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Agrivoltaic System: Current and Future Water, Energy, Food, and Land (WEFL) Needs in Benin, West Africa

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Abstract. Water, energy, and food are essential for all humans and require land use. In a land-limited country with high ambitions for solar PV and a growing population, balancing land use for energy and food is necessary to avoid sectorial competition and minimise pressure on land resources. Agrivoltaics, an integrated approach combining energy and food production on the same land, can help to provide clean water, clean and affordable energy, and quality food for the growing population. This innovative approach to the water-energy-food-land nexus (WEFL) has been experimented with and attracted greater research interest and acceptance in many countries, mainly in the North but not so much in Africa. Agrivoltaics is relatively new in West Africa, and minimal research and development have been conducted within the region. As a desk-based study, this paper reviews the WEFL state in Benin and discusses how agrivoltaics could be an asset for current and future WEFL to improve sustainable development in Benin.

Keywords: Water-Energy-Food-Land Nexus, Agrivoltaic System, Climate Change Resilience

1. Introduction

Access to services of general interest, such as water, energy and food, are vital need for human well-being, poverty reduction, and sustainable development [1]. Today, population growth, industrialisation, and climate change negatively impact developing countries and pose a challenge to ensure the sustainable provision of these basic needs. Water supply, energy availability, food security, and appropriate land use are linked because food production requires the availability of irrigation water through its extraction. Water treatment is necessary for food processing and use, redistribution of water for irrigation of agricultural landscapes requires energy, and energy production requires water [2], while energy and food production require land use and transformation. Consecutively, climate change projections indicate increased pressures on these resources around the globe, and at the same time, population growth and economic development pose critical challenges in providing water, energy, and food (WEF) security at the national and global scale. The Food and Agriculture Organization (FAO) report indicates that water, energy, and food demands have increased with population growth over the last few decades [2]. The situation calls for a 60% increase in food production, leading to an additional 10% withdrawal of water for irrigation and a 50% rise in energy consumption to meet the needs of the global population by 2050 [3]. This scenario could worsen the challenges of ensuring water, energy, and food security.

Fortunately, solar photovoltaic (PV) technology is a suitable solution to power the water-energy-food nexus systems and improve people's living conditions while protecting the environment. Indeed, adopting PV technology for access to water, energy, and food availability has been a top priority for most African countries, especially in the Benin Republic. However, developing energy facilities such as power stations is land-demanding. As written by Kapumpa et al. [4] for a case study, it generally takes about 1.2 hectares for one megawatt (MW) of PV solar power generation, depending on the location, considering the solar arrays, maintenance and site access. In the case of Benin, the latest PV power station built with a capacity of 25 MW peak occupied 26 hectares [5]. Power development intensifies competition for land resources, especially within the agricultural sector, which currently accounts for 12% (1.6 billion ha) of land globally for the cultivation of crops [6, 7]. Within a country with limited land area and a dense population, installing PV systems on agricultural land will lead to land-use competition between energy and food production [8]. Benin is one of the West African countries with limited land area and high ambition for solar photovoltaic in its national energy mix to supply clean, affordable, reliable, sustainable, and modern energy access to its population. Given an annual population growth rate of 2.7 in 2020, Benin's population is expected to reach 24 million by 2050 [9], which will significantly increase the demand for food and energy.

Hence, achieving a suitable balance between energy, food, and land utilisation is crucial. This may demand a comprehensive and integrated approach centred around a water-energy-food nexus system. Such a system should address growing energy requirements through decentralised technologies, mitigate the land use effects of energy development and enhance efficient food production, all while minimising water usage and environmental impacts [10, 11].

An appropriate solution is the innovative nexus system, agrivoltaics, which involves a land-use trade-off between agriculture and photovoltaic development [12–15]. In contrast to ordinary ground-mounted PV arrays, Agrivoltaic systems (AVSs) are elevated to allow agricultural equipment movement or room for grazing animals [8]. AVSs combine agricultural and renewable photovoltaic electricity production on the same land to increase the Land Equivalency Ratio (LER). Integrating rainwater harvesting from the PV systems for irrigation and panel maintenance has made the system serve a triple land-use purpose.

