POLICY PAPER

130

Multiple Uses of Solar Energy in Agriculture and Agro-Processing

NATIONAL ACADEMY OF AGRICULTURAL SCIENCES, NEW DELHI

September 2024

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CITATION : NAAS 2024. Multiple Uses of Solar Energy in Agriculture and Agro-Processing. Policy Paper No. 130, National Academy of Agricultural Sciences, New Delhi: 16 pp.

Published by Executive Director on behalf of
NATIONAL ACADEMY OF AGRICULTURAL SCIENCES
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Preface

The rapid agricultural growth in India has led to rise in greenhouse gas (GHG) emissions and it contributes about 13.44% of the country's total GHG emissions. Renewable energy, particularly solar power, can play a pivotal role in reducing reliance on conventional energy sources supporting India's commitment to achieving net-zero emissions by 2070. India has set an ambitious target of generating 500 GW of renewable energy by 2030, a crucial step towards sustainable energy independence.

Solar energy is widely used for open sun drying of crops, grains, and semi-processed foods. Technological advancements have enabled its use in more concentrated forms for heating, cooling, steam generation, and electricity production. Dairy, poultry, and modern piggery farms, especially in colder climates, have substantial water and air heating needs that can be met using solar systems. The adoption of solar energy, whether independently or in hybrid modes, can significantly reduce carbon dioxide emissions by harnessing the sun's power besides cost savings for farmers. Solar irrigation pumps have emerged as a promising technology to expand irrigation access, reduce dependence on fossil fuels, and are being rapidly deployed through various government schemes. These systems also help mitigate GHG emissions in agriculture.

Agri-voltaics, a novel green initiative, offers a true synergy between food and energy production, reducing energy demand, lowering carbon emissions, and addressing climate change and economic inequalities. It extends the application of solar photo-voltaic (PV) technology to various agricultural operations. Solar-powered agriculture delivers economic, environmental, and social benefits, including reduced reliance on fossil fuels, lower GHG emissions, improved energy security, and increased farmer incomes.

This policy paper is the outcome of a brainstorming session and provides an in-depth analysis of the current status, prospects, and future directions for solar energy applications in Indian agriculture. The recommendations from the discussion will serve as a blueprint for carbon offset in the agricultural sector. I firmly believe India will emerge as a global leader in establishing a solar-based economy.

The Academy gratefully acknowledges the efforts of late Dr. N.S.L. Srivastava, Former Assistant Director General (Engineering), ICAR, and Dr. C.R. Mehta, Director, ICAR-CIAE, for synthesizing and convening the session. My sincere appreciation to the Academy's Editors, Dr. V.K. Baranwal and Dr. R.K. Jain, for their dedicated efforts in bringing this policy paper to fruition. I trust this publication will help in shaping appropriate policy agenda to encourage carbon mitigation through the application of solar energy in agriculture.

September 2024
New Delhi

(Himanshu Pathak)
President, NAAS

Multiple Uses of Solar Energy in Agriculture and Agro-Processing

1. PREAMBLE

There has been considerable increase in energy consumption in the agriculture sector in India for various operations, which is responsible for the release of greenhouse gas emissions (GHGs) into the atmosphere. It has been estimated that the agriculture sector contributes about 13.44% of the total GHG emissions (NITI Aayog, 2024) and one of the options to reduce these GHG emissions is to increase the use of solar energy in agriculture so as to achieve India's commitment for the net zero emissions target by 2070. There is huge potential to use solar energy for diversified agricultural operations which is an effective way to not only meet India's carbon targets, but also to create opportunities for livelihood and diversify incomes in rural areas.

The government has launched different schemes such as "*Kisan Urja Suraksha Evam Utthan Mahabhiyan* (*KUSUM*) *Yojana*", "*Saur Krushi Vahini Yojana* (*SKVY*)", "*Sourya Jalnidhi*", "*Atal Solar Krishi Yojna*" etc. in different states to promote the expansion of solar power in India's agricultural system. The specific uses of solar energy for specific regions have been investigated. The research and development organizations have come out with different designs of solar dryers of different capacities meeting the specific requirements of crop commodities. The solar pump segment also has witnessed significant development in the recent past owing to the government's focus on clean energy transition. Various efforts have been made to develop solar powered tractors, sprayers, weeders and other small equipment to carry out various agricultural operations.

