Policy Paper 46

Harnessing the Potential of Solar-Powered Micro-Irrigation for Sustainable Intensification of Agriculture

S K Srivastava
Prabhat Kishore
Pratap Singh Birthal
P B Shirsath

भा.कृ.अ.प.– राष्ट्रीय कृषि आर्थिकी एवम् नीति अनुसंधान संस्थान
ICAR – NATIONAL INSTITUTE OF AGRICULTURAL ECONOMICS AND POLICY RESEARCH

Publication Committee

P S Birthal
Shiv Kumar
Raka Saxena
Kiran Kumara TM
Purushottam Sharma

The ICAR-National Institute of Agricultural Economics and Policy Research (NIAP) was established by the Indian Council of Agricultural Research (ICAR) to strengthen agricultural economics and policy research in the National Agricultural Research System comprising a network of ICAR institutions and State Agricultural Universities. The mandate of the Institute is:

- Agricultural economics and policy research on markets, trade, and institutions
- Growth and development models for sustainable agriculture
- Technology policy, evaluation, and impact assessment

ICAR-NIAP has emerged as a think tank in the area of agricultural policy and it has contributed to increased participation of the ICAR in agricultural policy-making. Besides ICAR, the Institute regularly provides research based inputs to the NITI Aayog, Government Departments, States, and other stakeholders for policy decisions in diverse areas related to agriculture.

Policy Paper 46

Harnessing the Potential of Solar-Powered Micro-Irrigation for Sustainable Intensification of Agriculture

S K Srivastava
Prabhat Kishore
Pratap Singh Birthal
P B Shirsath

ICAR – National Institute of Agricultural Economics and Policy Research
New Delhi - 110 012

S K Srivastava, P Kishore, P S Birthal, P B Shirsath. (2024). Harnessing the Potential of Solar-Powered Micro-Irrigation for Sustainable Intensification of Agriculture. Policy Paper 46, ICAR-National Institute of Agricultural Economics and Policy Research (NIAP), New Delhi.

Published
November 2024

Published by
Dr P S Birthal
Director
ICAR-National Institute of Agricultural Economics and Policy Research (NIAP), New Delhi-110012

S K Srivastava, Prabhat Kishore and P S Birthal are Senior Scientist, Scientist (Senior Scale), and Director at ICAR- National Institute of Agricultural Economics and Policy Research (NIAP), respectively; and P B Shirsath is Scientist at Borlaug Institute for South Asia. The views expressed in this paper are those of the authors and do not necessarily reflect the official positions of the institutes to which they are affiliated.

Printed at
M/s Chandu Press, 469, Patparganj Industrial Estate, Delhi 110 092.

Contents

List of Tables

List of Figures

Foreword

The Government of India has been promoting the adoption of micro-irrigation and solar energy in agriculture to foster more efficient and sustainable growth in the sector. Micro-irrigation systems enhance water use efficiency and facilitate precise nutrient application. The use of solar energy reduces cost of energy for irrigation, carbon emissions and dependence on fossil fuel. These innovations offer strong economic advantages to farmers through reduced input costs, higher input use efficiency, and the potential to improve crop yield and quality, besides environmental and climatic benefits.

These innovations are complementary in nature. However, they are implemented under two separate schemes, namely the *Pradhan Mantri Krishi Sinchayee Yojana* (PMKSY) for micro-irrigation and the *Pradhan Mantri-Kisan Urja Suraksha evam Utthaan Mahabhiyan Yojana* (PM-KUSUM) for solar energy. This approach results in missed opportunities for synergistic benefits. Converging or better alignment of the two to allow farmers simultaneous access to micro-irrigation and solar pumps has the potential to raise crop yields, lower water usage, and reduce energy costs resulting in increased farmers' income and decreased greenhouse gas emissions.

The evidence presented in this paper suggests that leveraging the complementarity between PMKSY and PM-KUSUM enhances overall system efficiency and reduces operational costs. Further, this approach provides long-term benefits beyond immediate economic gains. By minimizing water use and reducing carbon emissions, the integrated approach contributes significantly to sustainability goals.

The institutional framework suggested in the study for convergence of the schemes represents an advancement towards sustainable agriculture. It also provides comprehensive guidelines for implementing agencies at both central and state levels for integrated adoption of the two technologies. Furthermore, this kind of convergence approach facilitates resource optimization and reduces administrative barriers, ultimately benefiting farmers. The study's comprehensive approach, incorporating field-level insights from a diverse range of stakeholders adds substantial value to its findings and recommendations. It is a commendable work which needs due consideration in harnessing maximum benefits from PMKSY and PM-KUSUM.

Ramesh Chand
Member
NITI Aayog

Preface

Indian agriculture faces numerous biotic and abiotic challenges that are likely to intensify in the future. The three critical challenges are diminishing agricultural land, increasing scarcity of water and energy for irrigation, and climate change. Consequently, future growth in agriculture depends on innovations that enhance resilience in agriculture and promote judicious and efficient use of natural resources. Therefore, agricultural policies must be aligned to address these challenges. Micro-irrigation presents a significant option for water conservation and mitigate climate risk without adverse effects on agricultural productivity. Groundwater extraction, however, requires energy. Given the limited scope for further exploitation of fossil fuels, a transition towards renewable energy sources is imperative.

