ISSN 2347 - 3983
Volume 14. No.1, January 2026
International Journal of Emerging Trends in Engineering Research
Available Online at http://www.warse.org/IJETER/static/pdf/file/ijeter0214012026.pdf
https://doi.org/10.30534/ijeter/2026/0214012026

Environmental Effects of Solar-Integrated Building Designs in Imo State Using Structural Equation Modeling

Otta, Caesar Egwuchukwu, Gregory Chimere Enyinna, Ubani Emmanuel, Hyacinth Ugwuezi Enyinna
Affiliation:[1]Department of Project Management Technology,
Federal University of Technology Owerri, Nigeria.
pycongregco@gmail.com

Received Date: November 27, 2025 Accepted Date: December 31, 2025 Published Date : January 07, 2026

ABSTRACT

The integration of solar energy systems into building designs presents a sustainable solution for energy generation, offering economic, environmental, and social benefits. This study investigates the environmental effects of solar-integrated building designs in Imo State using structural equation modeling. Sustainability Theory inspired by the Brundtland Report, 1987 underpins this study. A structured questionnaire was administered to 225 respondents, comprising architects, engineers, builders, and contractors across the three senatorial districts of Imo State. Based on the findings, environmental effects of solar-integrated buildings demonstrate mixed outcomes: while renewable energy use significantly enhances environmental sustainability, the reduction in fossil fuel dependence contributes to favorable environmental impacts. The study concludes that while the deployment of solar energy systems substantially reduces reliance on fossil fuels and mitigates greenhouse gas emissions, their environmental benefits are not wholly linear, as they are mediated by technological efficiency, architectural adaptability, and broader systemic factors. It is recommended that building designs in Imo State should incorporate guidelines that ensure solar technologies are integrated in ways that minimize land-use pressures, heat-island effects, and material waste.

Key words: Solar Energy, Adoption, Sustainability, Integration, Building Design

1. INTRODUCTION

Embedding solar technologies into building design marks a major milestone in advancing sustainable development, especially in regions facing energy challenges. As a zero-emission, renewable resource, solar energy has become central to the global energy transition offering enhanced energy security, reduced environmental impacts, and decreased dependence on limited fossil fuels. This is underscored in the International Energy Agency's Renewables 2024 report, which highlights solar PV's dominance in projected renewable expansion and its role in approaching global energy tripling goals

Globally, the construction sector is a major contributor to energy consumption and greenhouse gas emissions. As urbanization accelerates, there is increasing pressure to adopt building designs that reduce environmental impacts while improving energy performance. Studies have shown that integrating solar energy into building structures reduces dependence on conventional energy sources, significantly lowers operational costs, and supports global climate change mitigation goals [1][2]. This approach is particularly relevant in regions with high solar irradiance, where solar energy systems can be deployed efficiently.

In the Nigerian context, the country faces significant energy challenges, with electricity supply being characterized by frequent outages, low generation capacity, and poor grid infrastructure. The nation's overreliance on fossil fuels for power generation and the high prevalence of diesel generators exacerbate environmental pollution and impose financial burdens on households and businesses [3]. Imo State, located in southeastern Nigeria, experiences similar issues, with many residents depending on self-generated power to meet their energy demands. These challenges underscore the importance of exploring alternative energy sources, such as solar, to complement the existing electricity supply and enhance energy security.

With the alarming rate of environmental degradation in the present century, caused, in large part, by the ubiquitous use of fossil fuels, an eco-friendly alternative for energy production becomes an unimpeachable necessity. One such pragmatic solution is the deployment of solar renewable energy. Imo State, a verdant region located in the Southern part of Nigeria, harbours the potential to harness this power effectively, thereby fostering significant environmental, economic and societal benefits [4].

Imo State is richly endowed with abundant sunlight, presenting an opportunity to tap into one of the cleanest forms of energy – Solar Energy [5]. Despite being in the tropics, which gifts it roughly six to seven hours of intense sunlight per day [6], Imo State is yet to fully harness this bountiful 'Solar Goldmine' for its industrialization.

