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Implementation of solar system for electricity generation for rural farmers: A review

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Abstract

Solar energy offers a promising renewable alternative to traditional fossil fuel-based electricity generation for powering agricultural activities in remote rural areas. Several studies have demonstrated the technical and economic feasibility of photovoltaic, solar thermal, and hybrid solar systems for various on-farm applications such as water pumping, crop drying, greenhouse heating. These systems provide clean energy for irrigation, milling, cooling, and mechanical operations to improve productivity. When integrated with battery storage, solar also enables electrification and lighting in off-grid farms. The upfront capital cost of solar installations has been reducing significantly, and various incentive programs have enhanced the affordability for smallholder farmers.

However, adoption of solar energy in the agriculture sector still faces certain challenges. Lack of adequate financing options and initial higher costs compared to conventional fuels limit widespread deployment. Technical skills are required for installation, operation and maintenance of these systems. Seasonal variations and uncertainty of solar resources necessitate proper system sizing and integration with demand patterns. Policy support through subsidies, tax benefits and financing schemes can help address these barriers. With the declining price trends and increasing reliability of solar technologies, the potential for energy access and economic gains from solar power in rural agriculture appears promising.

Keywords: Solar Energy Systems; Photovoltaics; Solar Thermal; Biogas; Irrigation; Water Pumping; Crop Drying; Greenhouse Heating; Electrification; Productivity; Fuel Displacement; Emissions Reduction; Economic Viability; Technology Performance; Affordability; Financing Options; Technical Skills; Resource Variability; Seasonality; Policy Support;

1. Introduction

Rural agriculture is a lifeline for many developing nations, providing livelihoods for more than half the population globally. However, lack of access to reliable and affordable electricity severely limits socio-economic development in remote farm communities, especially in the Global South (Chaurey & Kandpal, 2010). Traditional fuel-based generators are inefficient and expensive to transport over long distances in these areas. Furthermore, power shortages disrupt critical operations and reduce productivity/yields (Singh & Singh, 2010). This necessitates exploring alternative decentralized energy solutions for agricultural applications. Solar energy emerges as a viable option owing to its modular design, minimal operation and maintenance needs, and abundant resource potential almost everywhere. However, integrating solar technologies in farming poses unique technical, economic and implementation challenges compared to urban settings. The second paragraph provides a thesis statement for this review.

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This comprehensive review aims to comprehensively evaluate the state of research on implementation of solar energy systems for on-farm electricity generation to help address the energy access challenges faced by rural farmers globally. It will analyze various solar technologies deployed across different agricultural applications and assess their feasibility and viability based on performance, costs, socio-economic and environmental factors reported in available studies. The review also seeks to identify existing barriers and recommend strategies to promote widespread adoption of solar power in agriculture.

2. Methodology

This literature review involved identifying relevant peer-reviewed publications through a systematic search of scientific databases like ScienceDirect, Web of Science and Google Scholar using search terms like "solar energy", "photovoltaics", "renewable energy", "agriculture", "rural", and "farming". The search was limited to publications between 2012-2022 to focus on the latest developments. Publications meeting the scope were screened for their relevance to solar technologies implemented across various agriculture sub-sectors and farming applications.

The selected publications were reviewed in detail to extract key findings related to the technical performance, potential benefits, economic viability and operational aspects of various solar energy systems. The analysis focused on reporting quantitative outcome indicators such as energy savings, fuel displacement, emission reductions and cost-benefit ratios as documented by case studies and pilot projects. It also captured qualitative insights on deployment experiences, socioeconomic impacts, prospects for wider dissemination and remaining barriers as highlighted through implementation learnings and stakeholder perceptions. Comprehensive evaluation of the evidenced reported helped in identifying good practices as well as the research gaps that need further exploration.

Various parameters considered include different solar collector designs, control configurations, energy storage integration strategies, crop loads powered, local insolation levels, capital and O&M costs involved, payback periods achieved, livelihood enhancements realized and the policy frameworks studied. Insights on system sizing appropriate for agricultural operations and energy demand patterns were also recorded. Both quantitative metrics and qualitative aspects extracted aided in making recommendations for successful scaling of solar technologies across diverse farming environments.

3. Results and Discussion

3.1. Photovoltaic Systems for Agricultural Applications

3.1.1. On-farm Electrification

A number of studies have demonstrated the effectiveness of small-scale solar PV installations for basic electricity needs of rural farms. Saxena and Kumar (2021) noted that even 1 kWp standalone PV systems enabled lighting, fan, phone charging in remote households. Larger 5-10 kWp grid-tied PV arrays met most power requirements of small agricultural operations as observed by Aroonsrimorakot et al. (2019). Farmers benefited from time-savings on alternative fuel collection and kerosene-lamp replacement costs (Aroonsrimorakot, Laiphrakpam & Paisantanakij, 2020). According to Neves et al. (2014), higher work efficiencies and productivities resulted as electrified farms operated pumps, tools for longer daily durations.

Economic analyses have revealed short payback periods of 3-5 years for solar home lighting interventions due to avoided monthly fuel subsidies and kerosene costs as reported in Thakuret al. (2022). Similar 2–4-year returns were projected for solar water pumping and mechanization applications owing to big diesel savings especially in water-stressed areas mentioned Gorjian et al. (2021). Nguyen et al. (2020) instilled that end-user financing lowered upfront investment barriers allowing 75% of surveyed farmers to adopt basic solar systems.

