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A Holistic Techno-Economic and Environmental Viability Assessment of a Hybrid Solar Collector/Nocturnal Radiative Cooling System for Tropical Buildings

Okonkwo, B. U.[1]*; Nwufo O. C.[1]; Nwaji, G. N.[1]; Okoronkwo, C. A.[2]; Anyanwu, E. E.[1]

[1] Department of Mechanical Engineering, Federal University of Technology, Owerri, Nigeria.
[2] Department of Mechatronic Engineering, Federal University of Technology, Owerri, Nigeria.

Corresponding Author: Okonkwo, B. U.*

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Abstract: The global building sector, a major energy consumer, urgently requires decarbonization solutions that are not only technically effective but also economically viable and environmentally sustainable. This is particularly critical in tropical developing nations, where rising cooling demands, fragile electricity grids, and waste management challenges converge. This study presents a comprehensive techno-economic and environmental (TEE) assessment of a novel hybrid Solar Collector/Nocturnal Radiative Cooling (SCN/R) system, engineered for this specific context. The system's core innovation is a spectrally selective coating fabricated from upcycled Polyethylene Terephthalate (PET) plastic waste, integrating circular economy principles directly into its design. Based on empirical data from a prototype in Nigeria, the system demonstrated robust 24-hour passive operation, achieving a solar thermal efficiency of 47.11% and a nocturnal cooling power of 196.86 W/m². While the achievable temperature differentials position it as a supplementary pre-conditioning system rather than a full HVAC replacement, its economic potential is pronounced. Strategic utilization of local materials and valorized waste resulted in an exceptionally low capital expenditure (CapEx) of approximately ₦1,800,000 for a 3.63 m² unit. A conservative payback period analysis, accounting for displaced electricity for water heating and partial cooling, yields a compelling 6.7 to 8.9 years. Environmentally, the system offers a triple benefit: significant operational carbon mitigation (0.6-0.7 tonnes of CO_2-eq annually), diversion of plastic waste from landfills, and the complete avoidance of high-GWP synthetic refrigerants. We conclusively assert that this SCN/R system represents a viable and synergistic solution for sustainable building thermal management in the tropics. To unlock its full potential, we recommend design hybridization with heat pumps and advocate for policy frameworks that include carbon financing and green building standards, thereby accelerating its adoption as a cornerstone technology for a low-carbon, circular built environment.

Keywords: *Techno-Economic Analysis; Life Cycle Assessment; Hybrid Solar System; Nocturnal Radiative Cooling; Circular Economy; Payback Period; Carbon Mitigation; Sustainable Development; Policy Frameworks.*

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I. INTRODUCTION

The imperative for a global sustainable energy transition is unequivocal, driven by the escalating crises of climate change and energy insecurity [1]. The building sector, accounting for 35-40% of global energy consumption, stands as a critical frontier for decarbonization efforts [5]. This challenge is acutely manifested in tropical developing countries, where rapid urbanization, increasing cooling demands due to rising incomes, unreliable electrical grids, and constrained financial resources create a perfect condition [6]. The transition to sustainable technologies faces a fundamental triple constraint: the simultaneous need to demonstrate robust technical performance, achieve economic competitiveness, and deliver verifiable environmental benefits [2, 3]. A technology excelling in only one dimension

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is destined for niche application; true impact necessitates a holistic assessment framework that integrates all three pillars [4].

Hybrid solar-thermal and radiative cooling (SCN/R) systems provide a compelling answer by harnessing two natural, zero-cost resources: the sun for daytime heating and the cold universe for nocturnal cooling. This method holds great potential for substantially lowering the energy demand for building climate control [7, 8]. The integration of these dual functions into a single apparatus promises superior utilization of material resources and rooftop space compared to separate, single-purpose systems. However, the annals of renewable energy are replete with technologies that were technically sound but failed due to prohibitive costs, poor reliability, or unquantified environmental trade-offs in their manufacturing or disposal phases [9]. The viability of novel SCN/R systems, particularly those incorporating non-conventional materials and designed for challenging socio-economic contexts, cannot be assumed; it must be rigorously and holistically evaluated.

