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Smart Sustainable Agrivoltaics Systems: The Future of Sustainable Agricultural Technology (Agri-tech) and Green Energy

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***Abstract*—Agricultural productivity depends primarily on energy, water, and land resources, which are increasingly becoming more scarce and expensive. Electricity generation with photovoltaic (PV) solar energy technology requires significant amounts of space, especially in densely populated countries, generating a societal debate about allocating land (that may have alternative uses) for deploying PV systems. Rather than dedicating vast amounts of agricultural land to be used as solar farms, PV systems are deployed in agricultural lands so that a given piece of land can be used for agriculture and energy generation (the so-called agrivoltaics). A framework based on systems thinking is essential for the design and operation of smart, sustainable agrivoltaics systems to meet the design goals or to satisfy the expectation of all stakeholders (farmers, energy developers, policymakers, and local community members that may be impacted). In this paper, we propose a system-based conceptual and design framework for smart, sustainable agrivoltaics. We also discuss the benefits of agrivoltaics and the challenges to their adoption.**

***Index Terms*—Smart Farming Systems, Smart Green Energy systems, Smart Sustainable Agrivoltaics, Systems Thinking, Sustainable Agri-tech, Internet of Things (IoT).**

I. INTRODUCTION

Recently, there has been rapid progress in implementing PhotoVoltaic (PV) systems in agriculture. Agricultural productivity depends primarily on energy, water, and land resources [1], which are increasingly becoming more scarce and expensive. It is estimated that about 30% of the energy produced globally is consumed by the food and agricultural sector in producing agricultural inputs (fertilizers, pesticides, insecticides, herbicides, fungicides and many other agrochemicals), operating agricultural machinery in the farms, food processing, transportation, marketing, and consumption [2], making the possibility of integrating green energy harvesting systems into agricultural production lands to meet the evergrowing demand for energy in agriculture very appealing.

Currently, agriculture is facing severe challenges such as increasing land degradation [3], postharvest losses [4], the harmful effects of agrochemicals on the ecosystems on farms (and on human health) [5], water scarcity [6], the increasing cost of energy and fertilizer [7], and the effects of climate fluctuations and change on agriculture [8]. These challenges result in a decrease in yields, although food production costs keep increasing. According to the UN Convention to Combat Desertification (UNCCD.int) [9], about 40% of the global land is degraded, and the current rate of mismanagement of land resources such as soil, water, and biodiversity poses a significant threat to many species on earth including humans. Therefore, the arable land suitable for agriculture is continuously shrinking, although the demand for food keeps increasing, resulting in food insecurity.

The move towards sustainable energy systems, together with the evergrowing demand for energy (especially in the agriculture, manufacturing, transportation, households and public infrastructures, and construction sectors), has led to significant progress in PV technologies [10], and an average annual generation growth of 25% is required to reach a significant reduction in CO2 emissions by 2050 [11]. In practice, flatlands suitable for agriculture are also suitable for constructing solar farms and hence, a growing competition between the agriculture and energy sector for land resources. These challenges can be resolved by the dual use of land for both agriculture and solar energy harvesting, the so-called agrivoltaic system [10]. Exploring various approaches for the dual usage of land for sustainable food and energy production has recently received significant attention [1].

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Integrating agricultural and PV energy production operations may generate unintended consequences that, if not identified and taken care of at the design stage, may create conflict between the stakeholders or result in losses (e.g., crop failure, damage of PV infrastructure etc.). The authors in [12] discussed the problem of soil erosion caused by the integration of solar infrastructure in agricultural fields and highlighted the need to agrivoltaics with biochar and other regenerative farming methods to reduce soil erosion and to improve soil structure and its ability to hold water. The authors in [13] explored the opportunities and barriers to adopting agrivoltaics systems by conducting in-depth interviews with experts in the solar energy industry. Their findings suggest that to increase the social acceptance of agrivoltaics, land use planners, solar energy developers, and policymakers make design and policy decisions that strategically and meaningfully integrate agriculture and solar energy infrastructure deployment in such a way as to provide multiple benefits to local communities including the retention of agricultural land and local economic development. A system-based framework for the design and operation of smart sustainable of smart agrivoltaics to meet the design goals or the expectation of all stakeholders (farmers, energy developers, policymakers, and local community members that may be impacted) is essential.