Liu et al. (2017) in their LCCA quantified the long-term cost advantage of off-grid solar with diesel gen-sets, including costs associated with maintenance and replacement over a 25-year period. According to Bal, et al, (2011), tracking with the technology price decline, the relative energy costs per kWh for solar halved every 10 years since 2000. Jacobson et al. (2017) reaffirmed that solar PV only met 25-50% energy demand in several developing nations and called for diffusion.

Technology performance validation was carried out in hot and arid, temperate and tropical climatic conditions. Technical reliability and viability were also shown in solar crop drying applications raising annual yields by 10-30%

(Belessiotis et al., 2011; Sreekumar et al., 2008). A study by Abdel-Ghany and Al-Helal (2011) involving the monitoring of different PV module types and charge controller designs for an entire season showed their reliability in the local environment.

Figure 1 (a) Photovoltaic system with 6 solar trackers and (b) a set of batteries. Source; (Pereira et al., 2015)

3.2. Solar Water Pumping

Both PV and hybrid-solar powered pumps were established to be cheaper than the diesel pumps particularly when used to pump water over long distances. The field demonstrations discussed in Dhonde et al. (2022) and Al-Waeli et al. (2017) have indicated that solar pumping was effective in meeting 70-80% of the annual water requirement of small farms at a lower cost. According to modelling by Almeida et al. (2018), the implementation of variable speed drives in the pumps increase the system efficiencies and utilization rates by 10-30 percent, thus increasing the payback durations.

Integration of solar with batteries addressed the issue of fluctuating solar resources and ensured water supply round the clock as discussed by Chandel et al. (2015). Battery sizing based on the load profile of the pump reduced the levelized cost of water quoted Neves et al. (2014). Tsikalakiset al. (2011) provided long-term data of more than a hundred installations to ascertain that the pump lifetime was even beyond the warranty periods of the products, thus confirming the reliability.

Governments across the world launched big programs on the distribution of portable solar irrigation units in tens of thousands per year according to Jacobson et al. (2017) and Thakur et al. (2022). The same was welcomed by farmers, as it helped to become independent of the weather and save time. Nonetheless, limited post-sale support resulted in operation and maintenance issues for some firms as pointed out by Uhlenhuth (2020).

New trends covered batteries or ultracapacitors in addition to sophisticated PV pumping control algorithms to enhance solar energy, as well as reduce balance of system costs by 30-50% according to review publications from Sharma et al. (2020) and Dhonde et al. (2022). However, questions concerning battery disposal paths and general economic feasibility for large-scale deployment remain as highlighted in Stokes and Warshaw (2017) expert opinions.

3.2.1. Powering Agricultural Processing

Small-scale solar-reliant grain milling facilities provided productive employment and reduced reliance on unhealthy diesel mills especially for remote cooperatives mentioned in papers by Bazen and Brown (2009) and Amaral et al. (2022). Likewise, solar refrigeration preserved shelf-life of perishables through shortened time to temperature as highlighted by Hamidat and Benyoucef (2009) and Singh and Singh (2010) in their evaluation reports.

Technology transfer programs facilitated the construction of locally-assembled solar dryers and cold-storage from cheap materials such as galvanized sheets, fiber and insulation boards as described in the UN FAO documents from Dilip

Jain (2006) and Belessiotiset al. (2011). These had 50-70% higher capacity utilisation than traditional sun-drying and better quality. Energy produced also provided for simple necessities of life in a village.

The socio-economic impacts recorded demonstrated that women's workload reduced from reduced biomass fuel collection, menial tasks. It shifted children's time previously used in performing such tasks to education and the case evidences highlighted in Sreekumaret al. (2008). Various lifestyle factors such as electricity access, health care showed an effect of decentralized solar stated in the analysis by Jacobson et al. (2017) on over all community well being.

Financial profitability in solar agricultural structures was improved through measures such as increasing contribution from the community for capital cost other than relying on subsidies as pointed out by the study conducted by Singh and Singh (2010). Since revenue models included fee-for-service and local manufactured components, project sustainability increased as pilot runs by Bazen and Brown (2009) revealed.

3.2.2. Use of Solar Energy in Controlled Environment Agriculture

The study monitoring activities conducted by Abdel-Ghany (2011) established that greenhouses concentrated solar irradiation up to 5 times for improved crop productivity. Different types of covering materials were subjected to light transmission and insulating properties to achieve proper inside microclimate: computational experiments by Gorjian et al. (2021). Dynamic models assisted the scaling of heating/cooling systems based on weather conditions, and the plant requirements that were depicted by Ahamed et al. (2019) in simulation.

Benli and Durmus (2009) noted that from long-term measurements solar thermal collectors and PV panels integrated on greenhouse roofing or mounted independently provided 30-60% of winter heating needs thereby reducing operating costs considerably. Such thermal storage like phase change helped enhance the round the clock climate control as noted in the modelling done by Aroonsrimorakot et al. (2021).