This study will start by outlining the materials and methods employed. Then, the state of water and energy access, farming systems, food insecurity, land resources and utilisation in Benin will be highlighted. The most common renewable energy technologies applications across the water-energy-food nexus within agriculture in the country will be described while giving their limitations. The last section will discuss how agrivoltaics could be an asset for current and future water, energy, food, and land (WEFL) to improve sustainable development in Benin.

2. Materials and Methods

In this paper, narrative and scoping review methods are used. These methods are used to highlight the state of water, energy, food and land use state in Benin, the most common WEF nexus applications within agriculture in the country. The keywords used are energy access, water access, food security, farming system, land use, and the country's name, as indicated in Fig 1. Various national and international databases (including SIE, GOUV.BJ, World Bank and IEA) were consulted to find the data used in this paper. In addition, academic search engines, such as ResearchGate, Base, Google Scholar, and direct scientific sources, were exploited to search and download articles and scientific reports.

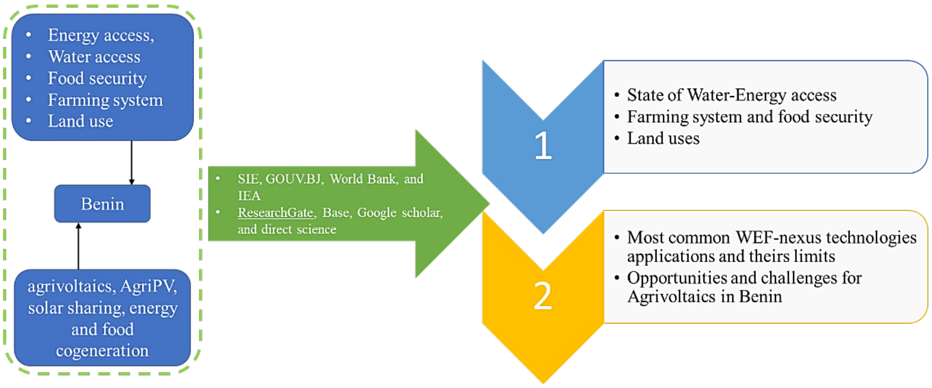

Figure 1: Methods Framework

2.1. Country Profile

Benin is a French-speaking West African country between 6° 22' 46.0128'' N and 2° 27' 4.7664'' E, boarded by Togo, Burkina Faso, Niger, Nigeria and the Atlantic Ocean (Fig 2). In 2021, Benin had 12.45 million inhabitants with an annual population growth rate of 2.7%. The country has a national poverty rate of 38.5% and an unemployment rate of 2.4%. The international poverty rate (proportion of persons living on less than $1.90 per day) was estimated at 19.2% in 2019 [16]. Benin experiences two distinct climates. The southern region has an equatorial climate with alternating dry seasons (November to March and mid-July to mid-September) and rainy seasons (April to mid-July and mid-September to October). A tropical climate is observed in the central and northern areas, with a dry season from November to April and a rainy season from June to September. With Global Tilted Irradiation (GTI) ranging from 4.68 to 5.94 kWh/m2/ day [17], photovoltaic systems are well-suited for deployment throughout the country for micro installations or solar PV power stations.