This paper proposes a system-based conceptual and design framework for smart, sustainable agrivoltaics. We also present an overview of smart, sustainable agrivoltaics systems to show that they are the future of sustainable agricultural technology (Agri-tech) and green (clean and sustainable) energy production. The rest of the paper is organised as follows: section II presents a conceptual framework for an integrated smart, sustainable agrivoltaic system. A system-centric framework for the design of sustainable agrivoltaic systems is presented in section III. In section IV, we discuss the benefits and the challenges of adopting agrivoltaics.

II. A CONCEPTUAL FRAMEWORK FOR AN INTEGRATED SMART SUSTAINABLE AGRIVOLTAIC SYSTEM

A conceptual framework for an integrated smart sustainable agrivoltaic system is shown in Fig. 1. The three interconnected circles in the Venn diagram represent the three basic elements of the framework -the PhotoVoltaic (PV) system, the agricultural system, and the ICT system. The overlap between all the three systems forms the Smart Agrivoltaic System (SAS).

A. PhotoVoltaic (PV) systems

Photovoltaic (PV) solar energy is electrical energy obtained from the direct conversion of solar energy into electrical energy and PV systems are the most promising renewable energy sources expected to provide cheap, inexhaustible clean, and sustainable energy [14]. They are emerging as serious contenders to rival leading energy sources to generate electricity for environment-friendly renewable and sustainable energy technologies and have been considered the most promising solutions to satisfy the evergrowing global energy demand because they are considered the safest, clean and abundant energy source for future renewable and sustainable energy technologies [15].

Despite the socioeconomic and sustainable benefits provided by PV systems, their adoption depends on factors such as efficiency (which depends on solar irradiance, temperature, humidity, and dust), cost (resulting from financial, human, and natural sources such as minerals and land required), lifetime (reduction of useful life due to degradation), and sustainability (environmental impact of mining minerals for PV system production, emissions from mining and manufacturing PV systems, and the environmental impact of disposing or recycling PV system when they will be adopted in a large scale) [16].

B. AgriVoltaic (AV) systems

Electricity generation with photovoltaic (PV) solar energy technology requires significant amounts of space, especially in densely populated countries [17], generating a societal debate about the allocation of land (that may have alternative uses) for the deployment of PV systems. Rather than dedicating vast amounts of agricultural land to be used as solar farms, PV systems are deployed in agricultural lands so that a given piece of land can be used for agriculture and energy generation (the so-called agrivoltaics). Agrivoltaics is the technique of combining agricultural and PV solar energy production on the same unit of land to significantly increase land-use efficiency and mitigated related land-use conflicts [18], [19]. Agrivoltaics are sometimes refered to as agrovoltaics [20], ”solar sharing” [21], and PV agriculture [22]. Thus, an agrivoltaic system [23] is the use of agricultural lands for both agriculture and PV solar energy generation.

An agrivoltaic system consists of agricultural and PV systems coexisting in the same environment, sometimes providing mutual benefits for each other [24], [25]. The deployment of PV systems to generate clean energy to satisfy the energy demands of the growing energy-hungry agricultural sector [19] and supply other industries could shorten the path towards green and sustainable economies globally. The classification of the various types of agrivoltaic systems was discussed in [18], [19].

In agrivoltaic deployments, food crops or livestock operations are co-located with photovoltaic systems in such a way as to ensure synergy between the agricultural and PV energy production systems aimed at optimising agricultural and energy production yields. That is, if the agrivoltaic systems are properly planned and designed, they can simultaneously improve crop yields, generate clean and renewable energy, conserve water (or reduce water usage), conserve (or regenerate) agricultural lands, and bring new economic development and tax revenue to rural communities [26]. Agrivoltaics are currently being deployed in crop production operation [27], [28] and in livestock production operation [29], [30].