The Government of India has initiated major schemes such as *Pradhan Mantri Krishi Sinchayee Yojana* (PMKSY) and *Pradhan Mantri- Kisan Urja Suraksha evam Utthaan Mahabhiyan Yojana* (PM-KUSUM) to promote applications of micro-irrigation and solar energy in agriculture. Although micro-irrigation and solar energy are complementary technologies, there is a lack of convergence between the two schemes. The need for convergence between micro-irrigation and solar energy at gross root level has been conceptualized jointly by the International Copper Association India (ICA India) and ICAR-NIAP. This study investigated the techno-economic feasibility of the convergence of the two schemes and suggested institutional and policy measures to achieve convergence. The findings indicate that transitioning to solar-powered micro-irrigation has significant potential to conserve groundwater and reduce greenhouse gas emissions. It is anticipated that the findings will provide crucial feedback for policymakers and other stakeholders in aligning agricultural policy with the goals of sustainable agricultural development.

The study has immensely benefitted from the comments and suggestions of experts, representing academia, industry, development agencies, and farmers' organizations. The authors are particularly indebted to Dr. S K Chaudhary, Deputy Director General (Natural Resources Management), Indian Council of Agricultural Research (ICAR), Dr. S

K Ambast, Chairman, Central Groundwater Board (CGWB), and Dr. P S Brahmanand, Project Director, Water Technology Centre, Indian Agricultural Research Institute (IARI) for their valuable suggestions. The authors would like to thank Dr. Adlul Islam, Principal Scientist, Natural Resources Management (NRM) Division, ICAR for his excellent review of the study. The authors acknowledge the insights provided by Mr. Mayur Karmarkar, International Copper Association India (ICA India) and Mr. Sanjay Dubey, International Institute of Energy Conservation (IIEC) on various aspects of irrigation and energy use in agriculture.

The support from the International Copper Association, India is gratefully acknowledged. Sincere appreciation is extended to Mr. K N Hemanth Kumar, ICA India, Mr. Abhishek Dhupar, IIEC and Mr Sanjay Namdeo, ICA India for their support and coordination of activities. Dr. Vister Joshi, Scientist at Krishi Vigyan Kendra (KVK), Jalaun, Uttar Pradesh and Mr. Arun Kumar, Senior Executive, National Commodity & Derivatives Exchange Limited (NCDEX), Jaipur assisted in monitoring field surveys. The authors gratefully acknowledge their contribution.

Authors

♦♦♦

Executive Summary

By 2047, India's food demand is projected to be twice its current demand. However, the agri-food production system encounters numerous biotic and abiotic challenges in producing sufficient quantities to meet this demand. The net sown area has remained static at approximately 140 million hectares, and the increasing scarcity of water and energy resources limits its intensification. Climate change is a significant threat to agriculture. Consequently, future growth in agriculture must be driven by technological innovations and judicious and efficient utilization of natural resources (i.e., land, water, and energy).

To address these challenges, the Government of India has been actively promoting micro-irrigation and solar energy utilization in agriculture. Micro-irrigation and solar energy are promoted through two distinct schemes: micro-irrigation by the Ministry of Agriculture and Farmers Welfare under the Per Drop More Crop (PDMC) component of the *Pradhan Mantri Krishi Sinchayee Yojana* (PMKSY), and solar pumps by the Ministry of New and Renewable Energy under the *Pradhan Mantri- Kisan Urja Suraksha evam Utthaan Mahabhiyan Yojana* (PM-KUSUM).

However, there is little synergy between these two schemes, which may deprive stakeholders of the potential economic and environmental benefits. This study has evaluated (i) the potential of micro-irrigation and solar energy applications in agriculture, (ii) their economic and environmental benefits, and (iii) the economic feasibility of integrating micro-irrigation and solar energy. Consequently, an institutional framework is proposed to improve the synergy between these technologies.

The key findings of this study are as follows:

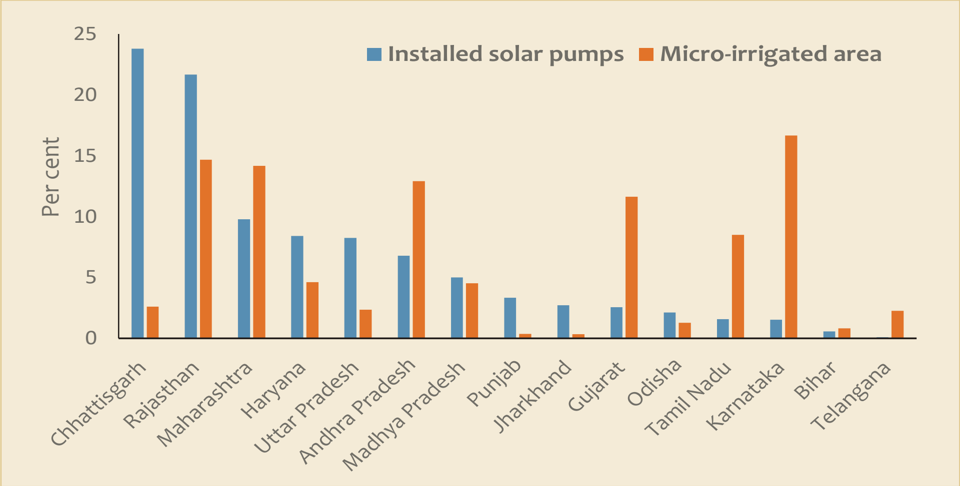
Micro-irrigation has expanded rapidly, yet its coverage remains limited: Micro-irrigation has been promoted since the 1970s; however, its adoption accelerated during the past two decades — the area under micro-irrigation increased from 4 lakh hectares per annum between 2005 and 2010 to 10 lakh hectares per annum between 2015 and 2023. In 2023, micro-irrigation accounted for 12.9% of the total irrigated area. India has the potential of 88 million hectares for micro-irrigation. If the current adoption rate continues, it may take 20 years to attain this potential.

