Energy Efficiency Through Zero Energy House Construction Using Solar Technology in Bungoma County, Kenya

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Abstract- A zero energy house is typically a house with net zero energy consumption on a yearly basis, which means that the annual energy consumption is equal to the amount of renewable energy produced on site. Bungoma County, Kenya has an average sunshine of about 9 hours in a day. The purpose of the study was to compare the consumption of power in a three bedroomed house within Bungoma County, Kenya when using grid power from Kenya Power and Lighting Company and solar energy in a zero-energy house. The power bills for 3 years were analyzed to determine the power consumption and the total cost. The consumption for the 3 years was 4,294 kWh at a total cost of Ksh. 106,090. For 20 years, the total cost of grid power will be Ksh. 707,267. The total cost of solar energy power in a similar three bedroomed zero energy house was calculated to be Ksh. 138,430 for a period of 20 years. Therefore, the cost of using solar energy was found to be about 20% of the grid power in Bungoma County, Kenya. The solar energy power is also environmentally friendly and ensures constant supply of power.

Indexed Terms- Bungoma County, Cost of electricity, Electricity consumption, photovoltaic modules, Solar energy, Zero energy house

I. INTRODUCTION

Global electricity consumption continues to rise as modern society becomes increasingly dependent on electrical power for daily activities. The housing industry has emerged as a leading consumer of energy, particularly for lighting, cooling, and various household applications, creating an urgent need for energy-efficient building solutions that can deliver lower utility costs while maintaining healthy indoor environmental quality and minimal ecological impact (Owuor et al., 2023). Within this context, the concept of zero energy housing has gained significant attention as a promising approach to achieving energy efficiency in the building sector.

A zero energy house represents an innovative architectural and engineering solution where the annual energy consumption equals the amount of renewable energy produced on site (Kwan & Guan, 2015). This approach has become particularly relevant in regions with abundant solar resources, such as Bungoma County, Kenya, where Weather Atlas data indicates an average of 9 hours of sunshine daily, creating optimal conditions for solar energy utilization. The significant solar potential in this region aligns with research indicating that solar photovoltaic (PV) technology has emerged as one of the most promising sources of clean and affordable energy (Khare et al., 2023).

Recent studies have highlighted that solar energy presents a feasible solution to overcome energy challenges, particularly in rural areas (Kapoor et al., 2021). The demand for solar energy electrification has experienced significant growth, driven by its advantages of minimal noise, low maintenance requirements, and absence of pollution (Pawar & Gaikwad, 2020). Moreover, research has demonstrated that rooftop solar PV systems offer substantial potential for consumers to reduce their electricity bills while contributing to environmental sustainability (Istepanian, 2020).

Climate projections for Bungoma County indicate that by 2050, the region will experience increased temperatures and reduced rainfall (Juma & Kelonye, 2016), suggesting an even greater need for sustainable energy solutions and potentially improved conditions for solar energy generation. This climate trajectory, combined with the current challenges of high electricity costs and unreliable grid power supply, creates a compelling case for investigating zero energy house construction using solar technology in this region. The primary purpose of this study is to evaluate the economic viability and energy efficiency potential of zero energy houses in Bungoma County, Kenya, through a comparative analysis of power consumption and costs between traditional grid power and solar energy systems.

II. LITERATURE REVIEW

2.1 Theoretical Framework

2.1.1 Zero Energy Building Concept

Zero energy buildings represent a comprehensive approach to energy efficiency in construction, fundamentally based on the principle of achieving equilibrium between energy consumption and on-site renewable energy production. Kwan and Guan (2015) established that zero energy houses are designed to match their annual energy consumption with the amount of renewable energy produced on site, creating a self-sustaining energy ecosystem. This concept integrates various aspects of sustainable building design, including optimal use of natural lighting, effective insulation, and efficient energy management systems.

The theoretical foundation of zero energy buildings extends beyond mere energy balance, encompassing the broader principles of sustainable development and environmental conservation. According to Rosen (2015), energy storage plays a crucial role in achieving net-zero status in buildings and communities, with various storage options including battery storage, thermal energy storage, and chemical storage systems contributing to the overall efficiency of these structures.

2.1.2 Solar Photovoltaic Theory

Solar photovoltaic technology operates on the fundamental principle of converting solar radiation directly into electrical energy through semiconductor materials. Sharma et al. (2018) explain that solar PV systems generate electricity through a process that involves minimal moving parts, resulting in reduced maintenance requirements and enhanced reliability. The theoretical efficiency of these systems is influenced by various factors, including solar radiation intensity, ambient temperature, and geographical location.

