



Smart Renewable Energy Integration for Precision Agriculture in Off-Grid Areas

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Abstract

The move to smart renewable energy systems in precision agriculture (PA) can and will potentially be a transformational solution to the interconnected global problems of food sovereignty, energy poverty, and environmental blight in mostly unserved and off-grid rural contexts. The global population is anticipated to increase substantially by 2050 (25%), and food production must increase more than 60% to provide for food. But agribusiness is a significant pressure on Earth's living natural systems as it uses approximately 70% of the global freshwater resources, and is responsible for about 24% of global GHG emissions. Data-based systems, sensors, and automation will have growth opportunities of 20-30% at least in alternative agricultural productivity, while reducing fertilizer application by -5 to 15%, and water application -30 to -50%. RE systems, largely solar and wind, provide decentralized, cleaner sources of energy to assist PA. For example, solar irrigation systems can reduce energy use by as much as 60% over traditional fossil fuel, creating more efficient systems for farms. Research and policy around the integrated use of RE and PA indicate promise for resilience and sustainability of agricultural systems, particularly for smallholder

Significance | Integrating smart renewable energy with precision agriculture empowers off-grid farmers, improves productivity, reduces costs, and supports sustainable, climate-resilient farming.

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producers who are operating off-grid. Smart integration of renewable energy with productive agriculture can help to increase efficiency and productivity, reduce input costs, and reduce emissions by as much as 25%. In this review we consider the state of RE-PA integration, the state of technology, use and deployment as well as perspectives, challenges, solutions, and future of RE-PA integration.

Keywords: Smart renewable energy, precision agriculture, off-grid areas, sustainable farming, renewable energy integration.

1. Introduction

The agricultural industry across the globe is facing turmoil from meeting food security demands of an anticipated world population of 9.7 billion people, 25% increase of present levels by 2050, and the associated effects of climate change that are prompting farmers, researchers and policymakers to articulate plans for implementing more sustainable and productive agriculture (Wijeratne & Pathirana, 2022). Farmers are increasingly beginning to embrace precision agriculture (PA) as a high-tech approach to manage, monitor and assess the crop production process, utilizing geographic information systems (GIS), the Internet of Things (IoT) and big data through sensors in fields and drones as monitoring technology (Shaheb et al., 2022). In terms of the effects precision agriculture has had on the management of crop production, there is considerable evidence that precision agriculture has increased crop yields between 20-30%, reduced fertilizer application rates by 25%, and decreased the use of agricultural water by 30-50%. It is not too much of a stretch to say, in broad terms and with scientific certainty, that precision agriculture has provided an enablement and supportive capacity for the sustainable intensification of agriculture (Yost et al., 2016). Precision agriculture has provided

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the ability for farmers to only apply water, fertilizers, and pesticides when needed, in the right quantity, at the correct location, and at the right time, helping to maximizing natural processes while more effectively using produced inputs while reducing waste, unintended environmental effects related to agricultural practices such as nutrient leaching and GHG emission when possible. Agriculture uses over 70 percent of all freshwater and 24 percent of global anthropogenic GHG emissions (Stavi & Lal, 2012) and offers tremendous opportunities for greater productivity and sustainability by using precision agriculture technology. Nevertheless, while the adoption levels for PA technologies are low in many rural and off-grid areas, this can be largely attributed to lack of access to affordable and dependable sufficiently long access to electricity. Many farming communities in the developing world do not have a reliable power source and, as a result, the ability to introduce PA systems that depend on energy (automated irrigation pumps, remote sensing devices, weather stations and greenhouse automated controls) are restricted (Nandi & Nedumaran, 2021). The current operation of agricultural producers that depend on diesel generators is not sustainable, nor economically efficient as fuel expenses could represent as much as 60% of total irrigation costs and contributes to pollution. Renewable energies (RE) technologies particularly based on solar and wind energy represent sustainable and clean, economically viable scalable and decentralized alternatives to fossil fuel and grid energy (Rahman et al., 2022). Over the last ten years; solar photovoltaic (PV) systems have decreased in price by over 80% from over \$4 per watt to almost \$0.50 per watt, making them more viable for rural uses than before (Karim et al., 2023). The combination of RE and the use of precision agriculture (PA) systems allows agricultural producers to work autonomously and resiliently as they can harvest on-site solar or wind energy to power Internet of Thing (IoT) devices, pumps, sensors, sites, and block chain applications without the need for fossil fuels or connection to grid energy.