Significant disparities exist in adoption of micro-irrigation: Karnataka, Rajasthan, Maharashtra, Andhra Pradesh, Gujarat, and Tamil Nadu are the predominant states in micro- implementation of micro-irrigation scheme. The proportion of irrigated area under micro-irrigation in these states ranges from 17.9% to 51.3%. Collectively, these account for 79% of the total micro-irrigated area. Conversely, states such as Uttar Pradesh and Punjab have less than 2% of their irrigated area under micro-irrigation.

Adoption of solar pumps for irrigation is increasing fast: Between 2013 and 2022 the number of solarized pumps increased 43 times, from 11,626 in 2013 to 501,673 in 2022 but their penetration remains low. In 2022, these comprised 2.3% of the total 21.5 million electric and diesel-operated groundwater extraction devices (GEDs). The solarization of all electric- and diesel-operated GEDs has the potential to generate 102 gigawatts (GW) of solar power. Attaining this potential by 2030 could contribute 36.6% of the target of 280 GW of solar energy.

Solar energy use is concentrated in a few states: Similar to micro-irrigation, the adoption of solar pumps is concentrated in a few states: Chhattisgarh, Rajasthan, Maharashtra, Haryana, and Uttar Pradesh. However, there is no significant correlation between the adoption of micro-irrigation and solar pumps. States exhibiting higher adoption rates of micro-irrigation demonstrate lower adoption rates of solar pumps. For example, Chhattisgarh has the highest adoption rate of solar pumps but one of the lowest adoption rates of micro-irrigation (Figure 1). Conversely, Karnataka, which has the highest proportion of area under micro-irrigation, significantly lags in the adoption of solar pumps.

Figure 1. States' share in micro-irrigated area and installed solar pumps, 2023



Coupling micro-irrigation has several economic and environmental benefits: Micro-irrigation enhances conveyance efficiency, and its integration with solar pumps can mitigate the over-extraction of groundwater resulting from unrestricted access to solar energy. Solar-powered micro-irrigation systems conserve energy and water while contributing to increased crop yields. The solarization of a single fossil-fuel (electric/diesel)-based GED reduces diesel consumption by 911 liters, electricity usage by 2875 units, and CO_2 emissions by 2.1 tons per well per annum, thereby alleviating the fiscal burden of electricity subsidies and diesel imports, and greenhouse gas emissions.

Substituting diesel pumps with solar-powered micro-irrigation systems is more attractive: Even in the absence of capital subsidies, the investment in a solar-powered micro-irrigation system can be recovered in five years solely from the savings in diesel costs. With capital subsidies of 45-55% on micro-irrigation and 60% on solar pumps, the payback period is reduced to less than two years. Conversely, the replacement of an electric pump with a solar-powered micro-irrigation system is not economically feasible because of the provision of free or heavily subsidized electricity for irrigation.

Notwithstanding the aforementioned advantages of solar power and micro-irrigation, there are technological, institutional, and policy challenges in their integration that need to be addressed.

Restructure institutional arrangement for integration of solar pumps and micro-irrigation: The guidelines of the PDMC and PM-KUSUM advocate for their joint implementation by a single state agency (i.e., convergence) or, alternatively, through effective coordination between different agencies (i.e., synergy). However, in most states, these programs are implemented independently. To achieve convergence, all processes, from registration to the supply of solar power and micro-irrigation systems, must be synchronized and executed by the same agency. Andhra Pradesh and Gujarat have implemented PDMC through Special Purpose Vehicles (SPVs).

The Government of India transferred PDMC to RKVY (*Rashtriya Krishi Vikas Yojana*) in 2022-23, providing greater flexibility and autonomy to states to implement micro-irrigation schemes as an integral part of their District Agricultural Plans (DAPs). The DAPs should be revisited to integrate PM-KUSUM with the PDMC. It is suggested that component B (off-grid solar pumps) of the PM-KUSUM be transferred to the RKVY for joint implementation.

Customize design and size of solar-powered micro-irrigation system: Fluctuating water pressure resulting from variable weather conditions leads to inconsistent water flow from solar pumps, which is incompatible with the high and consistent pressure required for the efficient operation of micro-irrigation systems, particularly sprinklers. Hence, there is a need to develop location-specific solar-powered micro-irrigation systems to ensure adequate water pressure and their automation to maintain uniform water flow.

Evolve innovative financing mechanisms**:** The substantial cost associated with solar-powered micro-irrigation systems presents a significant barrier to their widespread adoption, particularly by small-scale farmers, despite the availability of financial assistance can cover up to 75% of the margin money. Financial institutions should develop innovative financial products to facilitate the joint implementation of micro-irrigation and solar pumps on smaller farms.

Repurpose electricity subsidy: Reallocating electricity subsidies as capital subsidies for solar pumps, increasing the subsidy from 60% to 80%, may enhance the economic viability of replacing electric pumps with solar-powered micro-irrigation systems.

Prioritize states for the solarization of micro-irrigation: States with higher adoption rates of micro-irrigation have lower adoption rates of solar pumps and vice versa. It is essential to investigate the factors that contribute to the differential performances of these schemes. Promoting solar-powered micro-irrigation in states such as Uttar Pradesh, which possesses significant potential, is crucial for realizing full potential.

Target high-value crops: The estimated payback period and internal rate of return from investment in solar-powered micro-irrigation are predicated on savings from diesel and electricity. These estimates do not account for additional benefits such as enhanced crop yield and reduction in the cost of other inputs. The promotion of more lucrative crops, such as fruits and vegetables, which are particularly suited for micro-irrigation systems, can significantly enhance the internal rate of return and decrease the payback period.

Overall, if the full potential of both solar power and micro-irrigation is realized, groundwater can be saved to the extent of 65 billion cubic meters and carbon emissions can be reduced by up to 45 million tons per annum.

