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SOLAR ENERGY AND CLIMATIC CONSTRAINTS: ANY ALTERNATIVE FOR SUNLIGHT-DEFICIENT ENVIRONMENTS?

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ABSTRACT

In many regions across the globe, the transition to renewable energy is constrained not primarily by technological incapacity but by environmental limitations which is scarcity of direct sunlight. This engender the question: what alternative energy systems can effectively substitute for solar energy in sunlight-deficient environments? The principles of sustainable energy transition theory and that of resilience framework were employed to inquired into how climatic factors influenced the adaptability and integration of renewable systems. However, the problem emerges from the growing dependence on solar technologies in regions where persistent cloud cover, high latitude, and long winters reduce solar efficiency. A mixed-methods design, comprising climatic data analysis, comparative case studies in Nigeria, Kenya and Finland, and expert interviews helped in identifying viable alternative pathways such as wind, geothermal, tidal, and hybrid bioenergy systems as adaptive solutions. The findings of the study showed that hybrid systems that integrates wind and biomass can make up for low insolation levels, while geothermal and tidal power provided stable base-load potentials in coastal and tectonically active areas. The study concluded by emphasizing that the most sustainable energy strategies in such environments hinged on context-specific integration rather than replication of solar-centric models. It recommended a policy reorientation toward diversified renewable options with regional energy audits and adaptive planning.

Keywords: Renewable energy alternatives, solar limitation, hybrid energy systems, climate adaptation, sustainable energy transition.

1. INTRODUCTION

The quest for renewable energy has become a defining priority for nations seeking to reduce carbon emissions and achieve long-term sustainability. While global engagements often push solar energy as the cornerstone of this transition, its effectiveness is not universal. In regions characterized by prolonged cloud cover, high humidity, or low solar radiation, reliance on solar technologies has proven both technically inefficient and economically unsustainable. Kabeyi and Olanrewaju (2022, p.3) observe that "solar deployment in low-insolation regions frequently results in energy deficits and grid instability," exposing the limitations of a one-dimensional renewable strategy. This reality forces a deeper examination of how sunlight-deficient environments can diversify their renewable drive to meet growing energy demands.

Recent literature provides strong indications that hybrid renewable systems which integrates wind, hydro, geothermal, or biomass can bridge the climatic gap inherent in solar-dominated models (Natividad & Benalcazar, 2023; Spiru, 2023). These systems align energy production with natural climatic variations, improving overall reliability and resilience. The adoption of such adaptive frameworks reflects what Breyer et al. (2022) describe as the "contextual evolution of renewable energy systems," where technology deployment must align with geographic and environmental conditions.

This study seeks to build on these insights to examine feasible alternatives (Archibong and Afolabi, 2023) for regions where sunlight is limited in the drive for clean energy. It explores how adaptive integration of renewable systems can ensure energy security without overdependence on solar resources. The study's focus is both practical and theoretical because it assesses how hybrid and regionally optimized systems can enhance sustainability while informing more context-sensitive energy policies. In doing so, the study contributes to the global discourse on renewable diversification, while providing relevant insights to all sunlight-deficient environments seeking sustainable energy drive.

2. Objectives of the Study

The objectives of the study are to:

i. Examine the climatic and environmental factors that constrain the performance of solar energy systems in low-insolation regions.

ii. Assess the technical and economic feasibility of alternative renewable sources such as wind, geothermal, tidal, and biomass in these regions.

iii. Evaluate the potential of hybrid renewable energy systems as adaptive solutions to climatic constraints.

iv. Analyze case studies of regions that have successfully integrated diversified renewable systems under sunlight-deficient conditions.

3. Research Questions

To guide the logic of the study and achieve the stated objectives, the study will address the following research questions:

i. What specific climatic and environmental factors limit the effectiveness of solar energy systems in sunlight-deficient regions?

ii. Which renewable energy alternatives demonstrate the greatest adaptability and potential for integration in these environments?

iii. How can hybrid renewable energy systems be optimized to maintain a stable and efficient energy supply despite climatic limitations?

iv. What lessons can be drawn from regions that have successfully transitioned toward diversified renewable energy systems?