With this backdrop, National Academy of Agricultural Sciences organized a brain-storming session on "Multiple Uses of Solar Energy in Agriculture and Agro-Processing" in which the application areas of solar energy in the agriculture sector and their constraints were discussed. Policy options and researchable issues emanated from the deliberations have been brought out in this policy paper.

2. STATUS OF SOLAR ENERGY

Sun radiation gives energy between 900-1300 W/m^2 with an average of about 1000 W/m^2 on the surface of the earth. It is estimated that about 5000 trillion kWh/year of solar energy is incident over India's land area with most parts receiving 4-7 kWh/m^2/day. The National Solar Mission was launched in 2010 with special emphasis on solar photo-voltaic (PV) installation to promote and increase solar power in different sectors. India ranks 4th globally in installed capacity of renewable energy as well as in solar power capacity (REN21, 2022). Solar energy contributes the maximum (41%) towards total renewable energy regeneration in India. Total solar power installation capacity in the country has increased from 1.2 GW in 2014-15 to 12.8 GW in 2022-23 with the cumulative installation of 74.3 GW as on January 2024. These installations include ground-mounted grid connected solar, roof-top solar and off-grid solar power plants. National Institute of Solar Energy (NISE), Gurugram has assessed the country's solar potential of about 748 GW assuming 3% of the waste-land area to be covered by solar PV module (Ministry of New and Renewable Energy, 2024). There are three routes of converting sun-shine into different forms of energy: (i) by using photo-voltaic panels through which solar energy is converted into electricity and is used for lighting, heating, cooling and running different types of machines/appliances; (ii) by using solar heaters through which sunshine is converted into heat energy using solar collectors both flat and concentrating type and is used for thermal application; and (iii) by using thermo-couples through which heat energy is converted into electricity and is used for operating different appliances and machines.

3. APPLICATIONS OF SOLAR ENERGY IN AGRICULTURE AND AGRO-PROCESSING

Solar energy can be used either alone or in hybrid mode for different operations and its applications in agriculture and agro-processing sectors are summarized below:

3.1 Solar water pumping

Agriculture is a water intensive enterprise and lifting water from both surface and sub-surface sources consumes considerable energy. Most of the energy for water lifting is supplied using fossil fuel besides electricity leading to environmental degradation and carbon emission. Also, the power shortages and increasing diesel fuel costs affect agricultural practices. Emerging technologies include solar PV energy conversion for water pumping (Sontake and Kalamkar, 2016).

Solar water pumping system is essentially an electric pump system in which the electricity for running the pump is generated by PV panels and can be installed as a stand-alone system. The main advantage of solar water pumping is that it reduces its dependence on electricity from grid power or diesel engines. Once installed, there is no recurring cost of electricity or fuel. Besides saving in the cost of electricity or diesel, there are environmental benefits also. When one litre of diesel fuel is used, approximately 2.7 kg of CO_2 is released into the atmosphere which is saved in solar water pumping system.

The different types of available solar water pumping systems are categorized based on the energy storage, form of electric power input, types of pumps and tracking of power source. The solar water pumps based on the energy storage include with or without battery coupled/backup. The battery coupled system ensures water pumping even during low light periods, cloudy days and during night. However, they increase the cost and complexity and can reduce the overall efficiency of the system as the batteries dictate the operating voltage rather than the PV panels. Hence, most of agricultural water pumps are stand-alone without a battery backup system. The current generated by solar PV panels is DC and can be converted into AC by an inverter. Accordingly, the solar water pump can be classified as DC or AC-driven. In agriculture, most of the pumps installed are DC due to their low cost. Due to technological advancements, the conventional DC motor is replaced with a permanent brushless DC motor (PMBLDC) due to its high efficiency, silent operation, compact size, high reliability, and low maintenance requirement. The types of pumps are decided by the location of installation with respect to the water level and they include surface mount or submersible. The submersible pumps have several merits over surface mounts such as high efficiency, no cavitation, easy installation etc.

The performance of solar water pumps is governed by different parameters such as solar irradiation, size and type of system, water lifting head, operating pressure head etc. The size of PV solar water pump is very crucial to apply the right amount of water at a given time for agricultural purpose. The designed irrigation network and water head available for irrigation should be considered for determination of the size of the water pump (Rawat *et al*., 2016). Many researchers reviewed the various performance parameters of solar water pumps (Sontake and Kalamkar, 2016; Santra, 2021). The performance of these PV water pumps is analysed in terms of (a) head-discharge characteristics of solar PV pumping system under different solar irradiations (b) efficiency of the PV system (c) capacity utilization factor and (d) economics of solar PV pumping system.