C. Sustainable agrivoltaics

Agrivoltaic systems can be designed or adapted to suit sustainable farming methods like regenerative farming [31], [32] and agroecology [33]–[35] in such a way as to achieve sustainable agricultural goals such as soil regeneration, water infiltration & minimal erosion (both water and wind erosion), efficient water usage, minimal mechanical and chemical disturbance of the soil (less tillage and use of agrochemicals), and maximum soil carbon content. The solar systems can be designed and deployed in such a way as to enhance the adoption of sustainable farming practices such as amour on the soil surface, maximisation of Diversity, maximisation of living roots on the soil, minimisation of soil disturbance, and holistic integration livestock to regenerate or revitalise soil health.

Providing amour on the soil surface is essential to protect the soil against high temperatures, especially in sub-Saharan Africa and dry regions of the world where the dry season (where there is no rain) is relatively very long. At high temperatures, irrigation water provided to the crops quickly evaporates, resulting in excessive water wastage and low crop yields. At very high temperatures, the living organisms in the soil (e.g., the bacteria, fungi, nematodes etc.) that cooperate with the plants may not die. Also, soils that are not covered are vulnerable to wind and water erosion that carry away the soil nutrients, degrading the soil. In regenerative farming operations, cover crops [36] are seeded to provide amour on the soil surface.

In an agrivoltaic operation, PV modules [10] can be installed in such a way that they can provide amour to the soil surface to protect the soil against overheating, water evaporation, and wind and water erosion. For example, the PV modules could be mounted between the crops at some height with a certain tilt (this can be useful in dry areas, especially in sub-Saharan Africa and other dry places of the world), or they can be used to construct part of the greenhouse or tunnel (especially in cold areas of the world where it is desired to grow vegetables during the dry season). However, the PV modules may reduce sunlight transmittance and therefore reduces agricultural yield [37]. In holistic management [38], the paddocks can be built using bifacial PV modules. Then, the livestock is rotated between the paddocks to prevent over-grazing, which can lead to desertification [39].

D. *Smart sustainable agrivoltaic systems*

Modern technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), robotics, drones, satellite imagery, fog computing and cloud computing are currently being adopted to improve efficiency and productivity in the management of farms (so-called smart farming systems or IoT-driven agriculture [40], [41]) and in the management of energy infrastructures (smart energy systems). These technologies enable efficient and autonomous monitoring and control of agricultural and PV energy production processes, increasing productivity and the efficient use of resources.

It is very essential to pay attention to the technical details of the photovoltaic and agronomic management systems (crop and water management) to ensure the successful deployment and operation of agrivoltaic systems [42]. ICT-based management and control systems such as IoT sensors are used to gather environmental data (e.g., temperature, humidity, light intensity, shocks and vibration around the panel, wind speed, soil moisture, soil carbon content etc.). Multimedia data can be collected using drones or satellite imagery systems. The data is sent to fog computing or cloud computing platforms, which may be running some AI or Big data analytic algorithms. The results of the data analytics platforms are sent to human users or IoT actuator devices to manipulate some robots in the agrivoltaic systems. AI-based robots are used to detect and eliminate weeds and pests [43], [44], reducing the use of agrochemicals (minimising chemical disturbance and cost). Other regenerative farming operations can be automated using an ICT system, making smart, sustainable farming less laborious and attractive. The integration of sustainable agricultural systems, PV systems, and ICT systems to improve productivity and maximise crop/livestock and energy yields is what we refer to as smart sustainable agrivoltaics.

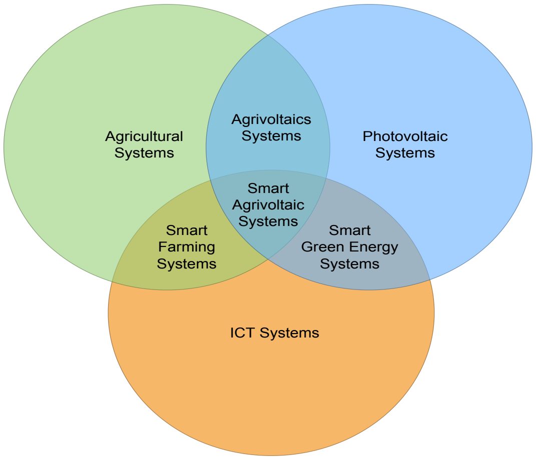

Fig. 1. A conceptual framework for integrated smart sustainable agrivoltaic system