4. Statement of the Problem

The global transition toward renewable energy has been solar-centered, often assuming uniform sunlight availability across regions. However, this assumption fails in sunlight-deficient environments where climatic factors such as frequent cloud cover, humidity, and low solar irradiance reduce photovoltaic efficiency. In such regions, solar installations deliver suboptimal performance and inconsistent generation outputs. These limitations translate into unreliable energy supply, high maintenance costs, and lower economic viability, particularly in areas already struggling with infrastructure deficits.

The major problem lies in the misalignment between energy transition policies and environmental realities. Many national energy strategies continue to prioritize solar expansion, even where local climatic conditions make such reliance unsustainable. Consequently, alternative renewable options such as wind, hydro, and biomass remain underutilized, despite their potential to complement solar generation and enhance grid resilience in low-insolation regions. The intermittent reliance on fossil-based backup systems contradicts national decarbonization objectives and exposes the fragility of solar-dependent grids. In many developing and emerging economies, energy governance structures remain rigid and technologically narrow, focusing on solar proliferation without systemic planning for climatic adaptation.

Literature Review

Regions with prolonged cloud cover face persistent challenges in maintaining stable solar power generation. Kabeyi and Olanrewaju (2022, p. 3) explain that solar systems perform poorly where "insolation levels fall below 3.5 kWh/m² per day," as the resulting intermittency makes it difficult to sustain grid reliability. In the same vein, Breyer et al. (2022) note that even in countries with ambitious renewable energy targets, solar power is often over-prioritized despite local climatic unsuitability. The authors argue that the global enthusiasm for solar energy often overlooks regional climatic realities such as seasonal snow, fog, and atmospheric moisture.

This overreliance on solar energy has direct implications for energy security as Thompson (2023) describes it as a "structural vulnerability" in renewable planning, particularly in mid- to high-latitude countries where sunlight varies drastically across seasons. His study of transition models across Europe shows that wind and hydro potentials often remain untapped even when solar infrastructure dominates energy budgets. Thus, a key insight emerging from contemporary literature is that renewable energy transitions must respond to local climatic data rather than depend on globally generalized models.

The limitations of solar efficiency in sunlight-deficient regions have, however, prompted greater interest in alternative and complementary systems. Spiru (2023) puts it that, the integration of hybrid systems that align renewable supply with natural climatic rhythms represents the next frontier of decarbonization. This understanding has led to the expansion of research around hybrid renewable systems, geothermal and tidal options, and the development of smart energy grids to balance intermittency. Consequently, hybrid renewable energy systems (HRES) have emerged as viable solutions to solar energy constraints. Natividad and Benalcazar (2023) define them as integrated systems that combine multiple renewable sources, often supported by intelligent control and storage technologies. Their study of rural Ecuador found that hybrid configurations of solar, wind, and biomass improved power reliability by 37% compared to solar-only installations.

Kumar and Majid (2024) affirm this view in their work on India's transition, observing that the coupling of wind and solar through intelligent management systems substantially reduces the impact of intermittent weather conditions. Their modeling demonstrates that hybrid plants can supply up to half of India's renewable generation needs in variable climates. León Gómez, De León Aldaco, and Aguayo Alquicira (2023) also note that hybrid systems are central to the next phase of sustainability planning because they combine "the stochastic strengths of different renewables to achieve steady energy outputs.

Spiru (2023) provides one of the clearest empirical justifications for hybrid adoption in sunlight-deficient contexts. Analyzing European and Asian case studies, he found that integrating solar with wind and hydro reduced system emissions by over 60% and stabilized output variance across seasons. Such integrations are increasingly supported by advances in energy storage technologies and grid optimization. However, León Gómez et al. (2023) posits that, battery limitations remain a "technical bottleneck" that could restrict large-scale hybrid deployment until cheaper and more efficient storage systems are developed.

The strength of the hybrid approach lies not only in technological blending but also in its resilience to climatic fluctuations. Kabeyi and Olanrewaju (2023) explain that, hybrid systems embedded within smart grids allow for "real-time balancing between sources," ensuring that wind, biomass, or hydro can automatically offset solar deficits. This integrative approach forms the backbone of modern adaptive energy transition theories.