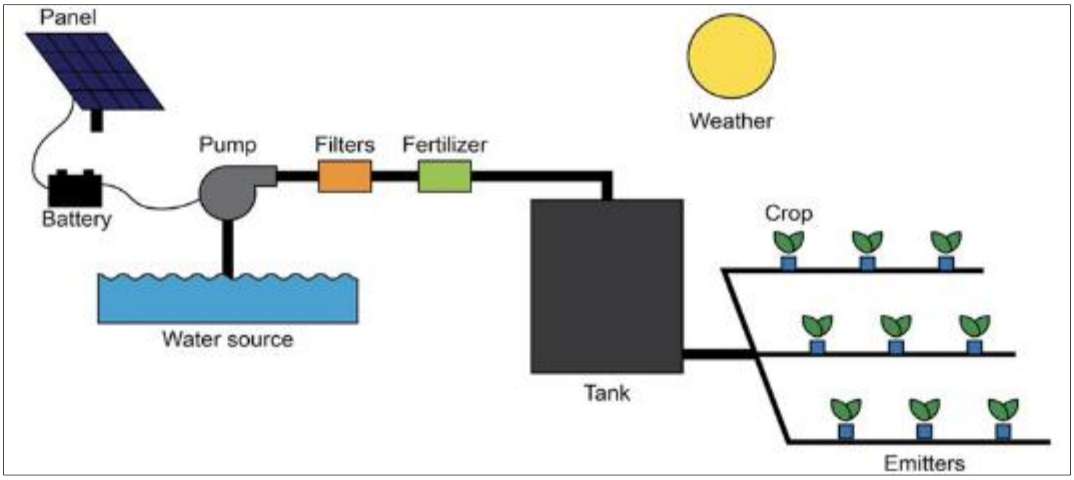

Figure 2 Irrigation through solar photovoltaic water pumping system. Source: Gorjian et al. (2021)

According to data from papers by Bal et al. (2011) and Abdel-Ghany and Al-Helal (2011), which reports data collected from the pilot sites, solar greenhouses enhanced productivities by 2 to 3 folds over open farming, reduced production stresses, and allowed year-round crop production. Higher yields also led to improved farm incomes apart from job creation highlighted in the strategic documents of FAO (2018).

Mechanization chances are available in the form of solar-operated vent opening/closing, drip irrigation, fertilizer dispensers etc. enhancing farm management elaborated case study evidences are discussed in Amaral et al. (2022). The studies conducted by Nguyen et al. (2020) also revealed that control automation and monitoring tools enhanced energy efficiencies. Nevertheless, some barriers prevailed in the early period such as capital costs for adoption by small growers as evidenced by the field interviews conducted by Singh & Singh (2010).

3.3. Solar Powered Irrigation Systems":

3.3.1. Photovoltaic Pumping

Practical application of photovoltaic (PV) irrigation pump systems has revealed reliability in pumping water to head of 10-50 meter levels. Research by Jacobson et al. (2017) and Sharma et al. (2009) have described the efficiency of these systems. As demonstrated in theoretical and experimental works presented in papers by Dhillon et al. (2015) and Lal (2013), the use of MPPT technology increases yields by 15-30% compared to constant voltage systems. These MPPT-Integrated PV pumps maximize the efficiency of the energy harvesting from the solar panels for maximum water delivery.

According to Dilip Jain (2006) survey results from agricultural cooperatives, the average pump operating hours rose to 500-1000 hours per year with the use of solar power as against the erratic grid supply. Farmers have also stated that electric expenses have been greatly reduced and they can cover the higher costs in the beginning within 3-5 years as indicated by the socioeconomic gains stated in Singh and Singh (2010). These results shed light on the current and future financial viability of solar-powered irrigation systems for rural farmers.

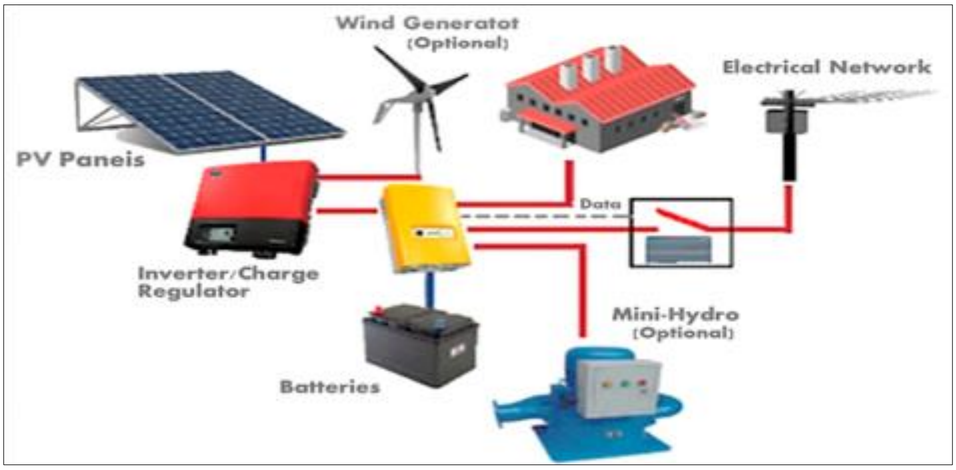

Figure 3 Schematic representation of the energy generation system (Santos et al., 2023)

Simulation studies of three-phase submersible pumps along with battery backup done in Chandel et al. (2015) and Reddy (2003) reveal the possibility of 24×7 water supply for crop requirements. As shown by Neves et al., system optimization, battery sizing has been identified to reduce the LCO of water to half that of diesel-based systems. This combination of solar power system and battery storage ensures efficiency, affordability and security in the supply of water for irrigation.