Renewable energy, particularly solar, holds the potential to support the growth and development of industries in Imo State. By generating electricity that adequately powers industries, renewable energy could facilitate the industrialization process by cutting costs, creating jobs, increasing productivity, and promoting sustainable development. Stringent measures towards this would transcend it from an economy highly reliant on agriculture and trade into an industrialized powerhouse. Integrating these technologies into urban and rural housing projects can contribute to meeting Nigeria's renewable energy targets and achieving the Sustainable Development Goals (SDGs), particularly Goal 7, which seeks to ensure access to affordable, reliable, and sustainable energy for all.

The problem therefore lies in the absence of a clear understanding of the effects of integrating solar energy projects into building designs in Imo State. Questions about the economic viability, environmental impact, and technical adaptability of these designs remain unanswered. Without empirical evidence and localized strategies, the potential of solar-integrated buildings to mitigate energy challenges and contribute to sustainable development in the state remains untapped.

Conceptually, integrating solar energy into buildings goes beyond merely installing solar panels on rooftops; it involves the seamless incorporation of solar technologies into the architectural and structural framework of buildings [7]. This integration can include designing buildings to optimize natural light and ventilation, using solar passive techniques to regulate indoor temperatures, and incorporating energy storage solutions. When effectively implemented, such designs improve overall energy efficiency and reduce the environmental footprint of buildings.

Modern improvements in building materials and construction methods have made it easier to incorporate solar energy into buildings. The quantity of energy that can be caught and held inside a structure determines the efficiency and efficacy of solar energy systems, hence building materials are crucial. Insulation is a crucial factor to take into account when choosing building materials while using solar energy. High-quality insulating materials can aid in the retention of heat produced by solar panels, increasing the system's overall efficiency [8]. Materials like cellulose, fiberglass, or spray foam insulation can be used to accomplish this. Utilizing reflecting or light-colored materials on a building's roof or façade is a crucial component of choosing construction materials for solar energy integration. The total effectiveness of the solar system may be increased by using these materials to reflect sunlight and lessen the amount of heat that is absorbed by the structure.

A structure's aesthetics and ability to blend in with the surroundings may both be influenced by the building materials used. Solar panels can be more seamlessly integrated into the architecture of a structure, for instance, by using building-integrated photovoltaics (BIPV). This may provide a more aesthetically pleasing building that fits in with its surroundings as opposed to sticking out as a distinct technological advancement (see figure 1).

Figure 1: Solar Panel [9]

In recent years, the adoption of sustainable building designs that harness solar energy has surged as a critical measure to reduce dependence on nonrenewable energy sources and mitigate climate change. Photovoltaic (PV) panels transform sunlight into electricity and are being increasingly integrated into buildings—either replacing conventional materials or complementing structural elements enhancing both energy resilience and environmental performance [6].

The panels, for instance, might be incorporated into the building's façade, mounted on the roof, or even utilized to design a shade system [10][11]. Solar panel utilization may reduce a building's overall energy consumption, save operating expenses, and enhance the internal environment by lowering the need for artificial lighting and conditioning in addition to offering a clean and sustainable energy source[12]. Moreover, by providing a source of electricity during power outages, solar energy may assist a building's resilience by being included into its design. Overall, using solar energy in sustainable building design is a win-win situation that helps the environment and the people who live there.

Theoretically, Sustainability Theory, founded by multiple contributors (inspired by the Brundtland Report, 1987) underpins this study. Sustainability theory emphasizes the need for development that meets the needs of the present without compromising the ability of future generations to meet their own needs [13]. It integrates environmental, economic, and social dimensions to promote long-term viability. Critics argue that vague and broad definitions of sustainability can lead to differing interpretations and hinder practical application. Balancing economic, social, and environmental goals often leads to trade-offs rather than holistic solutions. Critics argue that the theory focuses more on goals than actionable pathways.

The sustainability theory promotes the integration of solar energy as a step toward reducing the carbon footprint of buildings in Imo State. It also helps to assess the long-term benefits of solar energy projects in terms of environmental, economic, and social sustainability [14].

The literature on solar energy integration in building designs has been widely documented, addressing its advantages, limitations, and adoption patterns across different regions. Research by [1][6], underscores the economic and ecological benefits of embedding solar systems in urban structures, particularly through cost reductions and improved air quality. Nonetheless, these investigations have predominantly concentrated on urban settings, leaving insufficient attention to peri-urban and mixed-use environments where infrastructure and energy requirements vary considerably.

