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Green Energy Solutions for Enhancing Rural Agricultural Production: A Focus on Solar and Biogas Technologies in Sub-Saharan Africa

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***Abstract* - The development and subsequent application of green energy systems represent a technologically significant method for providing sustainable energy solutions to the prevailing energy crisis. Supporting agricultural production with environmentally sustainable green energy technology offers outstanding benefits for rural areas. Wide-ranging agricultural economic development could be achieved through investment in green energy technologies. This study, therefore, provides an overview of green energy as a solution that can be deployed for rural agricultural production and food processing. Concise systematic review techniques, along with descriptive approaches to solar and biogas energy technologies, were the primary methods adopted for the study. The study revealed that, with the use of various solar energy technologies and biogas production, agricultural production and food processing in rural communities can become less cumbersome and more economically affordable. This is because the technological pathways involved in deploying these energy systems are not complicated, and they align well with the small-scale sizes required in rural communities. From an industrial perspective, the deployment of green energy technologies, supported by reliable policy and financial backing from the government and stakeholders, could significantly enhance investment in rural agricultural production and processing industries in sub-Saharan Africa.**
***Keywords:* Clean Energy, Sustainable Development, Agricultura Production, Food Processing, Climate Change**

I. INTRODUCTION

The deployment of green energy technologies in agricultural production is an innovative approach to enhancing sustainable food production. The concept of environmental sustainability promotes sustainable agriculture with the potential to maximize crop production. By applying green energy technologies, sustainable agricultural production reduces the risk of environmental impacts and mitigates adverse climate conditions. In recent decades, significant efforts have been made to promote renewable energy as a means to decarbonize the atmosphere [1]. Global attention to the use of green energy technologies for socioeconomic development is an integral part of the Clean Development Mechanism (CDM) [2].

The fundamental objectives of sustainable agriculture include the following:

1. Promoting environmental sustainability by significantly reducing the exploitation of fossil energy sources.
2. Providing profitable farming mechanisms.
3. Protecting against land degradation and the overexploitation of agricultural nutrients.

Furthermore, sustainable agricultural production serves as a bridge between maximizing crop production and agri-food processing within the framework of environmental sustainability. The quest to replenish or maintain the soil's natural fertility is essential in agricultural production. Energy utilization is crucial to agricultural production, and it must be managed in a way that preserves environmental integrity. In Africa, there is a widespread reliance on non-renewable energy sources, such as natural gas and diesel, to operate generators for lighting, irrigation, and food processing.

From the perspective of reducing greenhouse gases (GHGs) and addressing the global energy crisis, promoting the use of green energy in the agricultural sector is essential. For example, rural farm water pumping for irrigation can be replaced with a cost-effective and environmentally sustainable solar submersible water pumping system. This study, therefore, focuses on a fundamental review of the benefits of deploying environmentally sustainable green energy technologies to boost agricultural production in rural areas.

II. SYNOPSIS OF ELECTRIFICATION AND ENERGY CRISIS SCENARIO IN SUB-SAHARAN AFRICA

Electrification in Africa is one of the most regressive situations in the global electrification stride. African energy policy, funding mechanisms, investment focus and energy legislative energy and energy planning strategies are highly constrained. This submission can be supported by the evidence presented in Fig. 1. Access to modern energy in Africa is more constricted in rural areas and urban grid-connected areas are poorly served due to many techno-economic factors. In Nigeria, about 45,456 non-electrified clusters were identified with an estimated 72.6 million people without electricity as shown in Fig. 2 [3]. The challenge of the energy crisis in Sub-Saharan Africa (SSA) has multidimensional negative impacts on different economically progressive sectors, especially the agricultural sector. Energy is a catalyst for all forms of modern development in their different facets.

The availability of energy can create an accelerated tendency for socioeconomic development. However, there is no doubt that presently, making energy available to all is currently not practically realistic, especially in SSA where energy poverty is posing a heightening trend. Encouraging efforts towards creating reasonable access to energy for people with socioeconomic inclination is very important. In SSA, the present poverty index is quite discouraging as more than half the population of people in the sub-African region live below the poverty line.

To promote the socio-economic well-being of the people, there must be sufficient access to energy. The prevailing unfortunate situation in SSA is that major electrification procedures have been planned in favour of large and centralized power generation plants, the construction of huge transmission lines, and the expansion of distribution power networks. The SSA region is made up of developing countries with thousands of scattered rural communities. The rural settlements are usually not in favour of grid extension due to high economic costs.