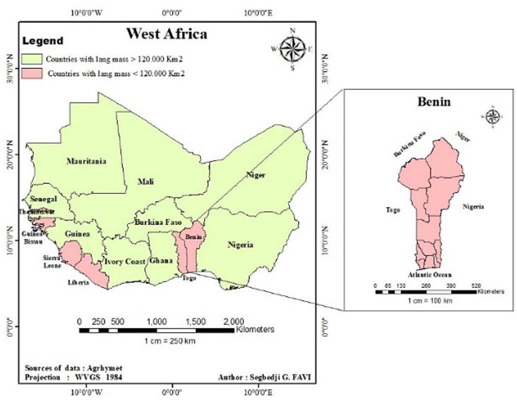

Figure 2 : Map of West Africa- Benin

3. State of water-energy-food and land access in Benin

Access to clean water and sanitation services is critical to improving health, human productivity, and economic growth [18]. Water-related challenges vary significantly from country to country across the West African region. From 2015 to 2020, the West Africa region is the most progressive within Africa regarding drinking water services access. By the end of 2020, access to drinking water in rural Benin had increased from 42% to 69%. Similarly, water access rose from 55% in urban areas in 2016 to around 74%. As a result, about 7 out of 10 Beninese now have secure access to drinking water [19]. In 2022, average water service coverage in rural communities raised to 73% at the national level compared to 42 % in 2017 [20].

The energy sector in Benin is characterised by the preponderance of biomass energy consumption (firewood and charcoal) at 69% and imported oil products at 47%[21]. Charcoal remains the primary fuel in urban areas despite efforts to promote LPG, whilst the rural population uses firewood in traditional stoves. The county relies on electricity imports for a significant share of its energy supply. Benin had one of the lowest electrification rates in the region (West Africa), with a significant disparity between the urban (56%) and rural areas (11%) in 2017. Over the last decades, the country's power supply has relied mostly on imports, representing about 75 to 85% [22]. The internal production is from thermal generators installed across the country and serve as backup generators when there is a lack of capacity from other country suppliers. Thus, reform programs, including electrification plans, have been implemented, where only 30% of the population had access to electricity in 2017 [23]. Through various projects of power plan implementation, including standalone solar power plants in the county, in 2021, the overall electricity access was 37.71% [24].

Food insecurity reached an unprecedented level in the West Africa region in 2022. Food-insecure people havencreased since 2014 and almost quadrupled between 2019 and 2022 [25]. According to the World Food Program (WFP) report 2019, more than 43% of households were on the verge of food insecurity, with 9.6% of the population food insecure and 32% of young children suffering from chronic malnutrition [26]. Impoverished rural households are primarily impacted by food insecurity, further worsened during the lean season and intensified by natural disasters like the annual heavy floods experienced during the rainy season. The agricultural sector in Benin, characterised by predominantly small-scale farming with low productivity, accounted for approximately 27.11% of the country's gross domestic product (GDP) in 2020 [27]. About 38% to 70% of the active population in the country rely on agriculture for their livelihoods [28, 29].

Furthermore, the country's main agricultural activities are mainly practised under rain-fed conditions with progressive declines in agricultural yields. These are exacerbated by the rainfall variability due to climate change and variability, significantly affecting the country's food production [30]. As a result, food insecurity is increasing; besides, the lack of energy prevents food grains, vegetables, and fruits from being processed, preserved, and used when needed.

With a land area of 112,760.0 km2, the country comprises 35% agricultural land and 27.8% forest area. Moreover, agricultural land experiences an annual growth rate of 6%[31]. Agricultural land refers to the share of land area that is arable under permanent crops and pastures. Forest area is land under natural or planted stands of trees of at least 5 meters in situ, whether productive or not, and excludes tree stands in agricultural production systems (for example, in fruit plantations and agroforestry systems) and trees in urban parks and gardens. Given the increasing competition for land access due to the rapid urbanisation in the last two decades, the land issue has become a major concern for the population in Benin. In addition, urbanisation also constrains WEF security and leads to ecosystem degradation, as in the case of poorly managed urban development. According to the FAO, by 2030, global demand for water, energy, and food is expected to increase by at least 30%, 45% and 50%, respectively. However, fulfilling these demands will necessitate the availability of an additional 175-220 million hectares of cropland.

4. Renewable energy in the water-energy-food nexus, most common technologies and applications within agriculture in Benin and limits

A water-energy-food nexus is an interactive approach across research, policy, and project implementation. In simple terms, direct water inputs are needed to produce food and energy. On the other hand, energy is required for storing and distributing food and water extraction, conveyance, and treatment. Natural resources and ecosystem services are also the basis for water, energy, and food security. Any restriction of one of these elements would disrupt the availability of the other.