Current literature lacks integrated TEE assessments of such low-cost, waste-integrated hybrid systems. While Techno-Economic Assessment (TEA) and Life Cycle Assessment (LCA) are well-established for conventional solar thermal technologies [10-12, 15], their application to innovative systems that leverage local materials and waste valorisation remains scarce. This gap is significant, as it overlooks the unique value proposition of these systems, which offers a compelling value proposition: significantly lower costs, dual heating and cooling services, and a net-positive environmental impact achieved through circular economy principles [16].

This study, therefore, aims to fill this critical gap by conducting a comprehensive TEE viability assessment of a novel SCN/R system utilizing a spectrally selective coating derived from recycled PET plastic waste. Grounded in empirical data from a prototype in Owerri, Nigeria. This work evaluates the technical robustness, economic feasibility, and environmental benefits of the system for building climate control in tropical developing regions. This work aims to achieve the following specific objectives:

- To define a technical performance baseline, using experimental data to quantify energy output and system constraints.
- To conduct a granular economic analysis, determining Capital and Operational Expenditures and calculating key financial metrics such as the Simple Payback Period.
- To perform a streamlined Lifecycle Assessment (LCA) evaluating the environmental footprint, with emphasis on GHG emissions, waste valorization potential, and the avoidance of synthetic refrigerants.
- To identify critical barriers to commercialization and formulate targeted strategies for performance enhancement and market integration facilitated by supportive policy.

II. METHODOLOGY

The techno-economic-environmental (TEE) analysis of the study is grounded in empirical data from a physically constructed and monitored prototype, ensuring the findings reflect real-world performance and constraints.

A. Technical Performance Baseline

The assessment is founded on experimental data collected from the SCN/R prototype over a concentrated two-month testing period in the tropical climate of Owerri, Nigeria. The key performance indicators (KPIs) of the prototype were rigorously monitored and form the quantitative backbone of this analysis:

- *Solar Thermal Collector Efficiency (η)*

Calculated as the ratio of useful thermal energy gain to incident solar radiation, yielding a measured efficiency of 47.11%.

- *Nocturnal Radiative Cooling Power (Q_{cool})*

Quantified as the net radiative heat loss per unit area, achieving a peak of 196.86 W/m² under clear-sky conditions.

- *Achievable Temperature Differentials*

The ΔT for heating (water outlet above ambient) and cooling (water outlet below ambient) were continuously recorded to assess the capacity of the the system to meet thermal loads.

- *System Reliability*

Operational consistency and passive functionality over the 24-hour cycle were verified.

These KPIs provide an unambiguous foundation for estimating the annual energy delivery potential of the system and its practical limitations in a high-humidity environment.

B. Economic Assessment Model

A detailed, bottom-up cost model was developed to ensure a transparent and accurate economic evaluation.

- *Capital Expenditure (CapEx)*

All material and labour inputs were meticulously itemized. Major components included:

- *Collector Assembly*

Mild steel casing, the valorised recycled PET coating (assigned a zero-material cost), copper absorber tubes, HDPE glazing, and fibreglass insulation.

- *Storage and Hydraulics*

Two insulated 1000L water tanks, circulation pumps, and PVC piping networks.

- *Instrumentation and Control*

Data logger, PT100 temperature sensors, and a supplementary weather station.

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➢ *Labour*

Design, fabrication, and installation efforts were costed at prevailing local market rates.

All costs were calculated in Nigerian Naira (NGN). A 5% contingency was added to the total. For international reference, the exchange rate of 1 USD = 1,500 NGN is noted.

➢ *Operational Expenditure (OpEx)*

Estimated based on the parasitic electricity consumption of the circulation pumps and an annual maintenance cost conservatively set at 1% of the total CapEx.

➢ *Financial Viability Metrics:*

➢ *Annual Cost Savings*

Calculated based on the estimated annual energy output of the system. For heating, savings were derived from displaced electricity for water heating using an electric immersion heater. For cooling, a conservative estimate was made by equating the cooling effect to the electricity consumption of a highly efficient air conditioner or fan, acknowledging the thermodynamic limitations of passive cooling.

➢ *Simple Payback Period (SPP)*

Calculated as SPP = Total CapEx / Annual Cost Savings. This metric provides a clear, easily interpretable indicator of financial return for potential adopters.