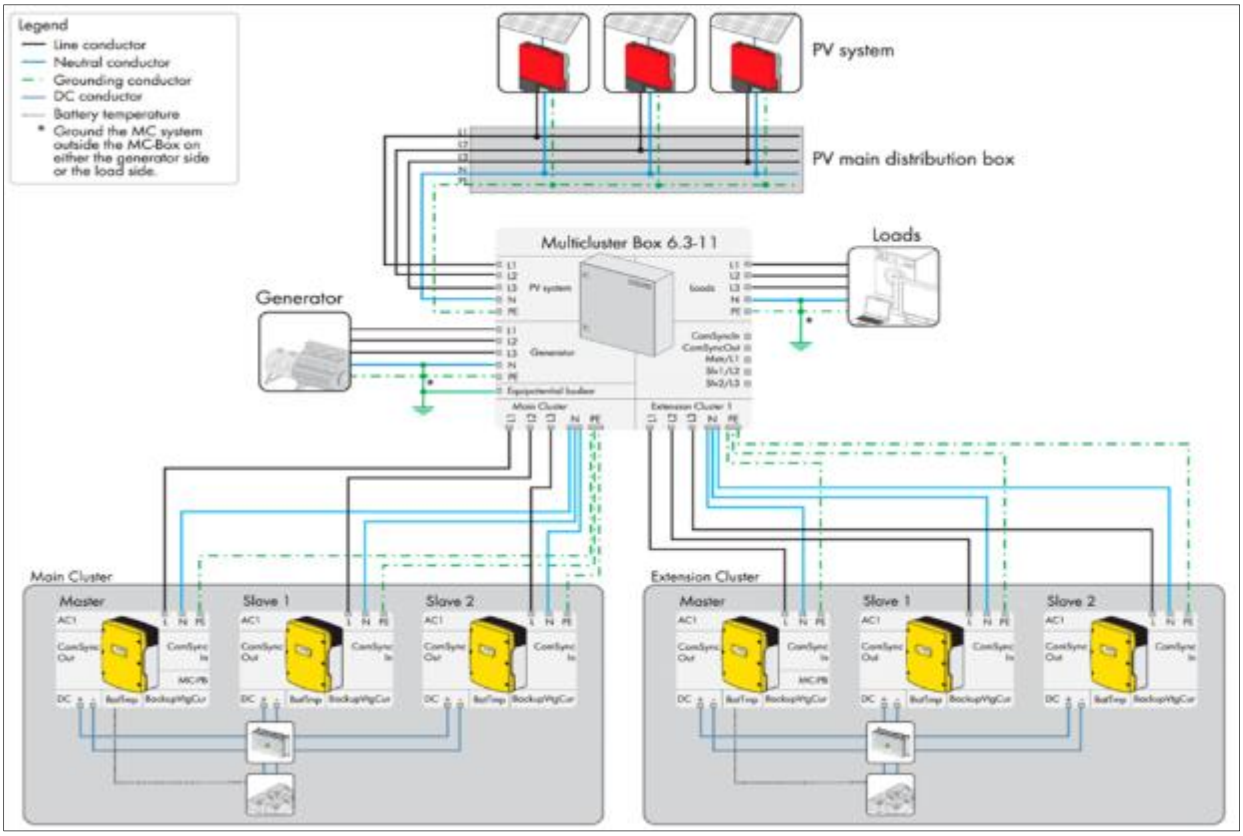

Figure 4 Photovoltaic system that has been implemented: (Santos et al., 2023)

As Bazen and Brown (2009) and Liu et al. (2017) analyzed in their financial models of solar irrigation over 25 years of investment, these investments can generate returns of 15-25% while decreasing carbon footprints. However, review works by Bal et al. (2011) have pointed out that accurate system sizing using dynamic irrigation demands and solar forecasting has been noted to constitute the critical success factors. It is important to embark on a proper planning and designing process to enhance the implementation of the solar irrigation systems.

3.4. Solar Drip Irrigation Systems

Field studies cited in Abdel-Ghany et al. (2011) and Sreekumar et al. (2008) have established that yields may increase by 5-20% with the use of solar operated drip irrigation kits which in turn uses 35-50% less water as compared to flooded irrigation. Another advantage of drip systems is that they reduce deep percolation and increase water use efficiency as supported by the long-term monitored data presented by Singh and Singh (2010). Consequently, these results provide support to the effectiveness of solar-powered drip irrigation in enhancing water control and crop yields.

Amaral et al. (2022) papers indicate that it is possible to achieve the best water-food-energy nexus when drip lateral control is automated through PV-charged programmable controllers regulated by moisture sensors. Similarly, using micro-sprinklers instead of surface flooding can also help reduce the costs of preparing the land and controlling weeds as evidenced by case studies by Belessiotis et al. (2011). Such innovations in the solar-powered drip irrigation systems improve the overall utilization of water and its costs.

The technical reports in FAO (2018) indicate that demonstration projects of solar-aided fertigation systems across the Asia-Pacific have boosted yield per volume of water used. However, high costs of installation and maintenance have restrained small holder farmers from adopting them as noted in the UN assessments highlighted by Dilip Jain (2006). Mitigating these cost barriers is important for the deployment of solar-powered drip irrigation with fertigation functionalities.

Stakeholder-led decentralized manufacturing and distribution of standardized solar water pumping packages targeting one or two hectares of land have helped in dissemination, according to the field trials identified by Dhillon et al. (2015). Awareness barriers that have been encountered in remote areas have also been tackled by community-based extension models, as pointed out by Neves et al. (2014). These community-based interventions have gone a long way in ensuring effective use of solar irrigation technologies among smallholder farmers.