III. A SYSTEM-CENTRIC FRAMEWORK FOR THE DESIGN OF SUSTAINABLE AGRIVOLTAIC SYSTEMS

Smart sustainable agrivoltaics consist of multiple systems (agricultural systems, PV systems, ICT systems, management systems, and other stakeholders such as policymakers and members of the local community that may be impacted in various ways) that interacting with each other achieve the goals or purposes of the various stakeholders. Each system consists of multiple interdependent parts that are interacting to perform their intended functions, and any modification in any part of the system will affect the performance of the system as a whole. The performance of the smart, sustainable agrivoltaic system depends on the interactions of all the various systems that constitute the agrivoltaic system. The interaction of the various parts of the system (including all the stakeholders) may create unintended consequences. Thus, a system-centric approach is neccessary to design and operation of smart, sustainable agrivoltaics systems to meet the design goals or to satisfy the expectation of all stakeholders.

The various stakeholders may have conflicting goals. The main goal of the farmer is to maximise yields, the main goal

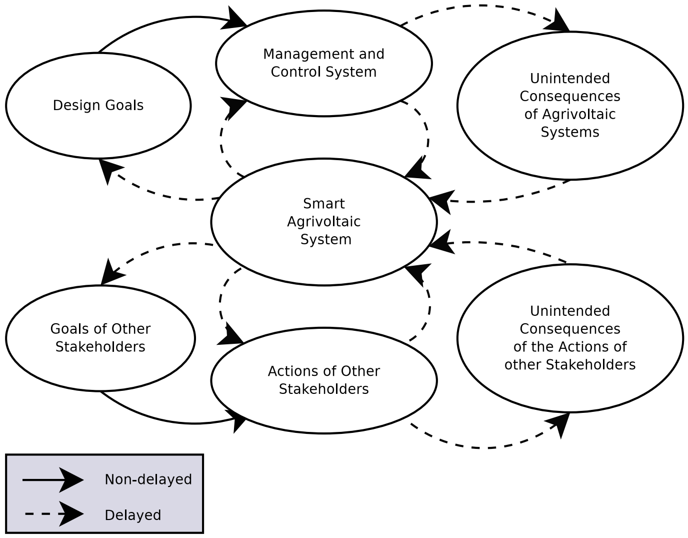

Fig. 2. A systems thinking framework for the design and operation of sustainable agrivoltaic systems

of the energy developer is to produce as much energy as possible and the goal of the policymakers is to ensure the environmental sustainability of the various stakeholders. In the Systems Thinking [45] framework in Fig. 2, the main stakeholders (farmers, energy developers, and policymakers or regulators) can use system thinking tools such as causal loop diagrams to identify the interconnections/relationships (especially none-linear and causal relationships), feedback loops, and the structures that are generating the observed behavioral patterns. They can then use the stock and flow models to model the accumulation of energy in the energy storage systems and the accumulation of carbon and other microbes in the soil as the soil is being regenerated, creating prediction models that can be use by management or policymaker for management or policy interventions to ensure that the goals of the various stakeholders are achieved.

IV. ADOPTION OF AGRIVOLTAICS

A. Benefits of Agrivoltaics

Agrivoltaics provide significant environmental and sustainability benefits. The most obvious ones are land use and water usage efficiency [46]. The authors in [47] demonstrated that the deployment of agrivoltaic can improve land and water use efficiency with a 20% reduction in the water required for irrigation. By co-locating both agricultural and energy production operations on the same unit of land in such a way as to maximise the synergy between the agricultural and PV systems, food and energy insecurity can be reduced simultaneously.

Agrivoltaics systems provide a mechanism to reduce CO2 emissions and simultaneously absorb CO2 from the atmosphere. Combining agricultural and PV energy generation systems on the same unit of land will significantly increase the production of clean energy from PV solar systems. If agrivoltaics are successfully deployed on a large scale with efficient energy storage systems, our dependence on environmentally unsustainable energy sources will be reduced. The authors in [48] demonstrated the feasibility of generating clean energy from pasture-based agrivoltaic systems to supply data centres. Their model for the considered area suggests that about 3 million tonnes of CO2 emission will be reduced annually. The authors in [49] proposed the agrivoltaic systems (AVS) to facilitate the transition to EVs by powering EV charging stations along major rural roadways. They showed that by powering rural charging stations in Oregon using agrivoltaic systems, about 673,915 electric vehicles can be served annually, reducing CO2 emissions by 21%.