According to Akçaba and Eminer (2022) and Archibong, et al (2025a) geothermal energy remains the most reliable renewable source for regions with stable subsurface heat gradients, providing year-round energy independent of surface weather. Their study of Northern Cyprus demonstrates how geothermal integration supports national energy security in areas with modest sunlight exposure. Similarly, Spiru (2023) shows that coastal and high-latitude nations can benefit from tidal systems, which offer predictable power curves and complement solar generation during low-irradiance months. However, the high cost of tidal infrastructure and environmental concerns regarding marine ecosystems continue to limit its acceptability.

Biomass energy also presents potential where agricultural residues or organic waste are abundant. Kehbila et al. (2021) notes that bioenergy, when managed through local cooperatives, can ensure "community energy autonomy" while addressing waste management challenges. They stress that hybridizing biomass with solar or small hydro in rural Kenya achieved a steady off-grid electricity supply despite cloudy climatic conditions. However, unsustainable harvesting practices remain a risk, underscoring the need for governance that integrates both ecological and energy planning.

The shift from solar dependence toward diversified renewables reflects a broader theoretical shift in sustainability research which is one centered on adaptation. Kabeyi and Olanrewaju (2023) describe adaptive transition as an iterative process of aligning energy technologies with dynamic environmental and socio-technical conditions. This positioning aligns with the Sustainable Energy Transition Theory, which views resilience and flexibility as indicators of long-term energy security. In Japan, Bogdanov et al. (2023) mapped transition pathways showing that a combination of wind, solar, and hydropower could sustain a 100% renewable system by 2050, provided that smart storage and flexible demand systems are developed. Their analysis demonstrates that the Japanese energy system's resilience is not dependent on sunlight alone but on the integrated exploitation of complementary resources.

Barone et al. (2021) support this understanding through their Canary Islands model, where hybrid optimization reduced energy dependency and operational costs. They report that solar dependency decreased by 43% once biomass and micro-hydro were introduced into the grid simulation. In Nigeria, Ekpotu et al. (2024) argue that the national Energy Transition Plan’s overreliance on solar technologies ignores available wind, biomass, and hydropower potentials. Their technical analysis calls for context-specific diversification to avoid grid instability and unsustainable financial exposure. The adaptive energy transition framework, therefore, encourages flexibility in technology choice, guided by climate data and local resource mapping. It moves beyond the one-dimensional push for solar expansion toward a more distinctive, system-wide transformation that accounts for environmental variability and socio-economic conditions.

5. Theoretical Framework

The Sustainable Energy Transition Theory (SETT) provides a foundational lens through which this study conceptualizes renewable energy adaptation in sunlight-deficient regions. It emphasizes that energy transitions are complex socio-technical processes, not merely technological substitutions. According to Sovacool and Geels (2021 p.58), sustainable transitions occur through “systemic change driven by interactions between technological innovation, social acceptance, and institutional alignment”. This means that achieving sustainability is not about replacing fossil fuels with renewables in a uniform manner, but about designing energy systems that fit local ecological and social contexts.

The theory stresses a shift from centralization to decentralization, where localized renewable mixes better respond to resource variability. In sunlight-deficient areas, this decentralization aligns with the principle of diversification which substitute or combine solar with regionally abundant renewables such as wind, geothermal, and biomass. Breyer et al. (2022) underscores this view, noting that the viability of 100% renewable systems depends on spatial and climatic compatibility, not on the universal dominance of any single source. In other words, a sustainable transition must be spatially intelligent and climatically adaptive.

Applying SETT, this study interprets the overdependence on solar energy not merely as a technological problem but as a systemic imbalance between innovation, policy, and environment. Thus, the theory provides the analytical foundation for assessing how multi-source renewable configurations can address the inefficiencies and vulnerabilities identified in the statement of the problem. On the other hand, while SETT emphasizes systemic transformation, the Resilience Framework (RF) focuses on the capacity of energy systems to absorb shocks, adapt to stress, and maintain stability under changing conditions. The framework, originally developed within ecological systems theory, has been widely applied to energy studies to conceptualize how systems recover from variability in supply or climatic disruptions (Folke, 2021). In renewable energy contexts, resilience refers to an energy system’s ability to remain functional despite fluctuations in generation, demand, or environmental factors.

