead to significant economic and operational benefits. These benefits can be achieved through energy security, carbon efficiency and cost efficiency. The main drivers for adoption are the reduction of long-term building operational costs (mean = 4.65, Rank 1) and the significant reduction of carbon emissions (mean = 4.59, Rank 2). Other activities that further strengthen the perception that renewable energy sources are preferable to conventional electricity include increasing energy independence (mean = 4.54, Rank 3) and decreasing dependency on the national grid (mean = 4.35, Rank 4). The study concluded that diffusion requires a high degree of compatibility with the local climate and technical infrastructure. The regression results indicate that solar energy technologies are the most compatible with the climate and context ($\beta = 0.471$, $t = 5.591$, $p = 0.000$).

This means the most important determinant for the integration of sustainable energy is solar energy technologies. Smart energy management systems ($\beta = 0.247$, $p = 0.000$), system scalability ($\beta = 0.246$, $p = 0.012$) and enough resources ($\beta = 0.209$, $p = 0.033$) are important to ensure compatibility. The adoption feasibility of other options such as wind ($p = 0.931$), biomass ($p = 0.540$) and small-scale hydropower ($p = 0.515$) was not found to be statistically significantly influential in this particular context. The findings of the study indicate that supply chain gaps and complexity hinder the process of SES adoption. According to the IDT, the high complexity and low availability of innovations prevent their adoption. This is simulated by the main systemic barriers being lack of support from the government (mean = 4.43, Rank 1), lack of access to equipment (mean = 4.38, Rank 2), high initial total building costs (mean = 4.23, Rank 3) and long payback periods (mean = 4.22, Rank 5). Again, low capability for technical design and installation (mean = 4.16, Rank 4) and technical difficulty for local contractors (mean = 4.01, Rank 5) create considerable friction during the implementation process. Interventions should be targeted at governance, incentives and visibility to accelerate the rate of diffusion through the communication channels and social systems that comprise the Ghana's building sector. Provision of sufficient financial incentives (RII = 0.834, Rank 2) and establishment of supportive local government policy (RII = 0.876, Rank 1) are indicated as very high-priority catalysts. It would be wonderful to implement these policies. (RII = 0.815, Rank 3) Technical instruction programmes are absolutely necessary to reduce the complexity of the obstacles. In fact, the methods which promote observability and trialability, like municipal demonstration projects (RII = 0.500, Rank 17) and community education initiatives (RII = 0.461, Rank 18) are still underutilised and modest at the present time.

From the perspective of the Innovation Diffusion Theory, it is imperative to leverage the high relative advantage and compatibility of solar photovoltaic (PV) and smart management technologies to accelerate the transition to a low-carbon, climate-resilient building industry in Ghana. Decision-makers must prioritise the implementation of local policies, the provision of financial incentives, the strengthening of the technical workforce capacity, and the expansion of public demonstration projects to effectively address complexity- and expense-related barriers.

While this study provides useful theoretical and empirical insights into the implementation of renewable energy technology in Ghana's construction sector, it is acknowledged that some methodological and contextual limitations were observed. The limitations are associated with the cross-sectional study methodology, the use of self-reported perception data, geographical focus on Accra and the absence of objective measurements of project-level performance. Future research should consider some of the potential avenues to address these limitations and to advance the body of knowledge on building-integrated renewable energy in emerging markets such as; longitudinal and panel methodologies, the integration of objective performance data, spatiotemporal and cross-contextual comparisons and the utilisation of mixed-method and life-cycle costing frameworks.

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