♦♦♦

1 Introduction

Technological transformation, supported by investments in irrigation, infrastructure, institutions, and incentives, has resulted in significant increases in agricultural productivity and food supplies in India, turning it from a food-insecure to a food-surplus nation. Between 1950-51 and 2022-23, food production increased 8.5 times compared with 3.7 times increase in population. Nevertheless, the need to produce more food remains critical. By 2047, India's food demand is projected 1.9 to 2.3 times the current demand (NITI Aayog 2024).

Conversely, the agricultural production system faces a confluence of several biotic and abiotic pressures to produce the required quantities of food. Land and water are the most limiting factors. Owing to the increasing demand for residential and industrial purposes, arable land has declined from 189.6 million hectares in 1950-51 to 180.1 million hectares in 2021-22 (GoI 2024). Approximately two-thirds of total arable land suffers from one or more forms of degradation (GoI 2017). The annual per capita availability of water has decreased drastically from 5178 m^3 in 1951 to 1486 m^3 in 2021, which is 13% less than the norm of 1700 m^3. Of the available 1097 billion cubic meters (BCM) of freshwater, approximately 85% is utilized in agriculture. Climate change is one of the most significant challenges to the sustainability of agriculture. Evidence indicates that since 1980, climate risks have reduced productivity growth in Indian agriculture by 25%, despite technical progress and expanding irrigation (Birthal and Hazrana 2019). Thus, increasing food production amidst these challenges is a formidable task.

Agriculture serves not only as a source of food, feed, fiber, and fuel, but also as the primary, if not exclusive, source of income and livelihood for 47% of the population, despite a significant decline in its contribution to the gross domestic product (GDP) from over 50% in the 1960s to 18% in 2022-23. Consequently, agriculture remains central to India's economic development policies. The current agricultural development agenda focuses on conserving natural resources and mitigating climate risk, while maintaining agricultural productivity.

Water is a critical input in agriculture, serving a dual role: enhancing agricultural productivity and resilience against climate risks (Lobell et al. 2009; Birthal et al. 2014; Srivastava et al. 2014; Birthal and Hazrana 2019). Since the beginning of the Green Revolution in the mid-1960s, India has invested substantially in irrigation. Public investment in irrigation has been complemented by significant private investment in groundwater irrigation, resulting in a threefold increase in irrigation coverage from 17.1% in 1950-51 to 54.9% in 2021-21 (GoI 2024).

Several key observations regarding India's irrigation development are as follows.

- Approximately 45% of the cropped area depends on precipitation. There exists significant spatial and temporal variation in precipitation. More than 85% of the annual precipitation occurs between June and September. Spatially, annual rainfall ranges from more than 250 cm in the Western Ghats and the Sub-Himalayan regions in the northeast to less than 40 cm in the northern parts of Jammu & Kashmir and western Rajasthan, resulting in substantial spatial differences in cropping patterns and agricultural productivity (CGWB 2023).
- About 88% of the ultimate irrigation potential (UIP)[1] has been created, which implies little scope for further investment in irrigation infrastructure (Srivastava et al. 2014). Still, a 23% gap exists between irrigation potential created (IPC)[2] and its utilization (IPU)[3] owing to several factors, including high conveyance losses, inefficient distribution and application methods, and the emergence of water-intensive cropping patterns.
- Groundwater has emerged as the primary source of irrigation, increasing its share to 60.5% of the net irrigated area in 2021-22 from 28.7% in 1950-51. The current stage of groundwater extraction at the national level is 59.3%, ranging from 12.5% in Assam to 163.8% in Punjab (CGWB 2023). Overall, approximately one-fourth of the total assessment units (blocks/mandals/taluka) are over-exploited or at a critical and semi-critical stage of exploitation. The northwestern and southern regions are hotspots for groundwater depletion. However, groundwater resources are underutilized in the eastern region. Hence,

1 Ultimate Irrigation Potential (UIP) is theoretically defined as the gross area that can be irrigated from all available water resources.

2 Irrigation Potential Created (IPC) is the gross area planned to be irrigated during a year.

3 Irrigation Potential Utilized (IPU) is the actual gross area irrigated during a year.

there is a dual challenge in water management: reversal of over-extraction in some regions, and promotion of its use in others.

- The provision of free or subsidized electricity for irrigation is the primary factor that contributes to groundwater over-extraction. Between 2010-11 and 2020-21, electricity consumption in agriculture increased two-fold, whereas electricity subsidies (at nominal prices) rose by a factor of five. In 2020-21, expenditure on electricity subsidies amounted to Rs 724 billion, or Rs 5383 per hectare of net sown area. However, significant inter-state disparities exist in electricity subsidies, ranging from Rs 104 per hectare in Kerala to Rs 17686 per hectare in Punjab.
- The number of groundwater extraction devices (GEDs) and the energy intensity of groundwater extraction have increased steadily, contributing to greenhouse gas (GHG) emissions, a threat to the sustainability of groundwater. Rajan et al. (2020) estimated that groundwater irrigation emits 45-62 million tons of CO_2 annually, contributing 8-11% of the total CO_2 emissions.
- Water-use efficiency in India is low compared to that in China, Brazil, and the USA. In India, it takes 2-3 times more water to produce the same quantity of food. Overall, there is considerable scope to increase water use efficiency to 60% from the current 35-40%.

Maintaining equilibrium between water demand and supply is essential for sustainable agricultural intensification. Various technological interventions can augment and conserve water resources while enhancing their efficiency.

Pressurized irrigation, based on drippers and sprinklers, often termed micro-irrigation, is one of several options for improving water-use efficiency and preserving water. Sprinklers can save 15-20% and drippers 40-60% water over conventional flooding method. Besides, these enhance the efficiency of other inputs (fertilizers) and crop yields and promote the cultivation of more remunerative crops, including fruits, vegetables, flowers, and aromatic and medicinal crops.