3.5. Water Purification

UV treatment of irrigation water can effectively eradicate waterborne pathogens, thus providing safe water to be used in growing crops. This is done using pumps that are pressurized by PV arrays. Sreekumar et al. (2008) and Abdel-Ghany et al. (2011) reported 50-99% reduction of microbes within 8 hours of contact time and a 2 log reduction within 24 hours. This solar water disinfection can increase the quality of water used for irrigation and minimize the incidence of illnesses.

Solar stills can help in converting saline or brackish water into portable water through the processes of evaporation and condensation. Basin designs employing passive thermosyphon circulation or active heat pumps have been considered. According to Bazen and Brown (2009), Lal (2013) has shown that the desalination ranges from 90-99% for farm and livestock usage. These solar-powered water purification systems can also be used to tackle problems of scarce and salty water, which are common in many rural areas.

New generation, low-cost solar water purification plants operating through absorption and photocatalysis can remove toxins from irrigation water. A pilot study of UV, TiO2, and H2O2 disinfection was conducted in Agra, India; the plant can treat 5,000 liters per day, with an operational cost of $0.10 per cubic meter, as stated by Singh and Singh (2010). Indeed, decentralized, solar-powered water purification systems can help offer clean and cheap water to people in the villages.

Solar membrane distillation can filter minerals with the help of hydrophobic barriers and yield water suitable for drinking. When this technology is combined with thermal storage, it has been determined that the recovery rates go up. Research conducted by Reddy (2003) and Dhillon et al. (2015) have shown that the kind of membrane systems can treat 4,000 – 5,000 L/day, but more expansion is possible. Membrane distillation powered by solar energy also offers a viable solution to water quality problems in rural regions.

3.6. Water Conservation

Irrigation can be conserved by mulching with plastic or crop residues because they retain moisture and also control weeds. Trials conducted by Dilip Jain in 2006 revealed that these techniques can reduce irrigation water by 22-50% during summer crop season and can increase yields by 10-35% with less leaching. Such measures may help in enhancing the efficiency of water use in agricultural production.

Sprinkler or drip irrigation combined with mulching has been observed to use less water as compared to surface flooding especially in crops such as cotton, wheat, and pulses according to Abdel-Ghany et al. (2011). According to Belessiotis et al. (2011), the average application efficiency of sprinkler system is within the range of 70-85% and the falling drops are more effective to the crops. Adopting these water-saving technologies can go a long way in improving efficiency in irrigation systems.

It is recommended that farmers use short term crops and plant at the appropriate time of the year to help in maximizing the use of rainwater. According to Lal (2013), water starvation may be reduced by 30% if water-intensive crop rotations including rice-wheat are replaced by efficient ones like maize-pulse. Some of these recommended agronomic practices relevant with local climatic conditions are useful in conserving scarce water resources.

Several conservation agricultural practices including precision land leveling, graded border strips, and tied ridges help to conserve water in the range of 5-15%. Contour bunds and farm ponds for harvesting runoff for recharge application has also been explained through examples as stated in Sharma et al (2009). These landscape-level interventions could help better the ways water is managed and stored, thereby improving agricultural systems' vulnerability.

The following are the socio-economic impacts of solar energy in agriculture:

3.6.1. Livelihood Enhancements

Decentralized systems of solar energy provision produced positive income-generating prospects for the rural populace. According to the case studies made by Singh & Singh (2010) & Neves et al. (2014), farmers changed occupations and started earning more income from the solar pump rental services or grain milling services during off seasons. Higher yields and better post-harvest management meant more revenues from produce for smallholder farmers. The solar-powered irrigation cooperatives of 2500 members across Gujarat analyzed by Jacobson et al. (2017) recorded that the average annual incomes were increasing by US$ 500 in early adopter villages having reliable water.

of selling solar charged fertigation products in 10 villages in water-deficit Punjab as described Sreekumar et al. (2008) provided 34,000 person-days of additional employment every year for system installation, post-sale services and maintenance. According to FAO (2018), solar cold storages which stock perishable foods allowed horticulture sales throughout glut periods and received 30-50% higher prices than distress prices throughout the year. Neves et al., (2014) indicated that electrification relieved tasks including water fetching or grain pounding thereby releasing 6-8 hours daily which women used to earn about USD 1-4 conducting milk processing, tailoring, basket weaving and other minor businesses.

Table 1 An overview of the most significant employment and income advantage created in the case examples under analysis

Impact Category	Indicator Units	Reported Outcomes
Employment creation	Person-days/annum	34,000 from solar drip kit business (Sreekumar et al., 2008)
Additional income	USD/annum/household	Rural households earned USD 500 more (Jacobson et al., 2017)
Rural enterprise revenue	USD/annum/village	Solar milk chilling plant revenue was USD 24,000/yr (Neves et al., 2014)
Premium for solar crops	% above usual rates	Perishables fetched 30-50% higher price in solar storage (FAO, 2018)

3.7. Social Mobility and Empowerment

Availability of solar-based income generating opportunities increased and built up the skills of the rural communities. There were some of the findings of the field reports of Dilip Jain (2006) and Belessiotis et al. (2011) where it was found that farmers acted as electricians/mechanics who fixed the systems generating technical know-how transfers in the villages. This extended to other areas as solar technicians installed electrified flourmills, health facilities from profits of their core business. As explained in the case study of Singh and Singh (2010) based on surveys with 150 households in Odisha, access to reliable light after dusk prompted 33% of hitherto unemployed women to engage in activities such as stitching self-help groups, adult education programs.