6. Methodology

6.1 Research Design

This study adopts a mixed-method research design, integrating both quantitative and qualitative approaches to explore viable renewable energy alternatives for sunlight-deficient environments. The choice of a mixed-method approach is informed by the Sustainable Energy Transition Theory (SETT) and the Resilience Framework (RF) discussed earlier, which collectively emphasize system complexity, adaptation, and contextual variation. Quantitative data are required to assess climatic and technical feasibility, while qualitative insights help interpret how governance, policy, and local practices shape renewable adaptation.

A comparative case study strategy complements this design, focusing on regions where sunlight deficiency constrains solar energy performance but where adaptive strategies have emerged. These include Northern Europe (Finland and Scotland), East Africa (Kenya), and Southern Nigeria chosen for their contrasting climatic, economic, and policy contexts. Yin (2021) notes along this line that, case study research allows for deep contextual analysis where multiple variables interact in complex, real-world systems. This approach enables cross-regional comparison of adaptive renewable configurations and policy outcomes.

6.2 Study Area Selection Criteria

The selected regions share certain characteristics: (i) variable solar radiation below 4 kWh/m²/day during extended seasons, (ii) existing or emerging renewable initiatives, and (iii) available climatic and energy production data for empirical analysis. For example, the Nigerian south and coastal Kenya experience high humidity and frequent cloud cover, reducing photovoltaic efficiency by up to 35% during peak wet seasons (Kabeyi & Olanrewaju, 2022). Conversely, northern Europe offers case models of integrated wind, biomass, and hydro systems that demonstrate climatic adaptability. These contrasts provide a robust empirical base for comparative evaluation.

6.3 Data Collection Techniques

Data collection is structured into two complementary streams:

i. Quantitative Data: Meteorological and technical data was gathered from authoritative databases such as the NASA Prediction of Worldwide Energy Resources (POWER) platform, World Bank Global Solar Atlas, and International Renewable Energy Agency (IRENA) datasets. Variables include solar irradiance (kWh/m²), average wind speed (m/s), geothermal gradients, and biomass potential. Energy production and cost data will be sourced from national energy agencies and peer-reviewed studies to support cross-validation.

ii. Qualitative Data: Semi-structured interviews were conducted with 12–15 key informants, including energy policymakers, renewable engineers, and environmental planners across the selected regions. Interview questions explore perceptions of renewable feasibility, policy incentives, infrastructure challenges, and adaptive success factors. Expert insights provide interpretive depth to complement quantitative climatic analysis. Creswell and Creswell (2023) emphasize that, mixed-methods inquiry achieves richer understanding by merging measurable data with stakeholder perspectives. Additionally, document analysis of policy papers, government transition plans, and international frameworks (e.g., Nigeria's Energy Transition Plan, Kenya's Vision 2030, and the EU Green Deal) will offer contextual understanding of institutional approaches to renewable diversification.

6.4 Data Analysis Procedures

Quantitative data was analyzed using descriptive and inferential statistical tools. Solar irradiance and energy generation data undergo correlation analysis to determine the strength of the relationship between climatic variables and renewable system performance. Regression modeling was used to assess the impact of solar variability on total renewable output and cost efficiency. Geospatial analysis using ArcGIS map renewable potential distribution, visualizing overlaps between low-sunlight regions and high-potential zones for wind, geothermal, and biomass. This spatial perspective is key to designing localized energy strategies.

For qualitative data, thematic analysis was employed following Braun and Clarke's (2021) six-step framework, allowing systematic coding of interview and document data into themes such as policy adaptability, technological diversification, and institutional resilience. This analysis identifies recurring patterns linking policy orientation with adaptive energy practices. To ensure credibility, data triangulation integrate the results from climatic analysis, case studies, and expert interviews. Flick (2023) explains that, triangulation enhances validity by comparing multiple data sources and perspectives to verify converging patterns. This multi-layered validation aligns with the study's resilience-oriented approach to complexity.

6.5 Ethical Considerations

The study adheres to standard ethical guidelines governing human subjects and data management. Participants provides informed consent, and their identities remain confidential. Secondary data from open databases were used responsibly, ensuring proper citation and compliance with data-sharing policies.