There is a close nexus between micro-irrigation and energy use. Micro-irrigation requires a reliable and affordable energy source. Traditionally, electricity and diesel have been the primary power sources for lifting groundwater. These are non-renewable and contribute to greenhouse gas emissions. In recent years, solar energy has emerged as a renewable and environmentally sustainable source of energy.

Box 1: Micro-Irrigation and Solar-Powered Irrigation

Micro-irrigation: Micro-irrigation is a technique that delivers small and controlled quantity of water directly to the soil surface or root zone of plants using drippers, sprinklers, or other emitters. Through precise application, it reduces water loss due to conveyance, runoff, deep percolation, evaporation, and waste; hence it improves water-use efficiency.

Solar-powered irrigation: Solar-powered irrigation (SPIS) uses solar energy through photovoltaic (PV) panels to generate electricity for powering pumps for extraction, elevation, and distribution of groundwater. It effectively replaces fossil fuels, curbing greenhouse gas emissions (GHGs) from current irrigation practices.

The essential components of SPIS are: (i) solar generators (comprising PV panels), (ii) mounted structures for optimal sunlight absorption, (iii) pump controllers, and (iv) surface or submersible pumps integrated with power motors.

Since 2008, the Government of India has taken initiatives to promote micro-irrigation and solar energy in agriculture. These include the National Water Mission (NWM), National Mission on Sustainable Agriculture (NMSA), and National Action Plan on Climate Change (NAPCC). In addition, several other schemes have been initiated, such as the Accelerated Irrigation Benefit Program (AIBP) and Command Area Development & Water Management (CADWM) scheme by the Ministry of Water Resources, River Development, and Ganga Rejuvenation (MoWR, RD&GR), the Integrated Watershed Management Program (IWMP) by the Ministry of Rural Development (MoRD), and On-Farm Water Management (OFWM) by the Ministry of Agriculture & Farmers Welfare (MoA&FW). In 2015-16, these schemes were subsumed in newly launched *Pradhan Mantri Krishi Sinchayee Yojana* (PMKSY). Solar power applications in agriculture are promoted under the *Pradhan Mantri- Kisan Urja Suraksha evam Utthaan Mahabhiyan Yojana* (PM-KUSUM) launched in 2019 by the Ministry of New and Renewable Energy (MNRE).

However, there is little synergy between schemes that promote micro-irrigation and solar energy. Micro-irrigation is promoted under the PMKSY, and solar power under the PM-KUSUM. Although solar-powered irrigation is a reliable and affordable source of irrigation (Schnetzer and Pluschke 2017), it may pose the risk of over-extraction of groundwater (Shah and

Kishore 2012; FAO 2017). To reduce this risk, coupling micro-irrigation and solar energy schemes is often advocated (Kishore et al. 2014; Shah et al. 2016; Bassi 2017; Goel et al. 2021; Yashodha et al. 2021). Nonetheless, there is little evidence on the costs and benefits of integrating the two schemes.

Given this context, this study addresses several critical questions regarding the coupling of solar power with micro-irrigation.

- Is the convergence of micro-irrigation and solar energy technologies economically feasible and environmentally sustainable?
- What are the technical, economic, and institutional barriers to integrating the two technologies?
- What institutional and policy frameworks are necessary for the effective convergence between micro-irrigation and solar energy?

The remainder of this paper is organized as follows. The following chapter presents a comprehensive overview of the advantages associated with micro-irrigation and solar energy, while also identifying the challenges inherent in their integration. Chapter 3 examines the rationale and economic feasibility of combining micro-irrigation and solar energy technologies. Chapter 4 provides empirical evidence from Rajasthan and Uttar Pradesh regarding the potential for the convergence of these technologies. The final chapter discusses the key findings and their implications.

♦♦♦

2 Micro-irrigation and Solar Power Use in Indian Agriculture

The increasing demand for food and non-food commodities amid the growing scarcity of land, water, and energy necessitates their judicious and efficient utilization in both agricultural and non-agricultural contexts. Pressurized irrigation systems comprising drip and sprinkler technologies have significant potential for enhancing water use efficiency, expanding irrigation coverage, and improving agricultural productivity and production. Sunshine, a renewable and clean energy source, has the potential to mitigate greenhouse gas emissions. This chapter provides a brief overview of the progress in micro-irrigation and solar energy, as well as their associated economic and environmental benefits.

2.1 Benefits of micro-irrigation and solar power

2.1.1 Micro-irrigation

Evidence from experiments and field surveys reveal several advantages of micro-irrigation over flood irrigation (Table 2.1). Micro-irrigation saves water, fertilizer, and energy, and improves crop yields, irrigation coverage, and cropping intensity. Thus, it contributes to a reduction in production costs, enhances productivity and resilience, reduces farmers' income, and improves affordable access to food. However, there is limited empirical evidence of the benefits that are realizable at the farm level.

The evidence presented in Table 2.1 demonstrates significant regional variations in the benefits of micro-irrigation. However, the general conclusion is that micro-irrigation can be profitably applied to all crops in different agro-ecological environments. Micro-irrigation is scale and crop-neutral, but it is more suitable for fruits, vegetables, and plantation crops, which are more remunerative than widely grown staple cereals (Namara et al. 2007). Studies assessing returns on investment in micro-irrigation have reported that it is financially viable (Narayanamoorthy 1997; Sarkar and Hanamashet 2002; Verma et al. 2004; Nagaraj 2020). Furthermore, micro-irrigation has been observed to influence changes in production portfolios towards more remunerative crops (Namara et al. 2007).