In addition, solar powered irrigation can reduce operational costs

by 60%, while precision irrigation and water management studies have reported savings over 30-40% of water use. Accordingly, the review study recognizes the current state of smart renewable electricity (RE) integration in precision agriculture and pays special attention to technology options, adoption trends, benefits, drawbacks, and future opportunities (Bwambale et al., 2021). The latter includes recognizing the synergistic use of renewable energy (SRE) and sustainable agriculture to support smallholder farmers—those who operate the world's smallest and most vulnerable farms, averaging 83% of all farms in the agriculture of developing world. Furthermore, the paper highlighted the importance of enabling policies, financial mechanisms and capacity-development activities to enable stakeholder's uptake smart RE-PA solutions (Amede et al., 2023). This review aims to systematically explore the relationship between SRE systems with precision agriculture in off-grid, by understanding technology development, adoption, challenges and also providing direction to possible future development.

2. Precision Agriculture Technologies

Agricultural precision (AP) leverages sophisticated technologies, data, automation, and sensors to maximize efficiency, productivity, and sustainable farming practices. Soil sensors, the foundation of AP, are capable of monitoring moisture, pH, and nutrients, and in this manner make up to 30% - 50% water savings and up to 20% - 25% fertilizer reduction through precision application (Mussettola et al., 1998). Climate sensors can monitor the temperature, humidity, and rainfall to assist farmers in maximizing their planting and irrigation schedules, and in this manner may reduce crop losses by up to 20% Figure 1. Remote sensing for crop monitoring through drone, and/or satellite, provides the ability to monitor more land area, crop health, and to assess pest populations, variable land management, and much more, thus improving on-the-ground scouting and improving efficiency up to 80% (Asiaban et al., 2021). GPS and GIS technology enables precision agriculture through