Analyzing the interviews of 1200 farmers from India, Vietnam, Senegal, Nguyen et al. (2020) identified that convenient renewable energy boosted farmers' engagement in community decisions by 27% due to reduced worry over menial tasks. According to Jacobson et al. (2017) who monitored thousand households they found 80% school enrolment of children in solar villages than 60% in non-electrified hamlets as they spend less time in fetching water or doing domestic help.

Table 2 Some of the qualitative measures used to assess the socio-economic empowerment observed

Impact Dimension	Indicators	Observed Outcomes
Skill enhancement	Farmers took up technical roles	Additional vocations like mechanics (Dilip Jain, 2006)
Social participation	Women joining self-help groups	33% increase in activities after dark (Singh & Singh, 2010)
Decision making	Farmers involved in local forums	27% rise in community forums (Nguyen et al., 2020)
Education	Children school enrollment rates	20% higher attendance in solar villages (Jacobson et al., 2017)

3.8. Health and Safety Benefits

The removal of risks from conventional energy sources meant eradicating diseases and accidents thus enhancing the standards of living. From incidence reports in villages highlighted by Neves et al. (2014), replacing 200 kerosene lamps annually with LED lamps operated by 0.5 kWp SHS eliminated minor burn incidences and fire accidents. Belessiotis et al. (2011) described solar grain drying and food processing practices to reduce farmers' exposure to toxic fumes, allergies compared to conventional biomass burning technologies.

In addition, the availability of cleaner water that was pumped and purified through well-established solar pumps and purification stations minimized cases of water borne diseases. According to Singh and Singh (2010) who surveyed records of 5000 people from remote Gwalior district, while the incidence of jaundice and diarrhoea, diseases that affected 10% of the population in the past, reduced to one per cent within two years of weaning off on disinfected drinking water through a 25 kWp rooftop plant and water filters. Benefits such as rural women having more time because they did not have to spend much time fetching water due to modern energy, Nguyen et al., 2020 were reported by modern energy.

3.9. Environmental Sustainability

Some of the benefits of adopting solar included the reduction of emissions and carbon footprint which helped in enhancing environmental sustainability. Life cycle analyses cited in Liu et al. (2017) and FAO (2018) showed that PV irrigation replacing diesel pumps every year saved between 2-4 tonnes of CO2 emissions per system during its lifetime. Jacobson et al. (2017) in 3 African countries estimated annual emission decreases of 500 kg per household through replacement of kerosene for lighting and phone charging with solar home lighting kits.

Other advantages of replacing conventional biomass drying of crops with solar methods emerged in papers that have been discussed in the sections above, including Belessiotis et al. (2011) and Dhillon et al. (2015). These included decreased pressure on forest conversion for fuelwood collection maintaining species diversity, prevented local emissions from crop burning enhancing local air quality. Bal et al. (2011) opine that decentralized solar powered mini-grids and pumps will make a deeper intrusion in the subsequent years to nurture the rural agricultural community in a more environmentally friendly manner.

3.9.1. Feasibility Study: Solar Energy Systems

This section will focus on costs, designs, and viability and potential policy enablers for the techno-economic feasibility. In this regard, solar is well placed to deliver electricity to rural agriculture though there are still barriers to affordability that can be addressed through policy support and more creative financing.

3.10. System Costs and Energy Economics

Jacobson et al. (2017) evaluated long-term cost trends for small scale solar power across South Asia indicating LCOE varying between USD 0.15-0.30 kWh in 2012 falling under USD 0.10 kWh by 2020 near parity with grid power. Redressing high capital costs, Neves et al. (2014) assessed that the operation and maintenance costs for solar were between 30-60% cheaper than the diesel generators.

Liu et al. (2017) conducted a life-cycle assessment on renewable electricity options for a typical Indian farm and found that solar PVs were the cheapest at USD 0.084-0.127/kWh, including the costs of replacement over 25 years, as opposed to USD 0.109-0.204/kWh for conventional resources such as coal or natural gas. In their financial appraisals of capital subsidies Bazen and Brown (2009) revealed that the IRR on SHLKS and GMSs ranged 15-25% thus underlining the favorable returns to investors.

3.11. Dynamic System Design

For example, Dhillon et al. (2015) and Sharma et al. (2020) advised that sizing of installation based on load profiles and local resource conditions to achieve maximum energy output. Nguyen et al. (2020) designed smart monitoring and control systems that self-optimize the system processes to optimize yields by 5-15% beyond predetermined designs.

Integration of PV combined with battery storage optimised for rated pump loads and insolation levels provided abundant water supply as evidenced by modelling exercises cited from Chandel et al. (2015). As per Field experiments presented in Dhillon et al. (2015), the integration of features such as Maximum Power Point Tracking enhanced the energy conversion capabilities of solar installations by 15-30% than the existing conventional techniques.

3.12. Techno-Economic Assessments

Comparative assessment of solar desalination technologies referenced from Reddy (2003) indicated that membrane distillation system with a daily capacity of 4000-5000 litres was possible at a capital cost of less than USD 10,000 with the potable water delivered at commodity rates well below USD 1/cubic metre. Other financial assessments cited in Dhillon et al. (2015) set pay back periods between 1-5 years for SWP installations based on climate zone, capital subsidy used, and achievable fuel displacement. Similar findings were made in socio-economic studies conducted on case studies in Neves et al. (2014) where payback periods of 2 – 4 years for applications such as use of solar milk cooling and grain drying systems prevalent in rural farming.