Table 2.1. Benefits of micro-irrigation

Reference	Location	Water saving (%)	Energy saving (%)	Fertilizer saving (%)	Yield/ income increase (%)	Area augmen-tation (%)	Cost saving (%)
Kapur et al. (2015)	Maharashtra	50-90	30.5	28.5	42.4-52.7	31.9	30-45 & 30.4
Narayanamoorthy (2003, 2005,2006, 2008,2018)	Maharashtra	8-84			114		50
Reddy et al. (2017)	Andhra Pradesh					55-60	25-40
Wrachienb et al. (2014)	Maharashtra	37			19-29		
Paul et al. (2013)	Odisha				57	54	
Biswas et al. (2015)	Bangladesh	50			25-27		
Kumar et al. (2016)	Uttar Pradesh	35					
Bhaskar et al. (2005)	Maharashtra	40-50			30-100		
Quevenco (2015)	Kenya	55			99		
Tiwari et al. 2014	West Bengal				21.05		
Chandrakanth et al. (2013)	Karnataka				65		
Priyan and Panchal (2017)	India	50-90	30.5	28.5			
Panigrahi et al. (2010)	Odisha				15.4		17.9
Chandran and Surendran (2016)	Kerala				13-47		
Bhamoriya and Mathew (2014)	Gujarat			20	20-30		
NCPAH 2014	All-India	25-40	30-40	20	30	30	40
Jha et al. (2017)	Punjab	40-42			9.13		
Vanitha and Mohandass (2014)	Tamil Nadu	50		100	19.05		
Rao et al. (2017)	Madhya Pradesh		40		11.03		
Chand et al. (2019)	All-India	17-50	6-36	25-40	12-43		11-36

Source: Chand et al. (2020)

The adoption of micro-irrigation differs significantly across farm classes and states (Palanisami et al. 2011; Suresh et al. 2018; Chand et al. 2020; Kishore et al. 2022), possibly because of financial, socio-economic, institutional, and policy factors (Kumar 2002; Suresh et al. 2018; Nagaraj 2020). High initial capital costs, lack of access to credit, fragmented land holdings, irregular power supply, high operational and maintenance costs, and poor training support for farmers have been identified as significant impediments to the adoption of micro-irrigation (Namara et al. 2007; Nagaraj 2020; Reddy et al. 2023).

Incentives and institutional structures also influence adoption of micro-irrigation (Malik et al. 2016). The establishment of Special Purpose Vehicles (SPVs), such as the Andhra Pradesh Micro-Irrigation Project (APMIP) and the Gujarat Green Revolution Company (GGRC), has accelerated the adoption of micro-irrigation (Pullabhotla et al. 2012; Palanisami 2015). Moreover, capital subsidies and their targeting profoundly affect its adoption (Bahinipati and Viswanathan 2019). Conversely, competing incentives, such as the provision of free or low-tariff electricity, discourage the adoption of micro-irrigation.

Although the positive impact of micro-irrigation on water-use efficiency at a lower geographical scale (i.e., farm level) is well established, it does not necessarily translate into water saving at a higher geographical scale (i.e., basin level). Micro-irrigation may lead to an increase in irrigation coverage and cropping intensity, and crop switching in favor of water-intensive high-value crops, thereby increasing total water demand.

The overall impact of micro-irrigation on the sustainability of groundwater is contingent on the competing demands for water and the incentives, regulations, and policies for its conservation.

2.1.2. Solar-powered irrigation

Regulation of energy for groundwater pumping represents one of the most efficacious indirect measures for groundwater conservation. According to the 6th Minor Irrigation Census (2017-18), approximately 76% of GEDs are powered by electricity and 22% by diesel. To enhance farmers' access to irrigation, state governments often provide electricity, either free or at minimal tariff rates. Improved access to irrigation through alterations in energy prices has played a crucial role in increasing agricultural productivity and food supply. However, this approach has resulted in unintended negative externalities, affecting natural resources and increasing fiscal burden on exchequers (Perez et al. 2024; Devineni et al. 2022; Kishore et al. 2024).

In India, agriculture accounts for approximately 20% of electricity consumption and 15% of diesel consumption (IEA 2015), which emit 45-62 million tons of carbon, accounting for 8-11% of the total carbon emissions (Rajan et al. 2020). Over time, the density of irrigation wells increased, resulting in a decline in groundwater levels and increased dependence on high-horsepower submersible pumps (Kishore et al. 2024). If this trend persists, the energy intensity in agriculture is anticipated to increase substantially, adversely affecting the health of natural resources and sustainability of agriculture.

The transition towards renewable energy sources, particularly solar energy, is imperative for ensuring energy security. India aims to meet 50% of its energy requirements from renewable sources by 2030 and achieve net-zero emissions by 2070. The target capacity for renewable energy by 2030 is set at 500 Gigawatts (GW), as compared to the existing installed capacity of 132.7 GW (PIB 2022; MNRE 2023). As of 2023, solar energy constitutes 54.5% (72.3 GW) of the total installed capacity of all renewable sources, with a target of 280 GW by 2030. Currently, only 9.6% of the solar energy potential of 749 GW (assuming that 3% of the wasteland area is covered by solar PV modules) has been exploited (MNRE 2024).

Solar-powered irrigation pumps have a minuscule share of 3.3% in the total solar power installed capacity. Hence, increasing the solarization of irrigation pumps can significantly improve economic access to irrigation, minimize the electricity subsidy burden, and reduce GHG emissions. Solar pumps are convenient to use, require minimal attendance, and have fewer maintenance problems (Kishore et al. 2014). Solar pumps save diesel and reduce air pollution. Gupta (2019) has reported solar pumps to reduce diesel and electricity consumption, but leading to an increase in groundwater consumption (16-39%) because of the increase in irrigation coverage and cropping intensity.