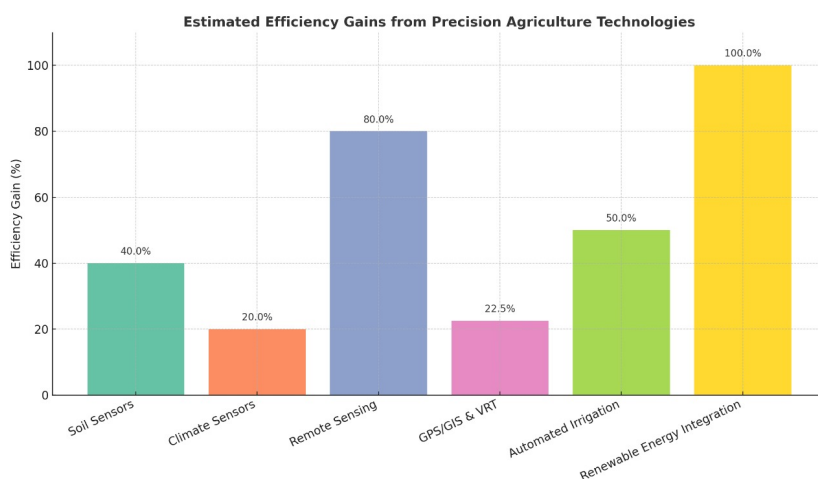


Figure 1. Estimated Efficiency Gains from Precision Agriculture Technologies

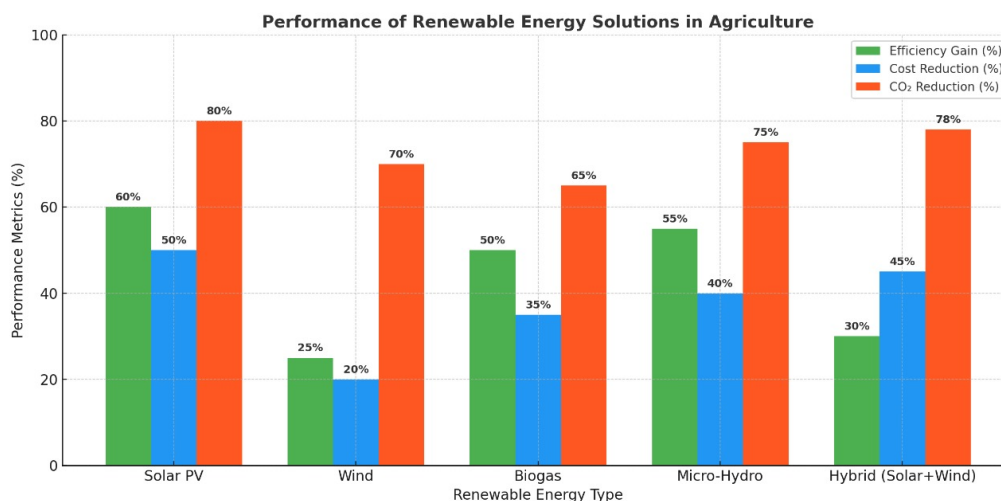


Figure 2. Performance of Renewable Energy Solutions in Agriculture.

support for site specific application of inputs commonly known as precision or targeted agriculture and where variable rate technology has the potential of being 15–30% more efficient than traditional application methods (Rutibabara, 2018). For agricultural practitioners, aspects of an automated irrigation system with friction use of sensors reduced many efficiency expenses via mechanical labor and reduces saved on water costs by 50% potentially based on methodologies measured (data). The systems consume energy as a continuous flow in the same away from deforming properties of a continuum on off-grid inabilities, this makes the energy accurate since off grid energy is not a continuous supply. the energy consumed by the sensors, controls and commas module will always be able to provide a continuous flow of energy (Meng et al., 2013). For this reason, renewable energy could potentially offer a pathway forward provisioned. Therefore, we point out that not just solar PV, not just about generativity, solar PV systems provide reliable energy provisions in off-grid setups that can cover any potential future fuels demands to any PA device when reliability to the energy, and connectivity is needed to support the PA systems. Given the possibilities for significantly up-scaling performance (PA) technologies and the potential impacts of that on off-grid agriculture, it is incredibly important that renewables be given a strong consideration in renewable provision of energy (Egeland et al., 2021).

3. Renewable Energy Solutions

Renewable energy is a reliable and sustainable substitute for fossil fuels and is now being recognized as a viable source of power for agricultural activities, especially by small-scale producers in off-grid rural areas where access to energy can be marginal. The most popular of these sources is solar energy and there are many areas that have a high solar irradiance level. Solar **photovoltaic** technologies (solar PV) can be employed to power irrigation pumps, recharge batteries that supply power to sensor networks,

and power lights, fridges, and cooling during the fade storage of grains (Majeed et al., 2023). In a solar powered system, drip irrigation could increase water use efficiency by as much as 60%, and reduced energy costs can be achieved by 40-60%, with the largest gains made in arid and semi-arid settings (Falcone, 2023). Wind powered systems tend to be a little more site and location-specific in their utility, however wind as a hybrid complimentary system is an important lever to supporting solar power, particularly in coastal and elevated locations, where wind can be fairing consistent. Small wind systems can be powered during periods of cloudy sky or at night which may be the optimum time to supply power. In terms of hybrid solar-wind systems studies have shown that the total availability of the combined systems was 20-30% higher than standing on solar only systems Aureoboaster (Asiaban et al., 2021).