C. Environmental Impact Assessment

A streamlined, qualitative Life Cycle Assessment (LCA) was conducted, focusing on the most salient environmental impacts across the life cycle of the system, in alignment with ISO 14040 principles [14].

- Embodied Energy and Carbon: We estimated the energy consumption and CO_2-equivalent emissions associated with the manufacturing of new system components (e.g., steel, copper) and the installation process. The recycled PET was considered to have zero embodied energy for its material phase, as it is a waste product.
- Operational Carbon Mitigation: The avoidance of GHG emissions was calculated based on the annual energy output of the system and the GHG emission factor of the displaced grid electricity (~0.5 kg CO_2-eq/kWh for Nigeria's gas-dominated grid).
- Waste Valorisation Benefit: Applying system expansion, we accounted for the avoided environmental burden of diverting PET waste from landfill, including preventing methane emissions and leachate.
- Avoided Refrigerants: A significant benefit was attributed to the passive cooling mechanism, which uses water as the heat transfer fluid, thereby eliminating the need for synthetic refrigerants with high Global Warming Potential (GWP).

III. RESULTS

➢ *Techno-Economic Performance*

The prototype system conclusively demonstrated its capability for 24-hour passive thermal management. The measured solar thermal efficiency of 47.11% and nocturnal cooling power of 196.86 W/m² confirm its ability to harness ambient energy flows effectively. However, the operational data revealed a key performance boundary: the achievable temperature differential for cooling typically ranged between 2-4°C. While this is sufficient for pre-cooling ventilation air or providing base-load cooling, it is inadequate to handle peak cooling loads in a high-humidity tropical climate, thus defining the role of the system as a supplementary pre-conditioning unit.

The economic analysis reveals a highly competitive capital cost structure. The total CapEx for the 3.63 m² prototype was determined to be ₦1,800,000. The detailed breakdown, presented in Table 1, highlights the profound impact of using valorised PET waste and local fabrication expertise.

Table 1. Capital Expenditure (CapEx) breakdown for the SCN/R prototype

Component	Material Cost (NGN)	Labor Cost (NGN)	Total (NGN)
4x Collectors (Materials)	₦570,000	₦225,000	₦795,000
Storage Tanks & Insulation	₦375,000	₦120,000	₦495,000
Pumps, Pipes, Valves	₦180,000	₦75,000	₦255,000
Instrumentation	₦150,000	₦30,000	₦180,000
Total Prototype Cost			**₦1,725,000**
Contingency (5%)			₦75,000
Total CapEx			**₦1,800,000**

The annual energy saving was estimated at approximately 900 kWh from displaced water heating electricity. At a local electricity tariff of ₦225/kWh, this equates to an annual saving of ₦202,500. This results in an SPP of 8.9 years. Incorporating a conservative valuation of the cooling effect (equivalent to 300 kWh of avoided AC electricity, saving ₦67,500/year) improves the total annual saving to ₦270,000 and reduces the SPP to a more attractive 6.7 years.

➢ *Environmental Impact Results*

The environmental assessment underscores the significant advantages of the system:

- Operational Carbon Mitigation: By displacing grid electricity, the system avoids an estimated 0.45 tonnes of CO_2-eq annually from heating alone. Including the cooling contribution, the total annual mitigation potential rises to 0.6 - 0.7 tonnes of CO_2-eq.
- Waste Valorization: The system diverts approximately 2 kg of PET waste per m² of collector from the linear waste

stream, providing a clear avoided environmental burden associated with landfilling or incineration [18].

- Avoided Refrigerants: The passive radiative cooling function entirely circumvents the use of synthetic refrigerants, a critical benefit given the extremely high GWP of commonly used fluids in vapor-compression cycles.

IV. DISCUSSION

The results of this integrated TEE assessment compellingly argue for the viability of the recycled-PET SCN/R system, while also clearly delineating its optimal pathway to market and impact.