Hence, it is most logically ideal and economically rational to think about the option of developing MG technologies with green energy, and renewable and sustainable systems. In Table I, the main differences between a green energy microgrid system and the conventional power grid system are highlighted. Therefore, the adoption of investment and deployment of technologies for green energy production is essential for a sustainable future from an environmental perspective.

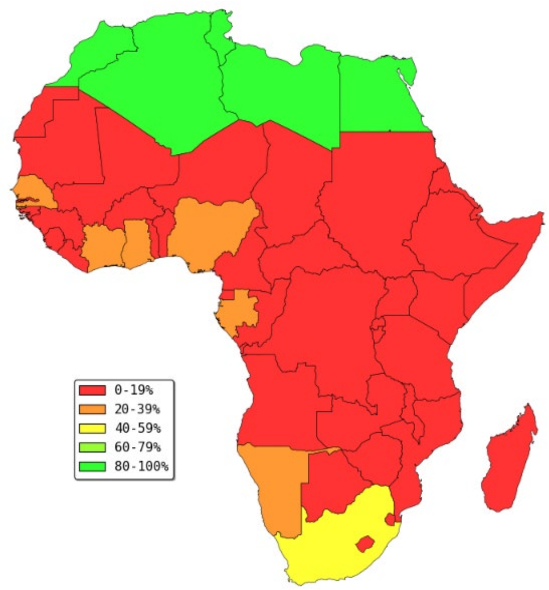


Fig. 1 Electrification scenario in Africa [4]

TABLE I DIFFERENCES BETWEEN SUSTAINABLE MICROGRID SYSTEM AND CONVENTIONAL POWER SYSTEM

Sustainable Green Energy Micro-Grid System	**Conventional Power Grid System**
Suitable for harnessing and generation of green energies.	Suitable for the generation of large amounts of power for commercial and industrial consumption.
It allows for the participation of the local community stakeholders.	Participation in the local communities could be difficult.
It can either work with or without the conventional grid, making it bi-directional in its mode of operation.	It is a characteristically unidirectional grid system.
It is a local power grid with autonomous control capability.	It is the most prevalent means of supplying electricity across the world with a large, centralized generation scheme.
It has the benefits of lesser energy cost, increased reliability and increased energetic independence.	It is usually expensive from the point of view of system installation, operation, and maintenance costs.
It requires fewer technologies to be implemented.	It requires more tedious work and complex technologies to be implemented.

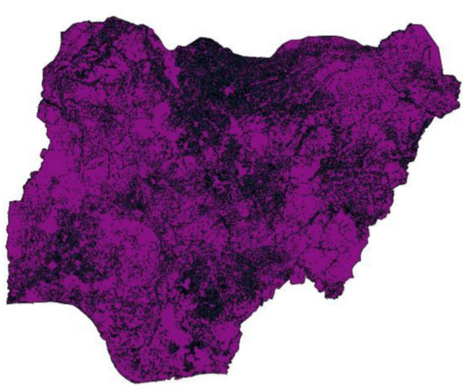


Fig. 2 Map of Nigeria showing the non-electrified clusters with black dots [3]

III. IMPORTANCE OF GREEN ENERGY FOR AGRICULTURAL DEVELOPMENT

Traditionally, rural energy is usually planned based on the socioeconomic demand of the people. It is quite obvious that the economic activities of the rural populace typically revolve around agricultural production. The development of energy is crucial to agriculture which is the basic progressive economic well-being of the rural populace. Energy generation for agricultural activities has recently increased due to the prevailing modernization in the sector.

Increasing energy demand for agriculture can be attributed to multiple factors such as population growth, climate change and global industrialization. It has been presented by the government of the United States that global dependence on fossil fuel consumption can be reduced through the application of green energy in the processes of agricultural production and food processing [5].

A similar report was presented by the Dutch government advocating for the substitution of natural gas power with solar-powered and biofuel technologies for agricultural greenhouses [6]. The purpose of this encouragement is to foster emission reduction, high energy efficiency, low cost of energy and low energy consumption scenario. The quest for the development of agricultural electrification through the application of green energy is part of the global structural transformation of the agricultural sector. The utilization of biomass-driven power technologies [7-9], off-grid solar photovoltaic power technologies [10] and photovoltaic greenhouses [11] can potentially reduce the level of global dependence on fossil fuel electricity for agricultural production.