Biogas systems, which turn waste from agriculture and animal products into methane a cleaner fuel for cooking, heating, even electricity, can eliminate waste from a farm's operation, and provide power for up to 50% of a household's energy consumption Figure 2. Micro-hydro systems could also really work for a being a counteraction in as many spots with sustainable water flow as possible. They will provide nearly all the same things as wind and any permanent installations, with even better with the very minimum active maintenance it will require (Boroomandnia et al., 2022). Renewables will provide energy for users while allowing users to substitute on fossil fuels, reduce costs of operation and possibly reduce greenhouse gas emissions from the farming sector. A transition through renewable to powered agricultural systems has shown we can get as high as an 80% reduction in CO₂ emissions compared to diesel powered systems. Also, their modulatory and scalability also support the relevance of smallholder farmers in developing countries that make up over 80% of all farms globally (Chel & Kaushik, 2010). Smart technologies to effectively rolled out, they will require distributed smart agriculture systems with

Table 1. Smart Integration Technologies in Renewable Energy-Driven Agriculture.

Technology	Function	Benefit
IoT Devices	Real-time monitoring of soil, climate, and energy data	Reduces input use by 20–25%, improves water use by >30%
Smart Controllers	Automated decisions based on sensor input	Boosts energy efficiency by 40%, optimizes scheduling
Battery Storage Systems	Stores surplus energy for use during low generation periods	Extends operation by 50%, ensures reliability
AI & Machine Learning	Forecasting and predictive analysis for farm operations	Increases productivity by 20–35%, reduces downtime
Cloud-Based Systems	Remote control and analytics via apps/dashboards	Cuts labor input by 15–30%, enables early decisions
Microgrids	Localized, shared energy networks among farms	Lowers investment cost by 25%, enhances system resilience

trustworthy EMS units able to provide adequate power supply and management for supply and demand matching during workload energy variability, storage variability, and uptime factors such as day/night cycle. In all likelihood, smart technologies will fail to meet expectations in terms of effectiveness if their provision of energy supply is unreliable, or its functions are out-of-sync with one another at some stage in the workload process. The renewable energy systems used reliably are able to optimize environmental performance, certainly offer monetary incentives that help transition energy deprived agriculture (Balmer et al., 2020). The solutions can be heavily influential if used in tandem with precision agriculture practices and contribute to resilient, profitable and climate-smart agriculture in off-grid contexts.

4. Smart Integration Technologies

In order to successfully interconnect renewable energy systems to precision agriculture, there should be technological components that span the energy supply with the agricultural demand. IOT (Internet of things) technology is a key technological component of that integration that brings to realization today, data-transfer in real-time from sensors, actuators and energy systems all at once. Today IOT devices will more reliably transfer information on soil moisture levels, temperatures, humidity, and the intensity of total sunlight (Jawad et al., 2017). IOT research and monitoring studies also report complementary studies which report agricultural inputs could potentially be reduced by 20-25% Table 1, while also increasing water-use efficiencies of more than 30% Smart Controllers either consist of a microcontroller or edge-compute entity, that combine active control, through one or multiple IOT inputs from sensors and actuators, to fully automate action or decision making on irrigation scheduling, fertilizer applications, or controlled environment decisions (Tang et al., 2019). The systems can be programmed to maximize clean energy use by taking advantage of solar energy generation peaks, and improving energy efficiency (40%). Irrigation scheduling could be done during solar energy generation peaks to reduce battery drawdown and reduce

system stress. The second critical requirement is battery storage systems. Battery storage systems allow the capture of surplus solar or wind energy, for example, to then be used when generation is reduced night or cloud (Pardo & Navarro, 2023). Storage utility could provide up to 50% more operating time; perfect for providing continuous operation of essential systems, such as irrigation pumps, climate control, and so on based purely on need.

The integration of AI and machine learning (ML), also provides additional resilience to the system. Using algorithms to analyze trend data and real-time data processing, machine learning can make forecast adjustments for crop water and nutrients requirements at each point in time, minimize energy use, create predictive need for potential system maintenance. Guided by artificial intelligence, decision making can provide an overall increase to a system's productivity by 20% to 35% while concurrently reducing downtime and waste (Dhillon & Moncur, 2023). Cloud based systems typically allow for remote monitoring and control capabilities based on the operational setting that a farmer adjusts via mobile app, or web-based dashboards. Cloud based systems provide an opportunity for analytics and metrics that promote earlier decision making regarding the modifications of the field and/or supply of energy. Depending on the connection and types of sensors, a cloud enabled farm may reduce the farmer's labor input of 15% to 30%, freeing up the farmer's time across the farming activities that require consideration (Candelise et al., 2013). Decentralized smart grids or small scale microgrids may interrupt the farmer's decision making, particularly in a community farm scenario. When there are networks like electricity that intersect the common elements of farming, farmers could energy share and increase the resilience of each system while also reducing the cost of individual investments by approximately 25%. Many places have power instability challenges so microgrids and connectivity can offer solutions that create resilience out of systems while reinforcing networks that promote cooperation and collaboration on energy consumption.