Until 2019, the solar water pumps were off-grid standalone system. Hence, the installed solar panel was utilized only at the time of irrigation which was not economically viable. As per Keskar *et al*. (2023), there was about 300–400 kWh/month of unutilized solar energy per pumping system, representing up to 95% of total energy generation. During the period, the after-sales and service network of these solar water pump manufacturers were limited to urban areas. As a result, the operation and maintenance of the solar water pump became a more cumbersome process for remote installations. In some investigations, theft or damage of costly solar panels was also reported.

Presently, about 8.0 million diesel water pumps out of total of about 30.0 million water pumps are being used for irrigation. It is projected that by the time targets of PM-KUSUM scheme are met, there would be saving of about 1.38 billion litre of diesel per year. Similarly, about 3.726 million tonne/year of CO_2 emission in the atmosphere will be reduced, which will help in minimizing environmental pollution besides global warming.

Solar water pumping systems have shown significant advancements from 2019 with introduction of Government initiatives. The performance, reliability and overall efficiency of the system for agriculture are continually improving with the use of advanced electronic systems. The first-generation solar water pumping systems used centrifugal pumps driven by DC/AC motors with hydraulic efficiencies varying from 25%

to 35% whereas the pumping systems at present use positive displacement pumps and progressing cavity pumps or diaphragm pumps with high hydraulic efficiencies of 70%. Maximum power point tracking (MPPT) technology is also being used to optimize the performance.

The carbon footprint of 0.75 kW solar PV pumping system was estimated as 0.009 kg CO_{2e} ha.mm^{-1} as compared to 1.214 kg CO_{2e} ha.mm^{-1} for electric pumps and 0.382 kg CO_{2e} ha.mm^{-1} for diesel operated pumps (Santra, 2021). Installation of solar water pumps gained pace in the recent past due to government policies. However, the higher share of unutilized solar energy provides a significant opportunity to use the energy for non-pumping purposes in agriculture such as operation of stationary equipment.

3.2 Solar energy for drying of high value crops, vegetables, fruits and agro-products

The application of solar energy is the most ubiquitous for removing moisture from different agro-products by mankind since ancient times. It is the simplest, most common and the least expensive technique to dry crops, fruits and other agro-products in open sunshine. The disadvantages of this method are that it takes long time and the material is subject to damage by birds, rodents, wind, rain and contamination by wind-blown dust and dirt. To improve the method, conventional fossil fuel and electrical energy based systems were employed leading to increase in CO_2 emission. The increase of CO_2 emission depends on products being dried and system being employed and varied from 17 to 910 kg of CO_2 per kg of product. The use of solar energy was a better replacement for the conventional energy for drying operation.

It was observed that use of the solar dryer for drying agro-products would save conventional fossil fuel and electricity up to 80%. Different types and sizes of solar dryers have been designed and developed by R&D organizations, educational institutions and private firms, meeting the specific requirements of fruits, vegetables, flowers, fish, medicinal and aromatic plants and other high value agro-products. These dryers can be classified as: (i) direct dryer in which the product is heated by direct solar radiation; (ii) indirect dryer in which air heated from solar energy is used for drying of products inside the chamber; and (iii) combined type dryer in which the product is dried, both, by direct radiation and by heated moving air. Most of the dryers use thermal energy converted from solar irradiation through different types of collectors or concentrators. The types of collectors used in the dryer are flat-plate collectors, parabolic concentrating collectors, and parabolic cylinders. The non-concentrating collector includes solar PV dryers.

The heat transfer mode in the solar thermal dryer is a combination of heat convection from the solar thermal dryer (drying fluid) to the drying materials and heat conduction from the surfaces of the drying chamber to the drying materials. The temperature in the most of solar thermal dryers for drying a given product is regulated by the solar collector design. The surface design of the collector is the crucial parameter to control the temperature. Some designs having natural convection are equipped with the chimney to accelerate the airflow inside the chamber through buoyancy force. Another design uses a fan fixed to the solar thermal dryer to circulate and regulate the velocity of the drying air. The earlier design of dryers was mainly cabinet type. These designs of varying capacities have been investigated at limited scale for different agricultural products such as fruits and vegetables, medicinal plants, dairy products etc. The overall efficiency of flat-plate solar collectors was reported to vary from 25 to 50% (Kamran, 2021). Different configurations of solar collectors and drying chambers have been incorporated to increase the overall performance specific to products and regions. These include evacuation tubes or air ducts, solar tracking, different types of insulation materials (Saikia *et al*., 2022), and surface glaze (Sethi *et al*., 2021).