IV. ENVIRONMENTAL ISSUES FROM ENERGY PRODUCTION AND CONSUMPTION

There are multiple environmental problems connected to the generation and consumption of fossil fuel energy resources. Conspicuous among the problems are climate change, disposal of toxic waste materials such as oils, air pollution due to incomplete combustion of fuels, water pollution and thermal pollution. Over the years, urban air pollution has become a serious challenge around the world which has drawn the attention of environmental experts and energy stakeholders. In this regard, it has been agreed by the international communities that energy and environmental policies must be fashioned together for sustainable development. Undivided stakeholders' views have been that financing the global electricity expansion must be accomplished through the optimistic development of green energy technologies, for the protection of global environmental dignity.

In the last few decades, the aggressive consumption of fossil fuels has resulted in critical environmental conditions with the attendant rise in environmental temperature. On a global scale, global warming due to the emissions of anthropogenic greenhouse gases (GHGs) has a series of socioeconomic and environmental consequences. In the majority of rural communities in developing countries, there is a lack of access to modern energy that has forced people to rely on traditional biomass fuels such as wood, animal dung, charcoal and crop residues for cooking heat energy. Traditional application of biomass for energy constitutes inefficient energy production. In unelectrified rural communities, lighting is provided by kerosene lamps, paraffin candles and portable battery touch lamps.

The use of wood fuel from the forest is causing a serious problem in terms of deforestation. Deforestation is the excessive removal of forest trees from a large area of land for biomass consumption. The use of unclean and inefficient traditional biomass constitutes environmental problems of flying ash particles with an attendant impediment to the human cardiovascular organs. The long-term exposure of women and children to the concentrated smoke from the direct burning of biomass residues is a risky health situation.

The incident of hysterical harvesting of wood fuel in different parts of African regions has destroyed the natural ecosystem through heavy deforestation. It is expected that well-protected forest reserves can help absorb a good percentage of carbon dioxide from the atmosphere. The present pace of deforestation in many developing countries especially in Africa is drastically affecting the local and the global environment with threatened increasing global warming potential.

Uncontrollable deforestation has negative impacts on humans and the environment. Deforestation results in the loss of trees and natural vegetation causing desertification, soil erosion, climate change, flooding, increased global warming potential, and many other problems for the people. In addition, deforestation can also foster the annihilation of wildlife due to the loss of diverse species of vegetation. In Africa, more than 10 billion trees are cut down annually, and if not controlled, the breaking point of our forest resources may be reached soon.

V. ENVIRONMENTAL AND ECONOMIC SUSTAINABILITY OF GREEN ENERGY TECHNOLOGIES

Production of green energy has lots of environmental sustainability benefits due to limited or zero emissions. The environmental benefits of green energy rely on the fact that the power generation comes from non-polluting sources such as water, wind, sunlight and biomass. Unlike fossil fuels with a high level of environmental pollution, green energy sources are constantly being replaced by nature in a way that allows sustainable development. The present state of energy activities leading to global warming must be mitigated to avoid leading to significant changes in the world's climate condition, which eventually will impact negatively on human existence and the environment.

The following are the key sustainability benefits of green energy technologies in the global agricultural sector.

1. Generating electric power with no emissions of greenhouse gases thereby making the environment free from aggressive anthropogenic air pollution.
2. Improving diversification of the global energy supply and thus limiting the overall level of energy importation across the globe.
3. Enhancing prosperous economic development through increasing physical job creation, manufacturing of the components and installation of the energy systems.

VI. ENVIRONMENTALLY SUSTAINABLE GREEN ENERGY IN AGRI-FARMING AND FOOD PROCESSING

Presently, there exists some undisputed scientific evidence that the average global temperature of the earth's surface is increasingly orchestrated by the excessive utilization of fossil-based fuels. Shifting attention to environmentally friendly alternative energy sources is a promising situation for sustainable foundations. Heating, cooling, transportation and electricity are collectively needed for sustainable agricultural production. Since the main sources of environmentally sustainable green energy are readily available in the rural agricultural community, farming activities and food processing capacity can be increased to raise income. The application of sustainable green energy technologies in agricultural production along agri-food chains represents the benefits of a sustainable solution. For instance, the substitution of solar water pumping irrigation systems with diesel-powered pumping machines improves access to water for farming even during a dry season period.