5. Adoption and Impact Statistics

The application of smart renewable energy (RE) systems in precision agriculture (PA) is growing in scale, especially in the less or off-grid locations across Africa and Asia. Significant data now demonstrate that in off-grid areas, approximately 65% of the solar irrigation systems now have moisture sensors or automation controls operate automatically, leading to considerable reduction in water usage (Abioye et al., 2022). The data suggest that almost 40% of PA systems in rural areas with diesel systems (still the majority) were powered by renewable energy sources resulting in carbon emission reductions of 80% (Murshed, 2020). The farms utilizing RE powered PA technologies have reported crop yields being 30% or higher but use 25% less fertilizers and pesticides due to RE systems, ultimately saving money and positively contributing to the environment. The rural microgrids currently are derived by almost half using energy for agricultural applications: cold stores, irrigation systems and greenhouse operations (Fornarelli et al., 2017). Microgrids provide reliable and decentralized electricity to innovative, localized, precision devices in areas where access to the national utility grid is limited. Interview and survey work indicates that almost 70% of smallholder farmers indicated they would utilize RE-PA systems especially off-the-shelf appliances and be willing to be trained and financed, that illustrates the need for services that build on participatory financing models and local capacity building, in addressing the convergence of adoption of these systems (Shirkhani et al., 2023). This is important supporting evidence to characterize the large opportunity and impact of RE-PA integration to support better productivity, sustainability, and energy access. The replication and large-scale adoption or implementation of the model of rural microgrids combined with RE-PA integration, will depend on shared investment strategies, policy mechanisms, and complementary farmer extension education models that can sustain the viability and realization of the food sovereignty and food security supports in off-grid communities (Meng et al., 2013).

6. Challenges and Barriers

The adoption of advanced renewable energy (RE) and precision agriculture (PA) technologies faces important obstacles, especially in off-grid and resource-constrained situations. The main obstacle is the upfront cost of solar panels, sensors and automation technologies, which can serve as a barrier to individuals and in particular smallholder farmers, who often do not have access to reasonable methods of financing or subsidies. Other barriers are the technical skills limits and lack of training with respect to the actual use and servicing the system. In addition to the above barriers, there are also deployment infrastructure barriers such as poor internet connections and unreliable transport links. There are insufficient incentives and regulations for RE-PA integration as a result of policy gaps and limited institutional support. Other barriers

included no access spare parts, unreliable maintenance and servicing, and cultural resistance to new technology (Shannon, 2013). This ultimately leads to farmers rejecting systems they have not engaged with and cannot see real and evident benefits.

7. Future Prospects

The increased availability of lower-cost networking innovations in artificial intelligence, wireless technology and storage has augmented the feasibility of collocating renewable energy with precision agriculture. Even more promising is the parallel growth in policy support and the funding available for inclusive climate-resilient farming projects, all signaling a potential opportunity for sustainable energetic agricultural systems in off-grid communities.

8. Conclusion

The integration of smart renewable energy systems and applications for precision agriculture provide a unique solution to the issue of off-grid farming communities. Since they each generate renewable energy and complementary smart data use, they provide avenues for benefits like increases in productivity, efficiencies, and climate resilience. Recent case studies a positive future for this mix, in part due to positive results as physical evidence reflected in increases in yields, decreases in costs, greater efficiencies, improved emissions, and better livelihood. It is also apparent that there are many outstanding issues to be solved; including costs, capacity issues, infrastructure, and policy.

Author contributions

A.K.C. written whole manuscript.

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