Later on, the demand of high capacities for industrial scale has raised further scope to develop cost effective solar dryers. Hence, the function of the solar collector was integrated in a greenhouse to develop a high-capacity large scale greenhouse solar dryer. Efforts have been made to utilize an existing greenhouse for drying purpose. However, their transferability into a greenhouse solar dryer still needs more investigation. Some issues in using greenhouse as a dryer include high heat retention, vapour condensation and light transmittance air flow pattern. Compared to a solar cabinet dryer, a good design greenhouse solar dryer has better control and uniformity in airflow during drying, promising for large-scale drying. Overall, greenhouse solar dryers are aimed for low temperature drying at commercial scale. The earlier design of green-house solar dryers has limitation to operate when solar radiation is deficient. Hence, researchers have designed some external auxiliary heating unit to supplement deficit energy to greenhouse dryer through biomass-based heating system (Sethi and Dhiman, 2020). These types of hybrid solar dryers have various advantages like lower drying time, improved drying efficiency, faster drying rate and low carbon emission for drying of high moisture crops. These dryers mitigate about 28–35 kg of CO_2 annually, however CO_2 emission was more in the case of active mode than the passive mode (Prakash *et al*., 2016) The application of solar PV energy into dryer was carried out to improve the efficiency of the solar collector, and supplement the electrical energy to other components of the drying system for further reduction of CO_2 emission.

In India, many firms are manufacturing different types of solar dryers, however, they are still costly. Some firms are also offering end to end solution including the buyback policy of dried products. There is a need to compile information of all types and sizes of such dryers and standardize the size and design for different regions and encourage more numbers of manufacturers and start-ups for wider adoption. The life cycle analysis needs to be carried out for net carbon emission during the drying of given products. A pilot scheme could be initiated to provide such dryers in selected villages by providing financial incentives to the farmers or village entrepreneurs for drying of perishable and semi-perishable agro-products. Based on the techno-economic evaluation, the scheme could be up-scaled to other regions. This will help in reducing wastage of agro-products, improve the quality of products, gives better returns to the farmers due to improved quality of products and reduction in CO_2 emission.

3.3 Solar greenhouse and covered crop cultivation

The greenhouse is now better understood as a system of controlled environment agriculture (CEA), with a precise control of air, temperature, humidity, light, carbon dioxide, water and plant nutrition. The main purpose of green-house technology is to provide a good growing environment for growing high quality plants round the year. The crops are protected from abiotic and biotic stresses. Greenhouse farming requires high investment and thus the crops which have high commercial value and sustainable market demand are cultivated in the greenhouses.

Generally, green-houses use sun light to meet their lighting needs for photosynthesis of plants but they do not use the sunshine for heat and rely on conventional energy sources like oil and gas to maintain the proper temperature for plant growth during winter or in cold regions which resulted in high energy costs and contribute to increase in greenhouse gas emissions (GHGs). The cost of energy consumption in conventional greenhouses often account for up to 50% of the production costs (Acosta-Silva *et al*., 2019).

Solar greenhouses are built to use solar energy for both lighting and heating purposes. A solar greenhouse is oriented towards the sun facing the south direction to absorb the maximum energy of the sunshine. The solar greenhouse has played a significant role in Trans–Himalayan region of India for production of leafy vegetables in sub-zero temperature during winter months. A number of passive solar greenhouse structures have been designed and tested for the region by Defence Institute of High Altitude Research (DIHAR) (Angmo *et al*., 2019). Most of these structures are passive solar greenhouses such as Ladakhigreen-houses, trench, poly trench, polyench, polycarbonate, fibre-reinforced plastic (FRP) and polynet. However, the trench type greenhouse is preferred by farmers due to low construction cost and protection from wind. Each year, an average of 700 greenhouses covering 44000 m^2 area are being established in Leh and Ladakh district. Now, green-house cultivation is popular among farmers for growing leafy vegetables during winter and raising of nursery in spring. The majority of farmers do not use the greenhouse in summer due to excessive heat that builds up inside the greenhouse. There is a need to improve the greenhouse design to make it economically viable and technologically feasible to grow a variety of crops. Solar PV technology was also used to provide external energy required for greenhouse cultivation (Nazir *et al*., 2023).