In addition, [15][16] have explored the contribution of solar technologies to the realization of zero-energy buildings (ZEBs), stressing the significance of innovation and supportive policies. While these works highlight key pathways to energy independence, there is limited examination of how novel storage solutions and hybrid energy systems might enhance solar energy utilization across diverse climatic conditions.

For rural contexts, [17][18] reveal solar power's potential in extending electrification and improving energy access, with affordability and awareness emerging as critical barriers. However, gaps persist regarding how creative financial mechanisms such as cooperative-based solar projects or pay-as-you-go scheme could promote adoption in low-income and remote communities.

Similarly, [2] have addressed the integration of building-integrated photovoltaics (BIPVs) within high-rise residences, affirming their sustainability and cost efficiency. Still, most of this scholarship is situated in advanced economies like China, Germany, and the United States, whereas research on the long-term viability of BIPVs in developing nations remains sparse.

Finally, studies including [9][12] emphasize the energy-conserving advantages of solar thermal applications for domestic water heating. Yet, there is a notable research void concerning their adaptation to larger-scale commercial and industrial contexts, particularly in regions endowed with abundant solar resources but constrained by weak policy frameworks.

Finally, while [19][20] have addressed policy and financial barriers to solar adoption in Nigeria, there is insufficient research on the role of digital innovations, such as smart grids and IoT-enabled energy management systems, in enhancing the efficiency and adaptability of solar-integrated buildings.

While existing studies have provided valuable insights into solar energy integration in various building contexts, significant research gaps remain in the areas of economic, social and environmental effects of integrating solar energy in building designs in Imo state, Nigeria Addressing these gaps will contribute to a more holistic understanding of how solar energy can be effectively integrated into diverse building environments to enhance sustainability and energy resilience. This study seeks to achieve this aim by investigating the environmental effects of solar-integrated building designs in Imo State using structural equation modeling.

2. METHODOLOGY

Given the nature of the objectives, quantitative modeling techniques was used. The population for this study includes residents of rural communities, NDDC officials, solar energy providers, community leaders and local business owners. The study employed purposive sampling and snow balling sampling in reaching respondents for the study. Structured questionnaires were administered to these research respondents which include Architects, Engineers, Contractors, Construction Professionals, Developers and Building Owners. Purposive sampling was considered appropriate as it offered credibility of the data collected and in accessing respondents due to the small sample size. 25 copies of the questionnaires were returned for analysis from each of the selected local government and areas making up a total number of 225 copies of the questionnaires used for the analysis.

Structural Equation Modeling was used to analyze the research question. The following is a possible representation of the equation for the research question:

$$ENVE = F(GHGR, RNWE, FOFR) \quad \ldots\ldots (1)$$

$$\eta = \beta 1\xi 1 + \beta 2\xi 2 + \beta 3\xi 3 + \zeta \quad \ldots\ldots (2)$$

Where:

- η: Dependent variable (Environmental Effects)
- $\xi 1$: Independent variable 1 (GHG Reduction)
- $\xi 2$: Independent variable 2 (Renewable Energy)
- $\xi 3$: Independent variable 3 (Fossil Fuel Reduction)
- $\beta 1$, $\beta 2$: Regression coefficients for the independent variables
- γ: Regression coefficient for the control variable
- ζ: Error term (residual variance)

3. RESULTS AND DISCUSSION

Table 1: Model fit measures II

Fit Index	Default Model	Saturated Model	Independence Model
CMIN	.000	.000	14.582
NPAR	10	10	4
DF	0	0	6
P			.024
CMIN/DF			2.430
RMR	.000	.000	.291
GFI	1.000	1.000	.970
AGFI			.950
PGFI			.582
NFI	1.000	1.000	.000
RFI	1.000	1.000	.000
IFI	1.000	1.000	.000
TLI			.000
CFI			.000
PRATIO	.000	.000	1.000
PNFI	.000	.000	.000
PCFI	.000	.000	.000
NCP	.000	.000	8.582
FMIN	.000	.000	.065
RMSEA	.000	.000	.080
AIC	20.000	20.000	22.582
BCC	20.457	20.457	22.765
BIC	54.161	54.161	36.246
CAIC	64.161	64.161	40.246
ECVI	.089	.089	.101
HOELTER .05			194
HOELTER .01			259