The use of solar-powered pumps is associated with farm income. Suman (2018) reported a significant positive impact of solar-powered pumps on farmers' income. Grid-connected solar pumps with a buyback arrangement for power reduce energy consumption and enhance farmers' income (Shirsath et al. 2020; Yashodha et al. 2021). However, grid-connected solar programs often suffer from periodic cancellation of renewable Power Purchase Agreements (PPAs) owing to falling solar tariffs and lack of feeder segregation (Yashodha et al. 2021). Grid-connected solar pumps are more expensive than standalone solar pumps (Raymond and Jain 2018).

The cost of solar-powered irrigation is lower than that of diesel-based irrigation (Kishore et al. 2014; Suman 2018; Yashodha et al. 2021). However, irrigation through electric-operated pumps is more economical because of electricity subsidies. Consequently, farmers relying on subsidized electricity do not find solar pumps financially advantageous even with a 60% capital subsidy (Raymond and Jain 2018). Conversely, studies have observed that returns from investments in solar-powered pumps are substantial, albeit not without subsidies (KPMG 2014; Singh et al. 2017; Gautam and Singh 2020; Upreti et al. 2023). Kishore et al. (2014) advocated for reducing capital subsidies on solar pumps, asserting that private benefits from solar pumps significantly exceed public benefits. Furthermore, additional issues are associated with subsidy-linked programs: limited financial resources, crowding-out autonomous adoption, discouragement of cost-cutting innovations, and bias towards large farmers. Instead, it is proposed that solar pumps be promoted through institutional financing without high subsidies. Raymond and Jain (2018) also recommend promoting solar pumps through interest subvention rather than capital subsidies.

In India, the use of solar energy for agriculture is low. The high initial investment, lack of finance, poor functioning of solar pumps at lower groundwater levels, and weak institutional arrangements have been identified as significant constraints to the adoption of solar pumps (Kishore et al. 2014; Singh et al. 2017; Upreti et al. 2023; Choudhary et al. 2022). Furthermore, as solar pumps provide unlimited access to energy, they may pose a significant risk to groundwater sustainability (Shah and Kishore 2012; FAO 2017).

Several studies have advocated bundling solar pumps with micro-irrigation to harness their complementarity (Shah et al. 2016; Bassi 2017). However, there is a lack of evidence regarding the economic feasibility of bundling these two technologies. This study is one of the earliest attempts to assess the techno-economic feasibility of bundling micro-irrigation with solar pumps.

2.2. Tracking micro-irrigation and solar-powered irrigation in India

2.2.1 Micro-irrigation

The concept of micro-irrigation originated from experiments on the utilization of clay pipes for irrigation in Germany in the 1860s (Bhamoriya and Mathew 2014). Research on this technology expanded to encompass perforated pipe systems in the 1920s. The concept of modern micro-irrigation emerged in Israel in the 1930s. The availability of cost-effective, weather-resistant polyethylene plastics during the 1950s facilitated the development of modern drip irrigation systems (Wolff 1987; Roberts and Styles 1997; Postel et al. 2001). Drip-irrigation technology proliferated globally during the 1960s and the 1970s.

In India, research on drip irrigation commenced at Tamil Nadu Agricultural University, Coimbatore, in 1971. The establishment of the National Committee on the Use of Plastics in Agriculture (NCAP) in 1981 in the Department of Chemicals and Petrochemicals (DCPC) marked a significant initiative to promote the use of plastics in micro-irrigation systems. Based on its recommendations, a centrally sponsored micro-irrigation scheme was initiated in 1982-83 (Narayanamoorthy and Deshpande 1997, 1998). The National Bank for Agriculture and Rural Development (NABARD) began financing micro-irrigation systems in 1985. The drip-irrigated area expanded from 1500 hectares in 1985 to 70,000 hectares in 1992 (Chakravarty and Singh 1994; Narayanamoorthy 1997).

To scale up micro-irrigation, again a centrally sponsored scheme, 'Use of Plastic in Agriculture', was started in 1992 (Table 2.2). This led to an increase in drip-irrigated area to 2,46,000 hectares in 1998 (Polak and Sivanappan 1998). In 1995-96, the Government of India established the Rural Infrastructure Development Fund (RIDF) with NABARD, which also provided financial support for micro-irrigation. The Command Area

Table 2.2. Timeline of micro-irrigation in India

Year	Program/Scheme
1971	First experiment on micro- irrigation in Tamil Nadu University, Coimbatore
1982	Centrally Sponsored Scheme on Micro-Irrigation (CSMI)
1992	Centrally Sponsored Scheme on the Use of Plastics in Agriculture
1995	Rural Infrastructure Development Fund (RIDF) of NABARD: MI component
2004	Command Area Development and Water Management (CADWM): MI component
2004	Integrated Scheme of Oilseeds, Pulses, Oil Palm and Maize (ISOPOM)
2005	National Horticulture Mission (NHM)
2006	Centrally Sponsored Scheme on Micro-Irrigation
2007	*Rashtriya Krishi Vikas Yojana* (RKVY): MI Component
2010	National Mission on Micro-Irrigation (NMMI)
2014	National Mission on Sustainable Agriculture (NMSA), On Farm Water Management Programme (OFWM)
2015	*Pradhan Mantri Krishi Sinchayee Yojana* (PMKSY)
2022	Per Drop More Crop (PDMC) component of PMKSY transferred to RKVY

Development and Water Management (CADWM) program also extended the financial support for micro-irrigation. Micro-irrigation was also an important component of schemes like the Integrated Scheme of Oilseeds, Pulses, Oil-Palm and Maize (ISOPOM) and the National Horticulture Mission (NHM).