Presently in India, about 110,000 ha area is under green-house/covered cultivation (Singh *et al*., 2020). This technology needs to be extensively popularized by creating more awareness and giving suitable financial incentives. Case studies of the adoption of such technologies by the progressive farmers of different regions should be done by R&D organizations and findings should be published for greater awareness. The zero-emission green-house should be part of the green-house policy to reduce the growing risk of climate change, energy demand, and CO_2 emissions from plants in the greenhouse environment. Some of the issues that need to be included in the solar green-house policy are as follows:

(i) Designing energy-efficient greenhouses that are well insulated, use natural light, and have efficient heating and cooling systems to reduce energy consumption.

(ii) Incorporating and using renewable energy systems (RES) and adopting thermal energy storage systems which can supply the energy load of green-houses and further reduce energy costs.

(iii) Using IoT systems to control environmental factors such as temperature, humidity, and light levels optimizing plant growth, reducing energy consumption, and minimizing waste.

3.4 Solar refrigeration and cold storage

The post-harvest losses of fruits and vegetables during transport, storage and marketing are high. As per a report by ICAR-AICRP on Post-Harvest Technology located at ICAR-CIPHET, Ludhiana, the post-harvest losses of fruits and vegetables were assessed as 8-16% and 8-13%, respectively in 2015 (Jha *et al*., 2015).Studies have shown that mature green fruits may be stored at 10-14°C for 30 days and ripened tomatoes at 4-5°C for 10 days under 85-90% relative humidity. A general rule for vegetables is that cool season crops should be stored at cooler temperatures (0-2°C) and warm season crops should be stored at warmer temperatures (7-13°C). The system employed for storage of products used conventional energy leading to high carbon-di-oxide emission. In contrast, solar energy based refrigeration/cold storage systems, with and without power backup systems emit very low CO_2. The replacement of conventional electrical energy by solar energy in existing refrigeration system could reduce about 95% of CO_2 emission (Garcia and Semedo, 2024). Many researchers have designed solar integrated refrigeration systems. The vapour absorption refrigeration (VAR) has proven to be used with solar power (Nikbakhti *et al*., 2020). The operational cost of the vapour absorption refrigeration system is cheaper as compared to vapor compression refrigeration (VCR) system.

A thermal storage (TS) based solar refrigerator system was also developed and commercially available in India to make the system grid-free without using costly batteries. These systems required additional collectors to supply the required energy for storage (Said *et al*., 2012). In India, efforts were made to develop and install solar powered cold storage systems and Government of India provides applicable subsidies of Rs. 3 x 10^5 per Mt.

Small and medium size cold storage units of 5, 10 and 20 Mt capacity would be suitable for farmers, farmer's cooperatives and entrepreneurs and are to be installed in villages to store fruits and vegetables for 3-4 weeks to overcome distress sale by farmers and to get better prices. Mobile cold storage systems are also available in 5, 10 and 20 Mt sizes. Such cold storages normally have two chambers in which temperature in one chamber is maintained in the range of 2-7°C and in the other chamber at 8-16°C. Medium and big size solar cold storage should also be installed at fruit and vegetable market/mandies to avoid spoilage of fruits and vegetables. The solar cold storages installed at different places by R&D organizations and private manufacturers should be studied for their economic viability. A pilot scheme for installing solar cold storage should be launched in a few selected villages and fruit and vegetable markets. It should be supported by financial incentives, to have experience and practical data on the basis of which a bigger programme to popularize solar cold storages and cold chains can be launched by the State and Central Govt. to reduce the carbon foot print and to minimize losses of different types of fruits, vegetable, medicinal herbs and other perishable and semi-perishable items.

3.5 Solar micro-irrigation systems

Indian agriculture mainly depends on ground water source for irrigating around 60% of the total irrigated area which has a huge carbon footprint and is a serious environmental concern. The estimates show that groundwater irrigation emits about 45.3–62.3 Mt of carbon annually and contributes to 8–11% of India's total carbon emission (Rajan *et al*., 2020). Although micro-irrigation systems save water and nutrients by allowing water to slowly drip to the roots of plants and minimize water evaporation but these systems require electrical energy to lift the water and operate different controls of the system. These systems can be integrated with solar power to make them grid free. Many research organisations have integrated micro-irrigation systems (sprinkler and drip irrigation systems) with solar power and evaluated their performance. The automatic as well as smart micro-irrigation systems are also developed and available commercially. These systems save water, energy as well as have better carbon footprint.