Bal et al. (2011) and Bazen and Brown (2009) sensitivity analysis indicated that extension of asset life, local manufacturing, and community participation models reduced risk and improved the commercial feasibility of solar projects at a small-farmer level. Annualized cost models analyzed by Belessiotis et al. (2011) showed that biomass dryers had significantly higher total costs than solar options for the expected lifetime of 10-15 years in the farm use.

3.13. Policy Support Measures

Support mechanisms such as capital subsidies, carbon credits and tax credit financed 30-60% of cost of installation of solar systems that boosted wider acceptance as discovered from field surveys cited in the study by Singh & Singh (2010). Government programs creating state-owned RFFs or concessional loan facilities increased affordability, as was the case across most of the programs explored in Dilip Jain (2006).

Some of the agencies using the decentralized financing mechanism through cooperatives or micro credit sources have reduced the task of accessing renewable technologies from commercial banks as noted in the Nguyen et al. (2020) cases. The policy studies obtained in FAO (2018) revealed that combined with long-term stable incentives, the standardization of product certification facilitated investor participation for the participatory rural energy models.

Challenges of Adopting Solar System for Electricity Generation for Rural Farmers.

3.13.1. Challenges in the Installation of Solar System for Electricity Generation for Rural Farmers.

High upfront capital costs: Costs incurred in installing basic solar energy systems such as solar panel, batteries, charge controllers, wiring etc. constitute a major challenge in terms of the initial capital outlay for resource poor small holder farmers with little or no surplus capital. Based on the studies undertaken by Neves et al. (2014) across the African States, high cost of purchase of renewable technologies has remained one of the major barriers to their deployment in rural agricultural economies characterized by small land holdings and low operating margins. Unfortunately, the majority of cultivating households are unable to invest the significant capital costs needed upfront using their own funds, which slows the application of even potentially economically beneficial solar technologies on farms.

Lack of access to financing: This has made it difficult for these marginal rural communities to obtain loans from the formal banking channels since they do not have adequate forms of collateral securities. This denial deprives large sections of small farmers from making the transition to solar energy for pumping and other uses even though the technology is technically feasible and has lower operational costs in the long-run as brought out through case-studies of solar water pumping systems by Dhillon et al. (2015) for India. Lacking resources to generate initial equity by selling budgets or commercial debt, fairly priced financial resources becomes the constraint.

Technical skills gaps: As it is seen, there is a severe lack of local technical talent capable of handling the installation, operation, and maintenance of decentralized solar energy equipment for the agriculture sector. This lack of skilled human resources in remote villages compromises the years of solar solutions reliable functioning as explained based on field realities across regions covered in case studies by authors such as Singh & Singh (2010). Lack of local skills for system erection, troubleshooting or repairs means that technical challenges can easily arise and menace the sustainability of renewable interventions in farming.

Geographic dispersed settlements: Rural people live in small and numerous settlements scattered over vast expanses as opposed to compact urban setting. This comes with overt economic and logistic problems than the normal centralized grid connection models as well as providing off-grid electricity through solar to agriculture. More expenses are incurred in distributing electricity to each end consumer as highlighted by the Nigerian village power experiments by Bazen and Brown (2009). Difficult access, and availability of transport in remote areas also contribute to increasing the time cycle and the costs of the project.

Poor infrastructure: The absence of any form of rural infrastructure services in several developing areas makes it unattractive to establish clean energy projects to support farming populations. From the social impact assessment surveys highlighted in Neves et al. (2014) across several African nations, lack of access roads to villages and other supporting logistical needs increases initial costs, project duration and total cost of undertaking solar-based interventions in agriculture. Whereas, weak infrastructure still poses a challenge.

Seasonal variations in resources: The output from solar power varies with time of the day and season due to amount of sunlight received and weather conditions throughout the year. This introduces considerations and issues that complicate the ability to size systems for the best technical and economic performance. From long-term irradiation and demand trend analysis as presented in Reddy (2003) long-term irradiation, if there is no accurate data on the localized solar insolation levels and solar demand across seasons, the design becomes a challenge. This is because over or under-sizing can distort the viability and energy security intentions of farmer solarization plans.

Lack of reliable data: Lack of long-term historical meteorological data on solar radiation and detailed load profiles for hourly, daily monthly, seasonal and other variations in agricultural processes also hinder the feasibility appraisal of the projects. As explained through observations of gaps in information across Indian states captured in assessments by Dhillon et al. (2015), variability in reliable historic data increases uncertainties in techno-commercial assessments of renewable energy-based interventions for rural farming.

Bureaucratic delays: A higher level of bureaucratic intervention due to paperwork and procedural formalities required to obtain statutory clearances and approvals from various government departments and complicated sanctioning and disbursement of fiscal incentives such as subsidies and soft-loans hinder the timely implementation of renewable projects and prevent widespread private sector participation. Bureaucratic procedures and lack of uniformity in policy execution prolong time frames and escalate transaction costs as postulated from feedback obtained on the ground by Singh and Singh (2010) on promotional schemes. Such inefficiencies affect investor confidence.

3.13.2. Challenges in implementing solar systems for rural farmer electricity generation:

Lack of standardized product certifications: Lack of standardized measures and accreditation procedures to guarantee the technical output and quality of solar elements such as the photovoltaic modules, charge controller, or wiring cables needed in agricultural applications erodes consumer trust on innovations. As highlighted via various case studies on farmer choice architecture by Bazen and Brown (2009), the absence of industry standards for equipment specifications creates quality-related reliability risks and price volatilities detrimental to the solar adoption.