Table 1: Overview of WEF nexus technologies and practices with intrinsic SDGs (2,6 and 7)

Nexus	Water	Energy	Food/Agriculture
Water		Water used for energy extraction and production and biofuels processing Hydro-power Water for energy production infrastructure cooling and cleaning	Water is used for agricultural production and irrigation.
Energy	Energy is used to run water infrastructure pumping, irrigation, and desalination.		Energy is used for mechanised agriculture in land preparation, irrigation, fertilisation, food processing, conservation, etc.
Food/ Agriculture	Plants are used in water purification and wastewater treatment	Production of biofuels and biogas uses food, agricultural residues and biomass.	

Water pumping is a significant energy consumer within a traditional water supply chain. Delivering water from surface or underground water sources to treatment plants requires significant energy inputs. Solar-based pumping solutions offer a cost-effective alternative to pumping sets that run on grid electricity or diesel. This technology has been widely used in the country, especially for horticulture production. The technical potential for solar water pumps on smallholder farms (less than 1 hectare) is at least 130 million across West, Central and East Africa [32].

Agro-processing energy needs vary depending on the products and enterprises involved, the depth of value chains, and market access. Across West Africa and especially in Benin, for example, communities relying on grains and cassava for their main staple food crop must have access to milling facilities. Many rural communities rely on diesel-powered milling equipment to process staple crops to meet food, feed, and poultry needs[33]. Despite the strong potential for renewable energy use in the agri-food industry in several value chains, adopting some technologies is still early. Unlike developed countries, cold storage facilities are not yet widely available in developing nations. Cold storage technology is expected to expand in sub-Saharan Africa and West Africa. A key factor behind the limited availability of cold storage technology in developing countries is the lack of electricity in rural areas where most food is produced [34]. In the case of solar grain milling, a key value chain in sub-Saharan Africa, business models and technologies are still in the pilot phase and not yet deployed on a large scale. The solar dryer is one of the common examples of renewable energy applications in food conservation in West Africa. Drying food grains in the fields by exposure to the sun is becoming very common in West African countries. Solar dryers use solar energy to facilitate drying, primarily for various food products. Solar dryers aid in their preservation and preparation by removing moisture from crops, vegetables, and fruits.

The nexus of food and renewable energy here refers to bioenergy, the energy produced from biomass which can be produced in solid, liquid or gaseous form through a series of processes or conversion pathways. Bioenergy is a significant renewable energy resource that can meet the electricity, heat, and transport fuel needs within and outside the agri-food sector [34]. There are three main categories of biomass sources: residues and wastes from other activities and product streams, forests and crops, and fast-growing grasses. Forest products (e.g. firewood) continue to be a major source of biomass for energy production, particularly for cooking, while biogas is also commonly used in the agri-food sector in Benin. Biogas is produced when bacteria digest organic matter (biomass and animal products) without oxygen. In areas where food residues, animal manure or agro-processing wastes are locally available, biogas can be a suitable solution to provide an alternative fuel source for cooking, heating and electricity production. In addition, the bio-slurry or digestate, a by-product from the methanation process, can be used as fertiliser to substitute chemical fertiliser.

The applicability of WEF technologies depends upon the specific context and varies according to project scope and implementation. However, this case focuses more on the limitations related to sectorial considerations and resource exploitation. From the most common WEF nexus technologies application within agriculture in Benin, it can be observed that. The solar-based irrigation system, including energy and water components for agriculture, is one of the suitable WEF nexus applications to enhance UN Sustainable Development Goals (SDGs) achievement in remote areas. However, the rational land use aspect is not integrated. Regarding food conservation technologies using solar dryers, the focus is the energy-food nexus with no link to land resources exploitation. The biogas system, interlinking waste food and water to produce energy for clean cooking challenges in sub-Saharan Africa and West African countries, has no link to land resources. So far, none of the nexus technologies or approaches has considered the WEFL nexus in a single application. The credit to agrivoltaics, an innovative solution that considered the land used efficiency in its applications