Recent theoretical advancements in solar technology have focused on improving system efficiency and durability. Okorieimoh et al. (2019) note that manufacturers typically guarantee solar photovoltaic modules for 20-30 years, with performance warranties ensuring at least 80% power output after 25 years of operation. This long-term reliability forms a crucial theoretical foundation for zero energy house design and implementation.

2.2 Empirical Review

2.2.1 Solar Energy Implementation Studies

Empirical research has demonstrated significant progress in solar energy implementation across various geographical contexts. Gul et al. (2016) conducted a comprehensive review showing that solar photovoltaic technology has emerged as a promising solution for creating clean, reliable, and affordable electricity systems. Their research highlighted the increasing efficiency and decreasing costs of solar installations, making them more accessible for residential applications.

Studies focused on developing regions have shown particularly promising results. Dewi et al. (2019) analyzed factors affecting PV system efficiency in tropical climates, finding that proper system design and maintenance can overcome environmental challenges such as high humidity and temperature variations. This research is particularly relevant to the Bungoma County context, given its tropical climate conditions.

2.2.2 Economic Viability Studies

Empirical evidence strongly supports the economic viability of solar PV systems in residential applications. Fikru (2020) analyzed determinants of electricity bill savings among residential solar panel adopters in the United States, finding significant cost reductions and positive return on investment over time. These findings align with research by Abreu et al. (2019), which documented increasing acceptance of rooftop PV systems among residential users, driven primarily by economic benefits and environmental considerations.

In the context of long-term economic analysis, Life Cycle Costing studies have provided valuable insights. Abu-Rumman et al. (2021) found that for a 20-year PV project lifetime, operation and maintenance costs constitute approximately 27% of the total system costs, with the remaining investment primarily concentrated in initial installation. This research helps inform financial planning and economic feasibility assessments for zero energy house projects.

III. METHODOLOGY

3.1 Research Design

This study employed a quantitative research design focused on comparative analysis of energy consumption and costs. The research approach was guided by established methodologies in solar energy system evaluation, following the framework outlined by Al-Najideen and Alrwashdeh (2017) for analyzing photovoltaic system designs in regional contexts.

3.2 Data Collection

The data collection process encompassed multiple phases to ensure comprehensive coverage of both existing power consumption patterns and solar energy potential. The primary data source consisted of electricity consumption records from Kenya Power and Lighting Company spanning three years (2021-2023) for a representative three-bedroomed house in Bungoma County. This approach aligns with methods used by Abdulhady et al. (2020) for analyzing energy yield patterns in residential settings.

Environmental data collection focused on solar radiation and climate parameters specific to Bungoma County. Following the methodology of Juma and Kelonye (2016), local weather patterns and solar exposure data were obtained from Weather Atlas records, providing crucial information about the region's average of 9 hours of daily sunshine. This data was essential for calculating potential solar energy yield and system specifications.

Technical specifications and cost data for solar energy systems were collected from local suppliers, focusing on commercially available 400W solar panel kits. The collection process included detailed documentation of component specifications, including solar panels, batteries, power inverters, and controllers, following the comprehensive approach recommended by Tan et al. (2022) for evaluating photovoltaic system components.

3.3 Data Analysis

The analysis phase employed multiple analytical techniques to process the collected data. Following the methodology outlined by Urbano et al. (2014), the study conducted a detailed analysis of electricity consumption patterns, calculating monthly and annual usage trends. The analysis incorporated the formula provided by Faturachman et al. (2021) for estimating solar panel output:

$$\text{Output} = \text{Rated power} \times \text{peak daily sunlight hours} \times 0.75$$

Cost analysis followed the Life Cycle Costing approach described by Abu-Rumman et al. (2021), incorporating both initial investment costs and long-term operational expenses. The 20-year projection period was selected based on manufacturer warranties and industry standards for photovoltaic module lifespans, as supported by research from Okorieimoh et al. (2019).

System efficiency calculations took into account various environmental and technical factors that influence solar panel performance. Following the methodology of Dewi et al. (2019), the analysis considered factors such as:

- Solar radiation intensity in the specific geographical location
- Ambient temperature effects on system performance
- Potential shading effects and installation angles
- System degradation over time

The economic comparison between grid power and solar energy systems incorporated both direct costs and projected expenses over the system lifetime. This analysis followed the framework established by Mandys et al. (2023) for calculating levelized costs of solar photovoltaic electricity, adapted to the local context of Bungoma County.

IV. FINDINGS

The analysis of electricity consumption and cost data revealed significant patterns in power usage and demonstrated substantial differences between grid power and solar energy systems in Bungoma County. This section presents the detailed findings from both the historical grid power analysis and the solar energy system calculations.