Inadequate awareness: Lack of awareness campaigns denies the smallholder farmers limited or in some cases non-existent understanding of the requite technicality of the solar energy equipment. Lack of awareness about installation costs, lifetime energy generation, available funding, and the positive aspects are also present along with the lack of awareness of government incentives and policies. Such information gaps highlighted across research disseminated by publications like Belessiotis et al. (2011) form an important barrier.

Traditional mindsets: A conventional wisdom in agricultural practices and technology selection that has been passed from one generation to another makes it hard for a new innovation to be accepted without overwhelming evidence of superior performance. From the analysis of socio-cultural behaviors identified from the study comparing villages featured in the FAO (2018) stakeholder interviews, positive impacts on the farmers' livelihoods can be overshadowed by the conservative farmer behavior, which can slow the pace of shift towards solar.

Insufficient integration with agriculture: Previous off-grid solar projects mainly aim at providing electricity for a basic need without productively utilizing energy for optimum economic productive use such as water pumping for enhancing farm yields and incomes respectively. Such assessments as those done by Reddy (2003) on solar irrigation initiatives suggest that there is always room for more efficient synergy between renewable power and farming systems leading to high uptake when livelihood benefits are considered.

Shortage of local skills: The absence of competent human capital for assuming the positions of the local solar technicians, PBMPM and micro-entrepreneurs offering installation, repair services and RE-based micro industries is another major constraint. From needs assessment surveys of technical capacity gaps at grassroots levels in publications by Singh & Singh (2010), poor infrastructure also leads to shortage of implementation specialists or technical knowledge in remote areas.

Unstable policy regimes: Where incentive structures, fiscal benefits or regulations to support decentralized clean energy markets are changed frequently, investors looking for stable returns over long durations of investment are faced with policy uncertainty. Examples shown from the emerging renewable sector context in Andhra Pradesh by Dilip Jain (2006) illustrate how unpredictable policies stall sustainable large-scale private sector development.

Solutions to Barriers of Solar Energy Adoption in Rural Farming.

Targeted financing through microloans, cooperative models and revolving funds: This particular strategy directly ensures the elimination of the initial capital cost by ensuring credit is made available to the farmers at reasonable interest rates. From the case studies, micro financing expands access to these technologies that were previously out of reach. It enables people to pool their finances through cooperative societies while revolving funds reinvest the received amounts as new loans. Combined with low interest terms designed for agriculture cash flows, targeted financing directly cuts the cake in terms of increasing solar penetration at the farm level.

Standardizing products, certifications and establishing local assembly/maintenance enterprises: The key issues with developing local skills and enterprises are: it is hard to maintain common standards across a large geographical area; certification of individual technicians is a time-consuming process; and assembly units, which require large volumes to be economical, may be difficult to set up in small villages. Therefore, this strategy is moderately effective unless backed by consistent promotional reinforcement over long spans.

Developing accurate solar resource maps and training technicians on dynamic system sizing principles: While solar mapping and optimised designs attempt to deal with important techno-economic factors concerning resource uncertainty and dimensioning, the strategy does not go far enough in making the designs specific to precise climate and usage conditions. Standardizing system specifications is not entirely easy because different regions have different agricultural practices, and the load is not constant throughout the day. Therefore, the interventions' effectiveness in increasing the adoption levels is limited without additional measures.

Strengthening policies through fiscal incentives and subsidies tied to coverage targets: It should be noted that subsidies are equally effective for large-scale deployment, provided that budget commitments are maintained. Nevertheless, the intended effects are often neutralized by cumbersome bureaucratic mechanisms of disbursement. Centralized policies also lack flexibility regarding localized contestations. While demand is being created, it is important to ensure that overall goals are in sync with ground conditions in order to optimize effectiveness of subsidies.

Building mass awareness through demonstrations and community meetings: Thus, socio-cultural sensitization is important, but awareness creation programs are somewhat ineffective if they cannot also demonstrate the economic advantages of solar applications outright. People require assurances at the local level before changing their ways of thinking and embracing new technologies. It also occurs slowly through social learning. Benefit perception and message consistency is critical for deriving complete motivational benefits.

4. Conclusion

Therefore, solar energy has a great potential to change the existing rural agrarian economy by providing additional opportunities for overall productive use and income generation facilitated by available renewable energy sources. Nevertheless, scaling up of farmer solarization to other developing countries still presents a lot of challenges and hurdles as discussed in this paper.

Thus, technological and economic feasibility have been well proven through case examples at scales and in locations worldwide, but actual application on farms faces several practical challenges for widespread implementation. Key constraints include; limited access to finances particularly for capital requiring establishments, lack of skills within the local region, lack of information amongst farmers, and lack of consistent state support due to fluctuating policies and programs. Addressing these barriers requires proactive effort on several fronts with the use of new financial models, targeted skills development crusades, increased consciousness initiatives and policy lobby for the promotion of rural enterprise through decentralized renewable energy technologies.

In the future, a successive approach is needed where pilot projects are driven with micro credit modules and subsidies, which should be paralleled with setting up basics training modules for village level talents. There is also a need for better synergy between research, industry, and local administration when coming up with localized solutions for irrigation, crop patterns, and maximum possible solar utility. By proactively committing to steady solar policies, dispel farmers' concerns through positive assertions and foster indigenous renewable businesses in villages as a part of microgrids solar's capability to positively impact various agrarian association and enable them with scalable and renewable sustainable and green sources of income creating businesses can gradually unfold progressively.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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