Source: *Author's Analysis (2025)*

In table 1, the proposed hypotheses were tested using path analysis in AMOS 27.0, employing 2000 resample boot camp at 95CIs. The analysis showed a good structural model fit. X^2 = 14.582, df= 6.000, X^2/df = 0.430, CFI =000, GFI=1.000 RMR= 0.291 RMSEA= 0.080, PCLOSE= 0.848. The model demonstrates an overall good fit to the data. Key indicators such as CMIN/DF, RMSEA, GFI, GFI, and CFI fall within acceptable thresholds, supporting the reliability and validity of the model.

Table 2: Standardized Regression Weights II

Regression Path	Estimate	S.E. (Standard Error)	C.R. (Critical Ratio)	P Value	Label
Environmental Effects of Solar-Integrated Buildings <--- GHG Reduction	-0.022	0.067	-0.323	0.045 (Significant)	
Environmental Effects of Solar-Integrated Buildings <--- Renewable	0.085	0.077	1.102	0.031 (Significant)	
Environmental Effects of Solar-Integrated Buildings <--- Fossil Fuel Reduction	-0.199	0.066	-2.994	0.002 (Significant)	**Significant**

Source: *Author's Analysis (2025)*

The findings in table 2 above showed that environmental Effects of Solar-Integrated Buildings <--- GHG Reduction. The relationship between GHG Reduction and the Environmental Effects of Solar-Integrated Buildings is negative but statistically significant. A negative estimate suggests that as GHG reductions increase, the environmental effects of solar-integrated buildings decrease. The significant p-value (0.045) indicates that this relationship is statistically reliable at the 5% level. According to the theory of sustainable development, reducing GHG emissions should ideally result in improved environmental outcomes. However, the negative sign suggests that GHG reduction might not always directly correlate with the anticipated benefits of solar-integrated buildings. It is possible that GHG reduction efforts are not sufficiently integrated into building designs or that other factors (such as energy efficiency, building materials, or regional context) are also at play in determining the overall environmental impact.The positive and statistically significant relationship between Renewable Energy and Environmental Effects of Solar-Integrated Buildings indicates that as renewable energy adoption increases, the environmental benefits of solar-integrated buildings improve. The p-value of 0.031 confirms that this relationship is statistically significant at the 5% level.

Previous empirical studies have shown mixed results in terms of the direct relationship between GHG reduction efforts and environmental benefits in construction [19]. For instance, some research suggests that while GHG reduction can help mitigate climate change, its immediate impact on building-level environmental outcomes may be diluted by other design or technological factors [20]. This suggests that GHG reductions alone may not be enough to ensure substantial environmental benefits in solar-integrated buildings unless combined with other sustainable building practices.

Numerous studies have demonstrated the positive impact of renewable energy integration on building sustainability and environmental outcomes [13] . For example, research by [14] shows that solar energy adoption in buildings leads to a significant reduction in energy costs and carbon emissions, particularly when combined with energy-efficient design and technologies. The results align with these findings, suggesting that renewable energy adoption is indeed beneficial for enhancing the environmental effects of solar-integrated buildings.

The significant negative relationship between Fossil Fuel Reduction and Environmental Effects of Solar-Integrated Buildings indicates that increasing fossil fuel reduction leads to a decrease in the environmental effects. A negative coefficient suggests that as fossil fuel use decreases (likely through renewable energy adoption or energy efficiency improvements), the environmental impacts become more favorable, i.e., more sustainable.

Discussion of findings

Environmental effects of Solar-Integrated Building Designs in Imo State: This objective examined how solar-integrated buildings impact environmental sustainability, focusing on greenhouse gas (GHG) reduction, renewable energy adoption, and fossil fuel reduction. Key Findings: GHG Reduction ($p = 0.045$): A statistically significant but negative relationship suggests that while GHG reductions occur, they do not necessarily translate to direct environmental benefits. Renewable Energy ($p = 0.031$): A positive relationship indicates that increased adoption of renewable energy enhances environmental outcomes. Fossil Fuel Reduction: A negative coefficient suggests that reducing fossil fuel dependency leads to favorable environmental effects.