4.1 Grid Power Consumption Analysis
Analysis of electricity bills from 2021 to 2023 revealed varying patterns of power consumption in the studied three-bedroomed house. Table 1 presents the annual consumption and cost data, showing a total consumption of 4,294 kWh over the three-year period, with an accompanying cost of Ksh. 106,090.

Table 1: Summary Consumption and Cost for 2021-2023

Year	Consumption (kWh)	Cost (Ksh.)
2021	1,351	31,309
2022	1,608	36,859
2023	1,335	37,922
Total	4,294	106,090

Monthly consumption patterns demonstrated significant variations throughout each year, as illustrated in Tables 2. The data shows fluctuations in both consumption and costs, with some months recording zero consumption due to power outages or billing system issues.

Table 2: Monthly Consumption and Cost for 2021

Month	Consumption (kWh)	Cost (Ksh.)
January	109	2,623
February	96	2,246
March	25	615
April	193	3,313
May	125	2,970
June	0	0
July	190	4,729
August	104	2,588
September	110	1,989
October	95	2,424
November	146	3,715
December	158	4,097

The analysis of daily consumption patterns yielded an average daily consumption of 3.9 kWh, as shown in Table 3. This figure served as a crucial baseline for determining the required capacity of the solar energy system.

Table 3: Consumption Metrics and Projected Costs

Metric	Value
Average Monthly Consumption (kWh)	119
Average Daily Consumption (kWh)	3.9
Average Yearly Cost (Ksh.)	35,364
Projected 20-Year Cost (Ksh.)	707,267

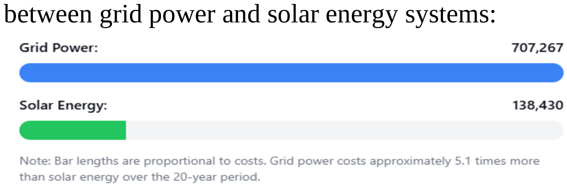
4.2 Solar Energy System Requirements and Costs
Based on the consumption analysis and solar energy calculations, the study determined that a system comprising two 400W solar panels would be sufficient to meet the household's energy needs. The calculations considered the average daily sunshine of 9 hours in Bungoma County and the efficiency formula:
Output = 400W × 9 hours × 0.75 = 2.7 kWh per panel
With two panels, the daily output capacity would be 5.4 kWh, providing adequate coverage for the average daily consumption of 3.9 kWh with a safety margin for peak usage periods.

The cost analysis for the solar energy system revealed the following breakdown:

Table 4: Solar System Cost Breakdown

Component	Cost (Ksh.)
Initial Installation (2 × 400W kits)	109,000
Maintenance (27% over 20 years)	29,430
Total 20-Year Cost	138,430

Figure 1 illustrates the comparative 20-year costs between grid power and solar energy systems:



The spatial requirements for the solar installation were found to be minimal, with the two 400W panels requiring only 3.2 square meters of roof space, representing less than 1% of the available 156 square meter roof area. This leaves ample space for future system expansion if needed.

The findings demonstrate that while the initial investment in solar energy is substantial (Ksh. 109,000), the total cost over 20 years (Ksh. 138,430) represents only about 20% of the projected grid power costs (Ksh. 707,267) for the same period. This significant difference in long-term costs provides a strong economic argument for the adoption of solar energy systems in residential construction in Bungoma County.

V. DISCUSSION

The findings of this study reveal significant economic and practical implications for the adoption of zero energy houses using solar technology in Bungoma County, Kenya. The analysis demonstrates that solar energy systems present a viable alternative to traditional grid power, with substantial long-term cost benefits and environmental advantages.

The economic analysis reveals that despite requiring a significant initial investment of Ksh. 109,000, the total 20-year cost of the solar energy system (Ksh. 138,430) represents only about 20% of the projected grid power costs (Ksh. 707,267). This finding aligns with research by Fikru (2020), who found that reducing electricity bills is a primary motivation for residential solar panel adoption. The substantial cost difference supports Istepanian's (2020) assertion that rooftop solar PV systems offer significant potential for consumers to reduce their electricity bills over time.

The technical feasibility of the proposed system is supported by the environmental conditions in Bungoma County. The average of 9 hours of daily sunshine aligns with the findings of Weather Atlas data, providing optimal conditions for solar energy generation. This advantage becomes particularly significant in light of Juma and Kelonye's (2016) research, which projects increased temperatures and reduced rainfall in Bungoma County by 2050, suggesting potentially even more favorable conditions for solar energy generation in the future.

The system's design consideration of two 400W solar panels, occupying only 3.2 square meters of roof space, demonstrates efficient use of available space while meeting the household's energy needs. This approach aligns with research by Al-Najideen and Alrwashdeh (2017), who emphasized the importance of optimizing system design based on local conditions and consumption patterns. The calculated daily output capacity of 5.4 kWh provides adequate coverage for the observed average daily consumption of 3.9 kWh, with additional capacity for peak usage periods.