5. Agrivoltaics for Current and Future Water-Energy-Food-Land Needs in Benin

Despite abundant resources that can enhance access to stable and sustainable energy, Benin still has low energy access and imports a significant part of its energy and electricity. Indeed, the solar irradiance (GTI) across the country varies from 4.68 to 5.94 kWh/m2/day [17], which can help solve water, energy, and food challenges with the appropriate technology. Thus, to achieve SDG 7 objectives, the government of Benin has established a minimum target of 36% renewable energy (including 450 MW of PV solar) in its energy mix by 2030 [35]. Nevertheless, developing energy infrastructure, such as power stations, necessitates land utilisation. Furthermore, Benin is the only country in the West African region with a limited land area of less than 120,000.0 Km2 with a high ambition for photovoltaic technology implementation by 2030, as indicated in Fig 3. Given the annual population growth rate of 2.7 and an area density of 108 persons per Km^2 in 2020, Benin's population is expected to be 24 million by 2050[9]. Although land-use competition between energy and food production cannot be perceived, the growing population will substantially increase food and energy demands. Therefore, large surface areas needed to cover population energy demand further through the country's photovoltaic power station will lead to land-use conflicts with other sectors like agriculture as food demand increases.

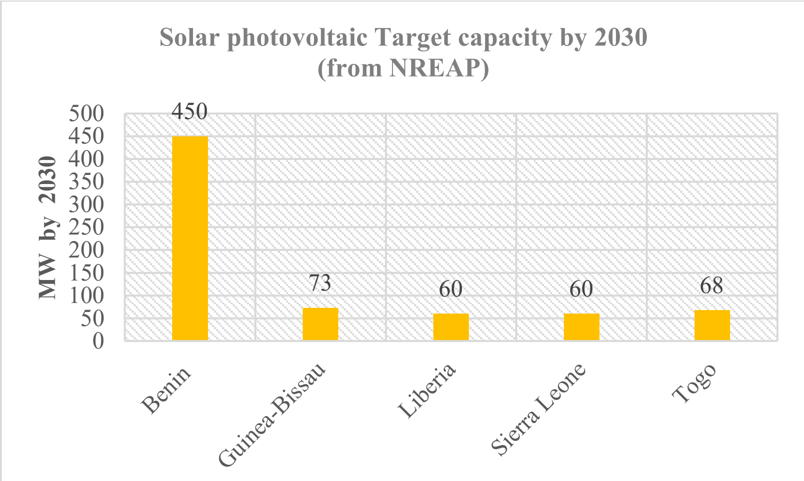

Figure 3: Countries with limited land in West Africa and their target PV capacity by 2023

Implementing agrivoltaics can make the WEFL nexus approach feasible throughout the country. Agrivoltaics can address future water, energy, and food demands, reduce land use and transformation pressures, enhance the population's livelihoods, and simultaneously protect the environment. Thus, agrivoltaics could play a crucial role in climate adaptation and mitigation, and in achieving the UN Sustainable Development Goals. Agrivoltaic application can be extended even further into rural areas, given the relevance of agriculture in providing employment and income for the local population. AVSs have the capacity to provide energy for various productive activities at the farm level, including water pumping, operation of labour-saving small-scale machinery, poultry raising, and fodder production.

Furthermore, AVSs can support value-adding processes such as grinding, packaging, threshing, and ensuring the availability of adequate cold storage facilities for perishable goods [15]. Using renewable energy to power electric and thermal agro-processing equipment, be it standalone systems or mini-grids, presents an increasingly cost-effective alternative. Additionally, it offers the advantages of reducing environmental impact, promoting the establishing a decentralised processing infrastructure, and minimising labour-intensive processing activities [34]. Installing an AVS makes the farm self-sufficient regarding its energy needs and becomes a suitable alternative to the recent price growing of conventional fuel in the region. AVSs can ensure that the solar panels are continuously cooled given the microclimate created by the crops under them, which ensures that they retain more energy as solar panels are less efficient when receiving intense heat.