GHG Reduction: Although the relationship is negative, it is statistically significant. It suggests that in the context of solar-integrated buildings, other factors may mediate the expected positive relationship between GHG reduction and environmental impact. Future research might explore these mediating factors.

Renewable Energy: The positive significant relationship aligns with the theoretical expectations that integrating renewable energy into buildings improves environmental sustainability. This confirms the growing body of empirical work that highlights the benefits of renewable energy for environmental outcomes.

Fossil Fuel Reduction: The negative significant relationship further emphasizes the importance of reducing fossil fuel dependence for improving environmental outcomes in solar-integrated buildings, as evidenced by both theory and empirical work. These findings underline the importance of integrated strategies that combine renewable energy adoption, fossil fuel reduction, and GHG reduction to maximize the environmental benefits of solar-integrated buildings. Empirical evidence supports the idea that reducing fossil fuel consumption has a positive effect on environmental sustainability. Studies by [21] have consistently shown that buildings that reduce fossil fuel dependence exhibit significant improvements in energy efficiency, environmental performance, and carbon emissions reductions. Furthermore, reducing fossil fuel use not only lowers greenhouse gas emissions but also decreases pollution associated with the production and combustion of these fuels, which directly enhances the environmental effects of solar-integrated buildings.

These findings align with the theory of sustainable development, which posits that reducing reliance on non-renewable energy sources improves environmental sustainability. However, the negative relationship between GHG reduction and environmental effects suggests that other factors such as energy efficiency, materials used in construction, and local environmental conditions may influence overall sustainability outcomes. Empirical Evidence by [11] suggests that while GHG reduction helps mitigate climate change, its direct impact on building-level sustainability varies based on other design and technological factors. [22] found that energy efficiency, building materials, and waste management strategies are crucial for maximizing environmental benefits in solar-integrated buildings. [13] emphasizes that solar energy adoption, when combined with energy-efficient design, significantly reduces energy costs and carbon emissions.

In theory, the integration of renewable energy, particularly solar energy, into buildings is expected to reduce reliance on fossil fuels, lower carbon footprints, and enhance the sustainability of the built environment. The positive relationship here is consistent with this theoretical framework, supporting the view that renewable energy adoption has direct benefits for environmental outcomes, especially in solar-integrated buildings. Theoretically, reducing fossil fuel use is a central tenet of sustainable development and environmental improvement. By transitioning from fossil fuels to renewable energy, buildings can significantly reduce their carbon footprint and overall environmental impact. This result supports the idea that fossil fuel reduction is a critical factor in enhancing the environmental outcomes of solar-integrated buildings.

Implications: For optimal environmental benefits, solar-integrated buildings should adopt comprehensive sustainability strategies, including energy-efficient building materials, improved insulation, and waste reduction programs.

4. CONCLUSION

This study demonstrated that solar-integrated building designs in Imo State present a viable pathway for addressing both energy scarcity and environmental sustainability concerns. It was established that while the deployment of solar energy systems substantially reduces reliance on fossil fuels and mitigates greenhouse gas emissions, their environmental benefits are not wholly linear, as they are mediated by technological efficiency, architectural adaptability, and broader systemic factors. Thus, the incorporation of solar systems into building designs holds profound potential to transform the energy landscape of Imo State by advancing climate resilience, reducing environmental degradation, and promoting sustainable urban development.

Contribution to Knowledge

The study contributes to knowledge by providing insights into environmental sustainability, emphasizing the need for energy-efficient building materials and strategies with the adoption of solar-integrated building designs.

5. RECOMMENDATIONS

Promotion of Eco-Sensitive Solar Design: Building codes in Imo State should incorporate guidelines that ensure solar technologies are integrated in ways that minimize land-use pressures, heat-island effects, and material waste. This includes prioritizing rooftop installations, environmentally friendly mounting systems, and recyclable photovoltaic materials to maximize environmental gains beyond just greenhouse gas reduction.

Environmental Monitoring and Performance Audits: Establish an environmental audit framework to continuously monitor the ecological outcomes of solar-integrated buildings. Such audits should track not only GHG reductions but also broader impacts such as air quality improvement, lifecycle emissions of solar panels, and biodiversity implications, thereby ensuring that solar adoption contributes holistically to environmental sustainability.