3.6 Solar energy for hot water, hot air and steam generation for dairy and agro-processing industries

The agro and food industries consume a significant amount of energy mainly due to heat production with fossil fuel burners for generation of hot water and steam which contribute a great in total CO_2 emissions. The solar thermal energy is a form of energy for heating of water and air. In heating of water and air, solar radiation is converted into heat and transmitted into a transfer medium such as water or air. Different research organizations and industries have investigated different heating applications of solar energy. The developed system can be classified into two main categories *viz*. active system and passive system. The active system includes the open loop and close loop systems whereas the passive system uses the system of thermo-siphon and integral collector storage (ICS). These systems are extensively evaluated in different dairy and agro-processing industries. These industries require large quantity of hot water, hot air and steam for bottle cleaning, pasteurization, bottle sterilization, milk sterilization, multi-stage evaporation, hot air drying, etc. Solar energy is already being used for heating large quantities of water and air in these industries and the cost of heating water and air using solar energy is much lower as compared to other sources of energy (Sharma *et al*., 2017).

For parboiling of rice, the paddy is soaked in hot water at 70-80°C for 3.5 h and dried by hot air at 50-60°C and the dried paddy is hulled or shelled. Parboiling of paddy is done for 200-250 days in a year. For heating of water and air for parboiling of rice, the use of solar energy is very economical. For steam generation, solar thermal plants use the sun's rays to heat a fluid (Propylene Glycol) at high temperature using parabolic concentrators. The fluid is then circulated through pipes so that it can transfer heat to water and produce steam. Culinary steam is used to achieve high temperature and moisture levels required to sterilize enclosed surfaces (closed tanks, pipes and valves) and for other purposes in food processing industries. Air heating solar collectors of different configurations were investigated for their energetic and exergetic performances (Bahrehmand *et al*., 2015). Several types of air heating systems are available commercially for different applications. The phase-change energy storage materials, hybrid thermal energy storage systems, and solar heat pump technologies were investigated for air heating in different industrial requirements (Srivastava and Rai, 2017).

Many researchers studied solar heating systems and highlighted different technical issues associated with specific applications during solar thermal energy integration (Yan *et al*., 2015; Jamar *et al*., 2016). The common technical issues are to maintain constant collector outlet temperature due to large temperature fluctuation of incoming radiation, the thermal loss in the solar collector arrays, limitation in solar thermal energy storage and control over the solar loop flow rate. Different solar energy storage methods were investigated to overcome the challenges. The key areas for further investigation include the use of phase change materials for building more energy efficient solar thermal storage, better solar thermal collectors like evacuated tubes, linear fresnel reflectors (LFR) and parabolic trough solar collectors (PTC) to provide high techno-economic and environmental benefits and design a new solar system based on the thermal energy requirement of the particular case. The use of solar energy for heating water and air, drying and steam generation in agro and food processing sectors should be promoted to reduce CO_2 emission. Dairy, poultry and modern piggery farms have substantial water and air heating requirements during winter and in cold climate hilly regions where they are raised in closed rooms which require controlled temperatures to have proper growth and quality of animals. The indoor air is required to be replaced regularly to remove moisture, toxic gases, odour and dust. Heating of air, where necessary, water heating and circulation of air can be done using solar energy operated appliances which can cut the energy costs of such farms by about 50%.

3.7 Stand-alone electric supply system for stationary operation by different machines

The stand-alone solar PV panel for irrigating water is now available at farmer's site. However, it is only used at the time of irrigation and the electricity generation potential is underutilized. On an average, 0.932 kg of CO_2 reduction is estimated with 1.0 kWh of energy generated by any solar photo-voltaic system. The stationary machines like threshers, maize shellers, groundnut decorticators, cane crushers, chaff cutters, cleaners and graders, small capacity flour, dal and rice mills and many other machines consuming fossil fuel can be operated using available solar energy to reduce the carbon foot print. Some organizations have evaluated these stationary machines and modified them to use with solar energy. However, their presence at farmer's fields is almost nil.