This, therefore, allows for increasing multiple cropping cycles with lower emissions and higher income levels for the farmers. Many countries across the world have deployed and continue to increase their existing potential for sustainable green energy technologies for sustainable agri-farming and food processing. A 250-kW mini-grid hydropower plant has been installed for a palm oil pressing plant in Sierra Leone. In New Zealand, Mokai geothermal power plant was established to process 250 million litres of milk annually in the country. A small-scale biomass cogeneration electricity plant was established in Uganda for the production of heat and electricity for agro-processing in a rural community in the Kamwenge district.

A. Biogas Technology for Agricultural Production

Organic waste produced in different parts of Africa from both edible and non-edible sources is in millions of tons daily. Organic wastes are a source of biogas production from waste materials such as wastewater, agriculture waste, livestock manure and many other biodegradable municipal waste materials. Improper discarding of biogenic waste materials is a major risk to public health and the human environment. Toxic chemicals, antibiotics, pathogens and a host of other poisonous substances can be generated from biowaste dumping sites. The surfaces of water bodies around our villages can be contaminated directly while the quality of underground water can be destroyed by leaching into the soils. It is thus important that biowaste materials could be captured into a carbon-negative energy system for biogas power generation. The process involves the production of methane through an anaerobic digestion process. The anaerobic digestion process involves the degradation of biowastes converting the waste materials into biomethane (biogas). Biogas usually contains approximately 50-70% methane gas, 30-40% carbon dioxide and traces of other gaseous impurities.

Capturing methane for the production of energy is one of the fundamental processes for mitigating global warming. The heat-trapping potential of methane in the atmosphere is excessively higher than carbon. For example, methane can trap heat 86 times higher than the same quantity of carbon dioxide in two decades. Globally, the available potential for biogas production has not been exploited for power generation. In the United States and China where there are over two thousand small-scale biogas power projects have been installed, not even 20% of the total potential has been explored. Fig. 3 shows an anaerobic digestion pathway for the production of biogas for energy generation**.** During the production of biogas methane, solid digestate materials with a more difficult breakdown process are produced. Solid materials can be used for the production of organic fertilizer as an added economic benefit.

The biochemical yield processes of biogas production from anaerobic digestion can be enhanced through the co-digestion of several waste materials combined in an anaerobic digestion chamber. Biogas can be utilized in different energy facilities like internal combustion engines, fuel cells and microturbines for power generation. It can also be burnt in stoves for cooking. In addition, biogas can be upgraded to a natural gas quality through the process of bio-mechanization for renewable natural gas production for use in vehicles and electric power gas turbines.

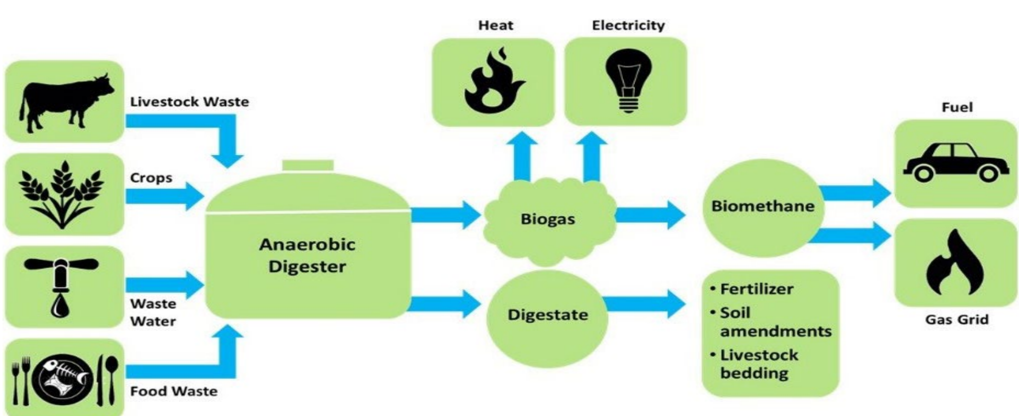


Fig. 3 Anaerobic digestion pathways for the production of biogas for energy generation [12]