Training & Workforce Development: Government and institutions should establish solar energy training programs for engineers, architects, and electricians. Encourage universities and vocational schools to incorporate solar energy courses and develop certification programs for solar panel installation and maintenance.

REFERENCES

1. Abdullah, W. S. W., Osman, M., Kadir, M. Z. A., &Verayiah, R. (2019). The potential and status of renewable energy development in Malaysia. *Energies, 12*(1), 24–37.
2. Adebayo, S. S., Adewale, B. G., & Oyedepo, O. A. (2020). Building orientation and design for optimal solar energy absorption in tropical regions. *Journal of Building Engineering, 25*, 101164.
3. Aliyu, A. S., Ramli, A. T., & Saleh, M. A. (2013). Nigeria's energy crisis: The way forward. *Energy Policy, 61*, 263–271.
4. Baker, E., Probert, S. D., & Crittenden, D. L. (2017). Renewable energy systems: Economic implications and cost-effectiveness of solar energy. *Energy Policy*, 104, 85-96.
5. Chukwu, E., & Okafor, M. I. (2020). Analysis of solar energy solutions adoption in public buildings in Southeastern Nigeria. *Journal of Energy Systems and Development, 12*(3), 45–62.
6. Federal Government of Nigeria (2020). *National Renewable Energy Policy*. Abuja, Nigeria.
7. Bhattacharya, S., Saha, S., & Kumar, S. (2015). Solar energy development: A review of cost and economic sustainability. *Renewable and Sustainable Energy Reviews*, 50, 394-403.
8. Chen, L. (2024). Green building practices to integrate renewable energy in construction. *Environmental Science and Pollution Research, 31*(5), 6825–6842.
9. Cozzi, L., Gould, T., &Bouckart, S. (2020). *World Energy Outlook 2020*. Paris: International Energy Agency.
10. D'Angelo, M., & Rossi, F. (2021). Adoption of solar thermal energy systems in residential buildings: A case study in Italy. *Sustainable Energy Review, 15*(2), 112–129.
11. Gade, L. (2021). *Assessing Environmental Impacts in Solar Building Technologies*. Journal of Sustainable Development, 38(4), 123-145.
12. Gonzalez, M., et al. (2021). Adoption of solar thermal systems for residential water heating in Spain. *Solar Energy, 214*, 567–579.
13. International Energy Agency (IEA). (2021). *Renewable Energy Market Analysis: Regional Overview*. IEA Publications.
14. International Renewable Energy Agency. (2024). *Geopolitics of the energy transition: Energy security*. IRENA. https://www.irena.org/publications/2024/Apr/Geopolitics-of-the-Energy-Transition-Energy-Security

15. Ogunleye, J. (2021). "Role of solar energy in sustainable rural electrification in Northern Nigeria." Energy for Sustainable Development, 62, 135-148.
16. Okonkwo, E. (2020). "Economic viability of solar PV systems in residential buildings in Abuja, Nigeria." Renewable Energy Economics, 3(2), 78-92
17. Oh, T., Hasanuzzaman, M.D., Selvaraj, J., Teo, S.C., and Chua, S.C. 2010. "Energy policy and alternative energy in Malaysia: Issues and challenges for sustainable growth. *Renew and Sustainable Energy. Review,* 14(4), 1241-1252.
18. Ohunakin, O.S., Adaramola, M.S., Oyewola, O.M. & Fagbenle, R.O. (2014), "Solar energy applications and development in Nigeria: Drivers and barriers", Renewable and Sustainable Energy Reviews, vol. 32, pp. 294-301, doi: 10.1016/j.rser.2014.01.014.
19. Wagner, D. (2020). *Renewable Energy in Sustainable Building Design*. Environmental Science and Technology, 54(11), 4525-4535.
20. Yoo, S., Lee, J., & Hwang, J. (2018). A review of the economic impacts of renewable energy subsidies. *Energy Economics*, 70, 234-245.
21. Zhang, L., Wang, X., & Yang, C. (2020). Cost-effectiveness of building-integrated photovoltaics in high-rise buildings in China. *Journal of Building Energy Systems*, 18(5), 154–167