3.8 Spraying and weeding using solar energy

The spraying and weeding operations in agriculture require less direct energy as compared to other unit operations. The solar sprayer and weeder have many advantages. Besides, reducing the cost of spraying and weeding, there is a saving of fuel, requires low maintenance, less vibration and less environmental impact than fossil fuel powered sprayers and weeders. Solar pumps are useful where grid electricity is unavailable. Different types of solar power sprayers such as manual backpack type hand compression sprayer and backpack power sprayers have been introduced by some R&D institutions and manufacturers. In both the cases, the desired pressure in the tank of the sprayer is maintained by the operation of a small solar operated motor fitted with the sprayer (Sinha *et al*., 2018). The electricity for running the motor is made available by a small lightweight solar PV panel. During operation, the solar PV panel is fitted with the sprayer in such a way that it is either at a height above the head of the operator or mounted at the back of the sprayer tank. The addition of a solar pump on hand compression sprayers has overcome the need for hand cranking. Solar PV pump operated sprayers have been mounted on tractors and used for spraying in row crops. Such units mounted on bullock carts have also been developed and used for spraying in standing sugarcane crop at a nearly stage. The battery powered weeders have been developed and commercially available in different designs and configurations (Ramesh *et al*., 2022). However, solar powered weeders and sprayers are still under investigation.

3.9 Solar powered tractors and power tillers

The use of solar energy in tractors and power tillers has the potential to reduce dependence on non-renewable energy sources, minimize carbon emissions, and promote sustainable farming practices. Some manufacturers are manufacturing small HP electric tractors and power tillers which are run on batteries similar to electric cars/buses. The batteries are charged either by solar power or using electric supply.

There is a need to make a techno-economic analysis and reliability of this concept by vigorous testing of the system.

3.10 Solar fencing, milking machine, insect trap, bird scaring device and snake repeller

Solar energy fencing for herds of animals, solar insect traps, solar bird scaring devices, solar snake repellers and many other gadgets have been developed by commercial firms and are also being marketed in small numbers. There is a need to extensively evaluate such devices and make recommendations for their adoption on a larger scale, based on their merit and economic viability.

3.11 Electricity generation using solar panels on field boundaries and agricultural wastelands for supply to grid system

Farmers can install solar panels at boundaries of their fields and wastelands for electricity generation to supply to grid system and can earn additional income without losing their fertile land. They can also adopt the technology of the agri-solar voltaic system in which solar PV panels are installed in the field in line at proper spacing and crops are grown in between the inter-row spacing. Selection of height of solar PV panels, row to row spacing and crops to be grown in between the rows are done scientifically in a manner that there are neither shadowing effects of PV panels on the crops nor the height of crops cause the shadow on the PV Panels. In this way, the farmers get income both ways, first due to crop yields and second by generating electricity for grid power. In this method, about 50% of the land area is covered by solar panels and only 50% area is available for cultivation. But, the total income to the farmers from both the sources is more as compared to that obtained with cultivation of crops alone.

4. STEPS UNDERTAKEN TO PROMOTE USE OF SOLAR ENERGY

India's initiative on solar water pumping was started since 1992. However, there was not much progress for two decades. Therefore, a flagship program entitled *Jawaharlal Nehru National Solar Mission* (*JNSSM*) was launched by Ministry of New and Renewable Energy (MNRE) in 2010 to boost solar power pumps, however, the set target for the mission was not achieved. Total number of solar water pumps installations was 25,000 by 2016 inspite of Government efforts through different schemes. With the learning from previous experiences, the Government of India has taken a step with the provision of decentralized grid connected solar power plants of high capacity in the new scheme during 2019. To popularize the use of solar water pumping systems for irrigation and other uses, Central Government launched a scheme named *Prime Minister - Kisan Suraksha Evam Utthan Mahabhiyan* (*PM-KUSUM*) on 8th March 2019 with three components: (i) installation of 10,000 MW of solar capacity through installation of small solar plants from 5 kW to 2 MW capacity, by individual farmers/

group of farmers/cooperatives/panchayats/farmers producer organizations (FPO)/user associations; (ii) installation of 2.0 million stand-alone solar powered agriculture pumps by individual farmers; and (iii) 1.5 million individual farmers having grid connected agriculture pumps will be supported to solarize pumps. PV capacity up to two times of the pump capacity in kW is allowed under this scheme. By December, 2022, 1.75 million stand-alone pumps of 5.60 kW capacity under component (ii) and 1.0 million under component (iii) have been installed. The scheme has been extended up to March, 2026.