The generation of sustainable bioenergy for agricultural production is a means of meeting the energy demand in the agri-food production sector. Going by the existing energy technologies, modern bioenergy can be used for the production, processing, and storage of food. Biomass residues generated from food production and livestock farming and processing are better feedstock for bioenergy production for domestic, commercial and industrial establishments. In countries like China, India, Bangladesh, Nepal, and the Philippines, biogas usage for energy production has been deployed at a very encouraging level. In addition, Brazil, India, and Thailand have long focused on the exportable production of electricity from sugarcane bagasse. The economically progressive cassava industry in Thailand has exploited biogas production for electricity supporting food production and processing the nation's agricultural sector. Millions of tons of risk husk wastes generated in Myanmar and Thailand have been used extensively for electricity production in the country for the agricultural sector and other productive activities.

B. Solar Energy Technologies for Agricultural Production

Rural electrification projects based on a standalone home energy system shown in Fig. 4 have gained tremendous impacts in many developing countries. In Fig. 5, a foldable and mobile onsite power supply for rural communities was designed by the Federal Polytechnic Nasarawa. The development of solar-powered electrification of rural homes is a step forward toward sustainable agricultural production.

Afterward, agricultural food production and post-harvest crop processing must also be modernized in line with sustainable green energy applications. Solar-powered mini-grids have been used in several rural communities around the world to reduce environmental impacts and promote the reduction of labour-intensive food processing activities. Solar-powered grain threshing and milling, which are major value chains in the agricultural business are still very premature in SSA. This is because the technologies involved are yet to be fully developed for their commercial viability. Among all the exploitable green energies, solar energy from the sunlight has the highest potential with the cheapest techno-economical investment.

C. Cold Storage for Refrigeration of Perishable Food Materials

Cold refrigeration of food materials is an important aspect of the agri-food chain for the maintenance of the economic values of perishable food crops, livestock materials and fisheries. During harvest losses of perishable food items are expected to be minimized to avoid unnecessary economic forfeiture. It is quite very obvious that some losses due to poor preservation of food items could disproportionately ensue. Therefore, in rural areas where connection to the grid electricity is not an option, there is a tendency to embrace the option of cold storage and refrigeration shown in Fig. 6 through the use of solar photovoltaic energy.

In SSA, there is usually a greater percentage loss of agricultural food materials between harvesting and processing. It is therefore important to understand that improving the deployment of cold stage and refrigeration solar-powered facilities could vehemently lower the current level of degeneration of perishable foods. From a negative environmental perspective, biochemical decomposition emissions from perishable food have been a worrisome challenge on a global scale.

The provision of refrigerated solutions based on green power technologies for rural farmers in off-grid communities is an environmentally friendly and cost-effective energy option. Presently, Kenya has deployed a few solar-powered cold storage infrastructures to some rural communities with the intent of minimizing the level of perishable food materials in the country.

The preservative scheme was reported to be generating a reasonable income level for the rural farmers in Kenya with an enhanced shortening value chain for the targeted food products.

Fig. 4 Rural electrification project based on a standalone home energy system

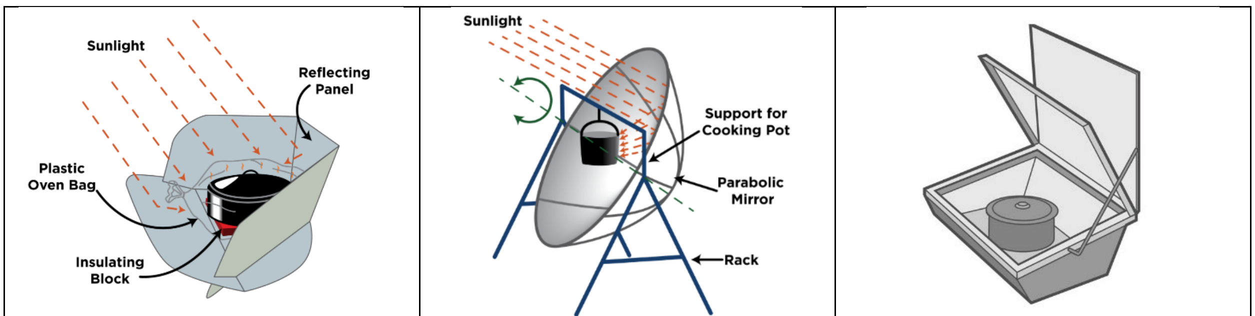
Fig. 5 Foldable and mobile onsite power supply for rural communities designed by the Federal Polytechnic Nasarawa