Another potential benefit of adopting agrivoltaic systems is its ability to enhance carbon sequestration [50], which will sequester CO2 from the atmosphere and store it in the soil, improving soil health and crop yields. Plants capture CO2 from the atmosphere and combine it with water in the presence of sunlight (during the process of photosynthesis) to produce sugars or liquid carbon, some of which is transferred to the roots and pumped out as root exudates [51] to feed the microbes (e.g., bacteria, fungi, nematodes etc.) in the soil, increasing the carbon stock in the soil and improving soil life or soil health. During the dry season in sub-Saharan Africa and some other dry parts of the world, vast amounts of land are left idle due to the inability of smallholder farmers in these regions to afford irrigation systems. Energy developers and farmers in these regions could engage in a partnership arrangement where the energy developers can build solar-powered micro-irrigation systems for farmers to grow their crops all year round. In return, the farmers will grant the energy developers the right to deploy their PV systems on the farms. In this way, huge amounts of clean energy will be generated during the dry season while the lands that are normally idle during the dry season (due to lack of irrigation) will be used to grow crops or graze livestock (reducing food insecurity), sequestering millions of tones of CO2 into the soil and regenerating the soils (that are currently degrading rapidly).

B. Challenges to the adoption of agrivoltaic

A major potential barrier to the adoption of agrivoltaic systems is the high investment cost involved and the concerns around returns on investments: Although PV systems are practical, sustainable energy sources to satisfy the growing energy demand in smart precision farming, the high investment cost is a major barrier to its widespread adoption [1]. The authors in [52] showed that agrivoltaic systems in current technological and economic conditions are not competitive when compared with PV systems and are also less attractive for agricultural farmers, due to the long return period of the surplus investment cost. The authors argued that due to the sustainability benefits of agrivoltaic systems, policymakers could consider the possibility of providing subsidies to farmer and energy developers to motivate them to embrace agrivoltaics to reduce CO2 emission. The value of the crop and energy yields may be insufficient to justify the heavy investment cost involved [53].

One of the potential factor that may make agrivoltaics to be less attractive to farmers is that the farmers are afraid of potential unintended consequences that may have a negative impact of their agricultural operations. Some of the potential unintended consequences of deploying PV systems in farms may include the possibility of soil erosion, decrease in soil carbon (due to less sunlight), decrease in yields [47]. Regions with high solar intensities suitable for solar energy generation also experience high rainfall intensities. The redistribution of rainfall by the solar energy infrastructure may cause erosion in some parts of the farm [12], creating unintended consequences like soil degradation and a subsequent drop in agricultural yields. Several unintended consequences still need to be understood, and to figure out how to deal with them.

Other factors that may stall the adoption of agrivoltaics are land use competition and social acceptance: the adoption of photovoltaics can be stalled because of limited social acceptance [29] as the land needed for agriculture is also the need to install solar energy infrastructure. For example, the large-scale adoption of solar energy deployment in some regions in the United States is hindered by land use competition and social resistance [13]. The authors in [26] studied how local opposition is slowing down agrivoltaics development in the United States, and they identified specific laws and policies that could enable agrivoltaics to flourish. Thus, the dual land use for agriculture and solar energy generation using agrivoltaics systems is essential. However, they may reduce crop yields (e.g., by 10% or more) [47], resulting in social resistance as food security is a major challenge for most communities.

V. CONCLUSION

A framework based on systems thinking is essential for the design and operation of smart, sustainable agrivoltaics systems to meet the design goals or to satisfy the expectation of all stakeholders (farmers, energy developers, policymakers, and local community members that may be impacted). In this paper, we have proposed a system-based conceptual and design framework for smart, sustainable agrivoltaics. We also presented an overview of smart, sustainable agrivoltaics systems to show that they are the future of sustainable agricultural technology (Agri-tech) and green (clean and sustainable) energy production. A system-based approach should be considered in the design and assessment of sustainable agrivoltaic systems while taking into consideration its benefits and challenges. In our future works, we will demonstrate how the proposed framework can be applied to the design and optimisation of agrivoltaic systems.

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