There is more flexibility in the choice of type of systems in the new scheme along with guidelines to manufacturers for international standards with modern testing procedures, to ensure quality products having minimum efficiency of 13% and more with 70% fill factor. In comparison to off-grid solar water pumping system, the grid-connected solar water pumping system is a better option as no huge investment is required as rural grid infrastructure is already in place. It also helps to improve the availability of power to agriculture feeders, which at present is only 7-9 hours a day in most of the states.

The Government of India started micro-irrigation programme in 2006 to popularize and promote micro-irrigation system in all states of India, modified it in 2010 and clubbed it with a bigger mission mode programme during 2015 named as *Prime Minister Krishi Sinchayee Yojana - Per Drop More Crop (PM-KSY-PDMC)*. By January 2022, about 13.78 million ha area was covered under micro-irrigation systems. There is tremendous scope for increasing area under micro-irrigation systems operated by solar pumps.

5. RECOMMENDATIONS

Based on the presentations and discussions on the use of solar energy for different purposes and modes in agricultural production, agro-processing and value addition of agro-products, it was observed that there was a need for focused research pertaining to standardization of specifications, facilities for evaluation and testing and pilot scale demonstrations of these technologies for their large-scale adoption. The major recommendations of the brain-storming session are as follows:

Policy options

- Further strengthening of the linkage between Ministry of New and Renewable Energy (MNRE) and Indian Council of Agricultural Research (ICAR) to promote the application of solar energy programmes in agriculture.
- Although testing facility of the solar energy gadgets and system is available at the National Solar Energy Institute. However, more testing centres preferable under National Agricultural Research System (NARS) should be established at centres of AICRP on EAAI to evaluate the performance and to provide certification to equipment available in the market.

- The solar water pumping system is mostly used as stand-alone system. The application of these systems should be augmented for other applications such as providing electricity to agro-processing centres and charging stations besides operating stationary agriculture machinery *viz.* threshers, cane crushers, chaff cutters, cleaners and graders etc. These systems can also be used to solarize the rural feeder and the farmer must be benefitted for providing each unit of electricity to feeder.
- Agri-voltaic systems connected with the grid and with proper layout configuration may be popularized and promoted at the national level and brought under subsidy program. The sharing of profit to farmers through net metering should be ensured. The mechanism of solar panel insurance against theft needs to be worked out.
- Large-scale demonstration of solar cold storage systems at farmers' fields and mandies to promote cold storage systems.
- To promote solar drying cum space heating systems for drying of fruits and vegetables, KVKs to be equipped with solar thermal systems for large scale demonstration, capacity building, awareness and popularization.
- Develop solar based green-house system model along with skill development programme for rural youth for high value crops.
- Economic and environmental assessment of use of solar energy for different applications to ensure the economic viability.
- Policy formulation to incentivize or reward stakeholders for use of solar energy in agriculture and other promising applications.
- Policy development for single window delivery of material/equipment, knowledge and market for wider adoption of promising solar energy based technologies in agriculture.

Researchable issues

- Focused research on designing low cost PV panels, which can be easily operated by farmers with minimal training besides its coupling with micro-irrigation system, green-house, agri-voltaic system and efficient heating materials and developing operational guidelines for applications of solar based drying, cold storage etc.
- Need for t more field trials of agri-solar voltaic system to recommend about the spacing between rows of solar PV panels, the height of installation of PV panels, arrangements for periodic dust removal from PV panels etc for different crops in varying agro-climatic regions.
- The solar water pumping system is being popularized in the agriculture sector on subsidy by the Government of India through different schemes. The advantages and constraints in implementing such schemes in farmer’s fields should be studied.

- Develop package of solar energy gadgets for use in different locations considering the need of agricultural production system and location specific insolation.
- Need to develop, demonstrate and popularise mobile PV power unit having foldable PV installation to operate different stationary agricultural machinery/gadgets for processing of farm produces in rural areas.
- Critically examine complete end-to-end value chain for economic benefits while working on solar drying and electricity generation.
- Explore the application of geo-thermal energy for heating green houses, aquaculture structures, poultry and animal shelters.
- Available solar energy-based equipment/gadgets need to be properly tested and performance parameters to be optimized along with standardization of specifications.
- Need to standardize the specifications and evaluate the performance of developed solar cold storage systems (5-10 t).

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