Agrivoltaics can help regenerate degraded land under water scarcity in the arid region in the country's North, as the system could serve for groundwater withdrawal. Moreover, given the country's coastal area and abundant rainfall, photovoltaic panels in an AVS can protect crops. The solar panels' surface can be used for water collection to be reused for irrigation. Many studies claim that AVSs have the most promising potential in arid regions, where various synergistic effects can occur. Thus, this system could be appropriate in the arid part of the country. According to Amaducci et al. [36], agrivoltaics can improve plant resilience to climate change by protecting crops from radiation stress, reducing water demand due to reduced evaporation, and increasing yields of shade-tolerant crops. The NREL also affirms that this system can improve economic development and food security, especially in rural areas, presenting promising opportunities for food production, water savings and renewable energy generation

[37]. Solar electricity production supports CO2 emission decrease and consecutively in global warming reduction, helping, therefore, to meet the national climate change targets [38]. In addition, having vegetation below and around solar panels could reduce the levels of dust and soil on the panel.

Although agrivoltaics has significant advantages, some challenges require a comprehensive understanding of technical and economic aspects and agricultural matters. Furthermore, factors affecting societal acceptance of this new application must be studied. From the project implementation perspective, agrivoltaic systems are challenging due to their close interaction with agriculture, the local economy, and the stakeholders on-site [38]. Ketzer et al. [38] argued that system design factors and operator modes are among the criteria that may influence the local acceptance, farmers' enthusiasm for AVS and economic factors on the market launch of agrivoltaics. Designing systems that allow for relatively low installation costs and easy maintenance is important, as the initial capital is often not affordable for many African rural communities.

According to Adelhardt et al. [14], the challenges hindering the implementation of agrivoltaic technology in Mali may be attributed to various factors. These include the scarcity of a proficient labour force for design, construction and maintenance, inadequate quality control measures during procurement and construction, and the complex supply chain. Similar issues are prevalent in many African countries due to logistical constraints, high transportation expenses, and security concerns. Selecting appropriate crops for agrivoltaic applications is essential, but it poses challenges in the West African context due to the limited best-practice pilot projects. However, experiments in Benin, Ghana, and Nigeria are underway and expected to show promising results. Furthermore, other experimental projects in East Africa with 2 to 3 years of data were conducted at pilot sites in Kenya, Uganda, and Tanzania [39].

6. Conclusion

Benin has committed to environmental preservation, recognising the global need to protect the planet. To this end, the country signed the Paris Agreement during COP21, which aims to mitigate greenhouse gas emissions worldwide and work towards limiting the global temperature increase to below 2°C. In line with this, the Benin government has set a minimum target of achieving 36% renewable energy in its energy mix by 2030, including 450 MW of photovoltaic (PV) solar power. However, developing energy infrastructure, such as power stations, requires land utilisation and transformation. Typically, it takes between 3.2 to 3.3 acres (1.2 to 1.35 hectares), depending on the location, to generate one megawatt (MW) of solar power, considering the solar arrays, maintenance, and site requirements. Hence, it is crucial to prioritise the adoption of agrivoltaics in developing countries with limited land areas and high interest in solar PV system implementation for their population energy demand, such as Benin. Nonetheless, it is important for stakeholders, such as developers, energy providers, and farmers, to thoroughly assess which agrivoltaic approach aligns best with their interests when considering long-term sustainability. It is worth noting that although investing in agrivoltaics may produce long-term benefits, there is an ongoing debate on whether the high investment cost in installing solar panels can be effectively offset, especially considering farmers' diverse financial profiles and risk tolerances.

Data availability statement

The data used in this document comes mainly from the national renewable energy plans of the highlighted countries. The data are available online and can be provided to readers upon request.

Author contribution

Segbedji Geraldo FAVI: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Validation. **Rabani ADAMOU:** Supervision, Validation. **Thierry Godjo:** Supervision, Validation. **Max Trommsdorff:** Methodology, Supervision, Writing – review & editing, Validation. **Nimay Chandra Giri:** Methodology, review & editing.

Competing Interests

The authors declare that they have no competing interests

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