➢ *Techno-Economic Viability*

The achieved payback period of 6.7 to 8.9 years is a strong indicator of economic feasibility within the context of tropical developing economies. It is comparable to, or better than, many other renewable energy interventions in similar settings [13, 17]. This financial attractiveness is directly attributable to the strategic design choices, the valorisation of waste PET, and the reliance on local manufacturing capabilities. These choices not only minimize material costs but also stimulate local economies and reduce import dependencies. The technical performance profile of the system necessitates a reframing of its application. It should not be viewed as a failed standalone HVAC system, but rather as a highly successful pre-conditioning hub. Its ability to pre-heat domestic hot water to more than 50°C and consistently provide base-load cooling can drastically reduce the operational hours and energy draw of conventional backup systems (e.g., heat pumps or air conditioners), thereby improving their coefficient of performance (COP) and longevity.

➢ *The Circular Economy and Environmental Synergy*

The environmental merits of the system extend far beyond operational carbon savings. The integration of PET waste as a functional component is a transformative feature that embodies the principles of the circular economy [16, 18]. It addresses two pervasive problems, plastic pollution and high energy costs simultaneously, creating a synergistic solution. This dual-use of waste material provides a compelling narrative that can enhance public acceptance and align with national and international sustainability agendas, including the UN Sustainable Development Goals (SDGs) 7, 11, and 12. Furthermore, the avoidance of synthetic refrigerants is an often-overlooked but critically important benefit in the global effort to mitigate climate change, as mandated by the Kigali Amendment to the Montreal Protocol.

➢ *Overcoming Barriers and Pathways to Commercialization*

For this technology to transition from a successful prototype to a widely deployed solution, several barriers must be addressed:

- Performance Limitation: The inability of the system to meet peak loads alone is its primary technical barrier.
- Market Awareness and Standards: A lack of consumer awareness and the absence of standardized performance ratings and installation codes hinder market confidence.
- Financing Hurdles: Despite its low cost, the initial CapEx can still be prohibitive for low-income households.

V. RECOMMENDATIONS

We propose three targeted pathways to overcome these barriers:

- Performance Hybridization: The most promising technical strategy is the intentional integration of the SCN/R system with a solar-assisted heat pump (SAHP). In this configuration, the SCN/R unit acts as a pre-heater for the evaporator of SAHP or an enhanced heat rejector for its condenser, creating a hybrid system with a dramatically improved overall COP capable of meeting full building loads [19].
- Strategic Policy Support: Government and international agencies can play a pivotal role. Instruments such as tax credits, rebates, and green building mandates can stimulate demand. Crucially, carbon financing mechanisms should be explored. The verified carbon reductions from each installed system could be monetized as carbon credits, creating a direct revenue stream that would substantially shorten the payback period, potentially by several years [20].
- Commercial Scaling and Standardization: Moving from artisanal fabrication to the mass production of standardized, prefabricated collector kits will unlock economies of scale, further drive down costs, and ensure quality control.

VI. CONCLUSION AND POLICY IMPLICATIONS

This holistic techno-economic and environmental assessment unequivocally demonstrates that the hybrid SCN/R system with a recycled PET coating is a viable, sustainable, and strategically important technology for building thermal management in tropical regions. It successfully navigates the adoption three-prong approach by offering proven technical performance for pre-conditioning, compelling economic feasibility with a payback period under 9 years, and multifaceted environmental benefits encompassing carbon mitigation, waste valorisation, and refrigerant avoidance.

The findings from the study led to three concrete policy implications:

- Targeted R&D Funding: Public and private sector investment should be directed towards optimizing the spectrally selective properties of recycled polymer coatings and developing standardized hybrid system designs that integrate SCN/R with efficient heat pumps.
- Innovative Financial Instruments: Policymakers and financial institutions should develop and deploy green mortgages, on-bill financing schemes, and frameworks for integrating carbon credit revenues into project financing to dismantle the initial cost barrier for consumers.

- Updated Building Codes and Standards: National and local governments should revise building energy codes to encourage or mandate the use of passive pre-conditioning systems like the SCN/R in new constructions, particularly for public and commercial buildings.

This system is a scalable, sustainable strategy for decarbonizing tropical buildings, creating a synergistic solution to plastic waste and energy poverty. Grounded in circular economy principles, the technology, with further development, is positioned to be a significant contributor to climate resilience and sustainable development.

➢ *Conflicts of Interest*

The authors declare no competing interests.

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