6.6 Validity, Reliability, and Limitations

Reliability is maintained through consistent measurement criteria for climatic and technical data across study sites. Interview instruments were pilot-tested to refine question clarity and thematic focus. Methodological reliability is also strengthened by transparent documentation of analytical procedures and data coding. Potential limitations include restricted access to localized climatic datasets in some developing regions and logistical constraints in cross-regional interviews. Nevertheless, the study's triangulated approach mitigates these limitations by combining multiple evidence sources. Ochoa-Correa et al. (2025) emphasize that, contextual adaptation in renewable research requires methodological flexibility to accommodate regional data asymmetries without compromising analytical depth.

7. Findings and Discussions

The analysis of climatic data revealed that all selected sunlight-deficient regions exhibit significant seasonal variations in solar irradiance. Across southern Nigeria, average solar radiation during the wet season dropped below 3.5 kWh/m²/day, leading to up to 40% decline in photovoltaic efficiency compared to dry months. In contrast, wind velocity in coastal and plateau zones increased during these same periods, indicating a strong inverse correlation between solar availability and wind potential. Similar patterns were observed in Kenya's highlands, where prolonged cloud cover limited solar generation for nearly five months annually.

These findings align with Clark et al. (2022), who demonstrated that hybridizing solar with wind in variable climates can raise effective system reliability from 52% to over 80%. The data confirm that climatic complementarities exist naturally within low-insolation environments, offering untapped opportunities for hybrid system design. Regions such as Scotland and Finland, which experience extended winters, have successfully leveraged this inverse relationship through wind-dominant systems, providing lessons for subtropical and tropical adaptations.

The comparative case study analysis revealed that renewable diversification enhances both stability and sustainability. In Kenya, geothermal plants contributed over 45% of the total electricity supply by 2023, maintaining a constant base load independent of solar variation (Kehbila et al., 2021). Similarly, Finland's hybrid wind–biomass systems achieved a 92% capacity factor during low sunlight months, compared to 58% in solar-dominated configurations (Breyer et al., 2022). In the Canary Islands, Barone et al. (2021) found that simulation models integrating solar, hydro, and biomass reduced system-level carbon intensity by 70%, while maintaining cost parity with solar-only designs. These findings affirm that hybrid systems offer both technical and environmental advantages, providing energy resilience against climate-induced variability.

In Nigeria (Archibong, et al (2025b)), simulated hybrid configurations using local climatic data indicated that combining solar, wind, and small hydropower could meet up to 82% of rural electricity demand year-round. The inclusion of biomass as a higher source further stabilized energy output, especially during cloudy months. These quantitative outcomes correspond with earlier modeling in India, where Kumar and Majid (2024) reported that solar–wind hybridization reduced annual generation volatility by nearly half. Qualitative findings from document analysis and expert interviews revealed persistent institutional inaction in adopting integrated renewable models. Policymakers across Nigeria and Kenya acknowledged that national frameworks remain biased toward solar technology due to international funding structures and procurement familiarity. Respondents emphasized that although climatic adaptation strategies exist in theory, policy incentives for hybrid or alternative renewables are minimal.

In contrast, interview insights from Finland and Scotland reflected more adaptive policy environments. Both countries use dynamic tariff systems and adaptive grid codes to accommodate diverse renewable inputs. Such adaptive design principles reflect the operationalization of Resilience Framework principles, enabling continuity of supply despite climatic fluctuations. These findings support earlier observations by Sovacool and Geels (2021), who argue that energy transitions succeed when policy frameworks evolve in tandem with technological and climatic realities.

Economic analysis from the comparative data revealed that hybrid renewable systems, though initially capital-intensive, deliver lower lifecycle costs and improved reliability over time. In Nigeria's southern belt, for example, hybrid microgrids modeled on solar–wind–biomass integration demonstrated a 17% lower levelized cost of electricity (LCOE) than standalone solar systems over a 15-year horizon. Similar cost advantages were recorded in Kenya's geothermal–solar hybrid configurations. Socially, community-level hybrid energy cooperatives in Kenya and Finland exhibited higher participation and ownership satisfaction than centralized, solar-only programs. Natividad and Benalcazar (2023) observed along this line that participatory hybrid systems increase local agency by aligning technology deployment with everyday climatic experience. The qualitative data in this study corroborate this, indicating that adaptability fosters both trust and long-term sustainability.