Maintenance considerations have been realistically incorporated into the cost analysis, following Abu-Rumman et al.'s (2021) finding that operation and maintenance costs typically constitute 27% of total system costs over a 20-year period. This approach ensures a more accurate comparison with grid power costs and aligns with Okorieimoh et al.'s (2019) research on the long-term durability of solar photovoltaic modules.

The reliability aspect of the solar energy system addresses a significant challenge observed in the grid power consumption data, where several months showed zero consumption due to power outages. This finding supports Khare et al.'s (2023) assertion that solar energy systems can provide more reliable power supply, particularly in regions with unstable grid connections. The consistency of power supply through solar energy systems can contribute to improved quality of life and economic productivity.

Environmental benefits, while not directly quantified in this study, align with broader sustainability goals. As noted by Gul et al. (2016), solar photovoltaic technology has the potential to shape clean, reliable, and affordable electricity systems for the future. The adoption of zero energy houses in Bungoma County could contribute to reduced carbon emissions and environmental impact, supporting global sustainability initiatives.

The findings also demonstrate the practical applicability of zero energy house concepts in developing regions, supporting Kwan and Guan's (2015) definition of zero energy houses as achieving net zero energy consumption through on-site renewable energy production. The success of this model in Bungoma County could serve as a template for similar initiatives in other regions with comparable climatic conditions.

The study's results indicate that the transition to solar energy systems in residential construction represents not just an environmentally conscious choice but a financially prudent decision for homeowners in Bungoma County. The significant cost savings over the system's lifetime, combined with the reliability of power supply and minimal space requirements, present a compelling case for the adoption of this technology in new construction and retrofitting projects.

VI. RECOMMENDATIONS

Based on the findings of this study and their implications for residential energy consumption in Bungoma County, the following recommendations are proposed for various stakeholders:

For County and National Government

The government should develop and implement comprehensive policies to promote zero energy house construction using solar technology. Specific measures should include:

1. Creation of a regulatory framework that mandates consideration of solar energy systems in new residential construction projects, similar to successful policies implemented in other regions.
2. Development of financial incentives to offset the initial installation costs of solar energy systems. These could include:
   - Tax rebates for homeowners installing solar systems
   - Subsidized loan programs for solar energy installations
   - Grants for low-income households transitioning to solar energy
3. Establishment of quality control standards for solar equipment and installation services to ensure system reliability and performance, addressing concerns raised by Okorieimoh et al. (2019) regarding system durability.

For Financial Institutions

Banks and financial institutions should:

1. Develop specialized loan products for solar energy system installations, with favorable terms that consider the long-term cost savings demonstrated in this study.
2. Create mortgage products that incorporate solar energy system costs into home loans, making the initial investment more manageable for homeowners.

For Construction Industry

Building professionals should:

1. Integrate solar energy considerations into initial building designs, following the findings of Owuor et al. (2023) regarding green building technology and energy efficiency.
2. Develop standardized approaches for retrofitting existing homes with solar energy systems, considering the spatial requirements and technical specifications identified in this study.

For Educational Institutions

Technical training institutions should:

1. Develop comprehensive training programs for solar system installation and maintenance technicians to address the growing demand for qualified personnel.
2. Include zero energy house design principles in architecture and construction curricula to prepare future professionals for sustainable construction practices.

For Homeowners and Property Developers

Property owners should:

1. Consider the long-term cost benefits of solar energy systems demonstrated in this study when making construction or renovation decisions.
2. Implement proper maintenance schedules as recommended by Abu-Rumman et al. (2021) to ensure optimal system performance and longevity.

For Research and Development

Future research should focus on:

1. Long-term performance monitoring of installed systems to validate the projected benefits and identify areas for improvement.
2. Development of more efficient storage solutions to address power availability during low-sunlight periods.
3. Investigation of innovative financing models to make solar energy systems more accessible to a broader population.

For Implementation and Monitoring

To ensure successful adoption of these recommendations:

1. Establish a monitoring and evaluation framework to track the implementation progress and impact of solar energy systems in residential construction.
2. Create a feedback mechanism to gather data on user experiences and system performance, which can inform future improvements and policy adjustments.
3. Develop public awareness campaigns to educate residents about the benefits and proper maintenance of solar energy systems, addressing the knowledge gaps identified by this study.

These recommendations are designed to address the key barriers to solar energy adoption while maximizing the potential benefits identified in this research. Their implementation should be phased and coordinated among various stakeholders to ensure optimal outcomes.

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