Fig. 6 A conceptual solar-powered cold storage system

D. Solar Cooking Technologies

Solar cooking can be achieved through a solar PV system, solar oven cooker box, or solar dish cooker. A solar cooker is a device that captures sunlight directly from the sun and converts it to the heat energy required for cooking food or drink. There are three different kinds of solar cooking systems as shown in 6. The main difference between them lies in the speed of their cooking potential. Solar cookers operate based on the concentration of sunlight, conversion of the concentrated light to heat energy and retention of the heat energy for some certain period. Different kinds of solar cookers trap and retain heat energy at different temperatures ranging from 70-400^{o}C depending on the materials used.

The heat generated by the solar cooker is focused on the bottom of the cooking pot based on the design arrangement of the cooker. In cloudy weather, the efficiency of solar cookers is very poor, thus taking a longer period to cook food. In recent times, solar induction cookers using solar PV panels have been developed as an alternative solution to the different kinds of solar cookers shown in Fig. 7.



(a) Solar oven cooker: slow cooker | (b) Solar dish cooker: fast cooker | (c) Solar box cooker: slow cooker

Fig. 7 Different types of solar energy cookers [13]

E. Solar-Powered Food Processing Machines

Today, there are many solar-powered food processing machines in existence. An example of such a machine is the sesame oil extraction designed by the University of Hohenheim as shown in Fig. 8. This machine allows for extraction from sesame seeds based on a solar-power compression engine. The oil yield from the use of this machine has been adjudged to be good based on the oil extraction efficiency of the machine. Structurally, the integrated components of the machine comprise solar PV, a power control unit and a mechanical compression unit. Apart from the extracted oil, sesame seed cake produced can be used as animal fodder for additional revenue generation.

Fig. 8 Sesame oil extraction solar energy system designed by the University of Hohenheim

F. Solar Drier

Drying is an age-long activity in human society used for several domestic purposes. An illustration of a solar drier is shown in Fig. 9. Driers are used in many fields of human endeavours such as cloth drying, food processing, paper industries, and others. Solar driers are faster drying systems than conventional open sun air driers due to the higher inner temperature of the dryer than the normal outer temperature. The high speed of drying inside a solar drier has the potential to reduce the risk of decomposition of food materials with good nutrient qualities. The ability of the drier to maintain better product quality is based on its protection against dust, pests, pathogens and moisture.

Fig. 9 Solar drier

VI. CONCLUSION AND RECOMMENDATIONS FOR STAKEHOLDERS

In the current global context, advancements in energy usage in agricultural production and the efficient processing of food materials can play a crucial role in ensuring food security. Food security is an essential component of the much-anticipated global Sustainable Development Goals. The deployment of green energy technologies in agricultural production requires coordinated efforts from government agencies, stakeholders in the agricultural sector, financial institutions, international organizations, researchers from academia, and various agricultural support groups. These efforts are necessary to combat the rising global atmospheric temperatures. The exploration and promotion of green energy technologies for agricultural production are expected to increase worldwide due to the global pursuit of sustainable development. This approach is central to reducing global warming by lowering carbon-based emissions.

Detrimental environmental pollution caused by energy use in agricultural production must be discouraged by all means. A delicate balance between optimizing crop productivity and maintaining economic stability should not be subjected to unnecessary risk.

The deployment of green energy technologies in sub-Saharan Africa (SSA) is an integral part of the Clean Development Mechanism (CDM), as has been successfully promoted in countries like India. However, it is crucial that government support is evident in terms of financing mechanisms and policy initiatives that promote climate change mitigation, reduce fossil fuel consumption, and protect environmental integrity.

Therefore, the following recommendations are necessary for this study:

1. Effective participation by government and policymakers is crucial to ensure that farmers are adequately guided in adopting new farm tools powered by green energy technologies, particularly those that can boost investments in rural food processing.
2. Facilitate reasonable access to business financing solutions for agri-enterprise owners to encourage investments in rural food processing.
3. Promote the use of energy-efficient appliances in rural areas and encourage innovation in green energy development with strong operational viability.
4. Encourage multi-stakeholder partnerships between green energy service providers and rural energy consumers.
5. Provide long-term support to farmers through policy and financial assistance from the government and stakeholders to help them obtain sustainable energy inputs for self-generation of energy.

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