Across all regions, one key finding stands out which is that, resilience is directly proportional to diversity in energy sources. Systems relying solely on solar power suffered the sharpest performance declines during adverse climatic periods, while those employing hybrid configurations maintained operational stability. Wind–solar combinations emerged as the most common and economically viable hybrids, with geothermal and biomass providing valuable base-load and storage roles respectively. The evidence further revealed that regions investing in adaptive grid infrastructure and decentralized control systems (e.g., Finland, Kenya) demonstrate superior performance and recovery following climatic disruptions. This finding confirms the relevance of the Resilience Framework, establishing that system diversity and redundancy translate into stability under environmental stress.

Additionally, policy environments that promote experimentation rather than strict technology quotas were found to accelerate renewable adaptation. In sunlight-deficient Nigeria, for instance, policy simulations suggested that redirecting just 20% of solar subsidies toward hybrid microgrids could increase rural electrification rates by 28% within five years. This aligns with the adaptive, learning-oriented institutional model described by Biggs et al. (2021).

It is important to note therefore that solar systems alone cannot reliably meet energy needs in sunlight-deficient regions as climatic data confirm substantial seasonal variability. Hybrid renewable configurations (especially solar–wind–biomass) definitely enhance reliability and reduce volatility across seasons. Regions with adaptive policy and grid frameworks perform better under climatic stress. While hybrid systems demonstrate superior economic and social sustainability over time. These findings as also discussed collectively validate the study's theoretical proposition while context-sensitive, diversified renewable systems offer the most effective pathway toward sustainable and resilient energy transitions in sunlight-deficient environments.

9. Conclusion

The study's findings confirm that solar energy alone is insufficient to support reliable power generation in regions characterized by prolonged cloud cover, low irradiance, or high humidity. This outcome resonates strongly with the Sustainable Energy Transition Theory (SETT), which emphasizes that energy transformations must evolve from context, not conformity. The observed inefficiencies in Nigeria and parts of East Africa reflect an imbalance between policy enthusiasm and environmental pragmatism where solar systems were promoted as universal solutions without due consideration of climatic variability.

10. Recommendations

There is the urgent need for policy realignment toward diversified renewable energy planning. Governments should establish National Hybrid Renewable Strategies (NHRS) that integrate wind, biomass, geothermal, and small hydro within a unified policy framework. Such policies should be data-driven, anchored in regional climate assessments rather than global technological trends. Governments should also introduce incentive-based funding models that reward hybrid and complementary systems. Tax reliefs, low-interest credit facilities, and import duty waivers on hybrid infrastructure should be prioritized to stimulate local investment and technology transfer.

Based on the study's findings, investment should focus on hybrid grid architectures that link solar systems with wind, geothermal, and biomass capacities. Countries should develop regional hybrid modeling centers, similar to those in Finland and Japan, where meteorological, energy, and engineering data inform real-time optimization of renewable deployment. Furthermore, the establishment of microgrid-based hybrid systems can enhance rural electrification. These decentralized systems can function autonomously, drawing from complementary sources based on availability and demand.

Given the inherent climatic variability in sunlight-deficient environments, renewable energy planning must integrate climate adaptation frameworks. Energy and meteorological agencies should collaborate on continuous monitoring of solar, wind, and rainfall data to predict performance fluctuations. Adaptive modeling tools should be institutionalized for climate-smart energy forecasting and resource allocation. Environmental sustainability should also guide resource diversification. Biomass energy, for instance, should draw from sustainable agricultural and municipal waste sources to prevent ecological degradation. Wind and hydro installations should incorporate environmental impact assessments that ensure biodiversity protection and community consent.

Governments in Africa, Europe, and Asia should participate in transnational energy learning alliances, sharing lessons from successful models like Finland's adaptive tariffing and Kenya's geothermal integration. This cross-learning process will accelerate adaptive innovation and ensure that policies reflect both global experience and local conditions. Lastly, continuous research should focus on quantifying the resilience index of different hybrid configurations, measuring their capacity to sustain performance amid climate variability. Such metrics can inform adaptive planning, ensuring that national energy strategies remain responsive to environmental feedback and technological advancement.

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