The Task Force on Micro-irrigation, established in 2004, estimated the potential of micro-irrigation at 69 million hectares, in contrast to its utilization of 2 million hectares. Subsequently, a centrally sponsored scheme on micro-irrigation (CSS-MI) was implemented in 2006 to expand the micro-irrigation coverage. It comprised a three-tier organizational structure. At the national level, the Executive Committee on Micro-Irrigation (ECMI) was responsible for approving the Action Plan, while NCPAH was tasked with coordination. At the state level, the State Micro-Irrigation Committee coordinated activities, and at the district level, the District Micro-Irrigation Committee was responsible for its implementation. The Precision Farming Development Centres (PFDCs) provided research and technical support to states. *Rashtriya Krishi Vikas Yojana* (RKVY), initiated in 2007, further incentivized states to promote micro-irrigation.

In 2010, CSS-MI was expanded as the National Mission on Micro-irrigation (NMMI), which remained operational until 2013-14. Effective from April 1, 2014, the NMMI was incorporated into the National Mission on Sustainable Agriculture (NMSA) and implemented it as an "On Farm Water Management (OFWM)" scheme by the Ministry of Agriculture & Farmers Welfare. In 2015-16, the central government, consolidated all water management schemes, and introduced the *Pradhan Mantri Krishi Sinchayee Yojana (PMKSY)*, which aimed to provide comprehensive solutions all along the irrigation supply chain. In 2015-16, the OFWM was integrated into the Per Drop More Crop (PDMC) component of the PMKSY. In 2022-23, the PDMC was transferred to the RKVY.

2.2.2 Solar-powered irrigation

Recognizing the potential of solar photovoltaic (PV) pumps as alternatives to diesel pumps, the Ministry for Non-Conventional Energy Sources (MNES) (now the Ministry of New and Renewable Energy Sources or MNRE) initiated a program in 1993-94 to implement 50,000 solar PV water pumping systems for irrigation and drinking water, particularly in areas not connected to the power grid (Purohit 2007) (Table 2.3). Solar pumps are promoted through capital subsidies and cheaper institutional credit flows. However, this target could not be achieved because of the high initial capital investment requirement and insufficient attractive subsidies (Yashodha et al. 2021).

Table 2.3. Timeline of solar-powered irrigation

Year	Program/Scheme
1993	Scheme to deploy 50000 solar water pumps for irrigation and drinking purposes
2008	National Action Plan on Climate Change (NAPCC)
2010	Jawaharlal Nehru National Solar Mission
2010-2013	Phase-I
2014-2017	Phase-2
2018-2021	Phase-3
2019	*Pradhan Mantri- Kisan Urja Suraksha evam Utthaan Mahabhiyan* (PM-KUSUM)
2023	PMKSUM with amendments

In June 2008, the Government of India implemented the National Action Plan on Climate Change (NAPCC). As a component of this initiative, the 'Jawaharlal Nehru National Solar Mission (JNNSM)' or 'National Solar Mission (NSM)' was initiated in 2010 with the objective of increasing the proportion of solar energy in the total energy mix. Initially, the mission aimed to achieve an installed capacity of 22 GW by 2022, which was subsequently revised to 100 GW in 2015 (PIB 2015). Until March 2017, solar irrigation pumps were implemented under the Mission's 'Off-grid and Decentralized Solar PV Applications Scheme.'

Table 2.4. Initiatives of state governments for solar-powered irrigation

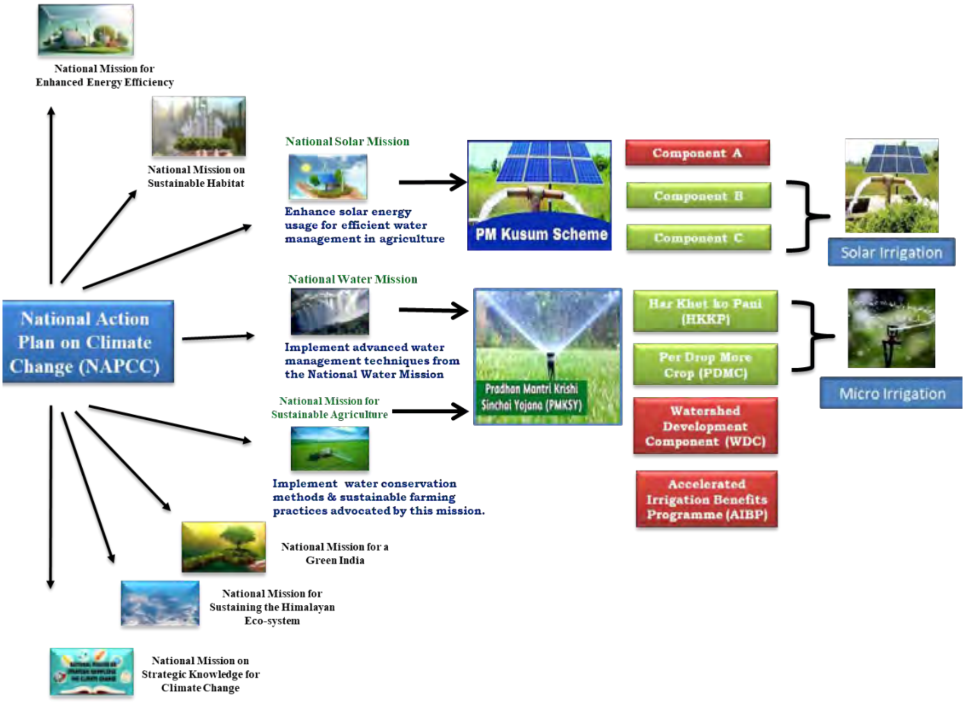
Year	Scheme name	State
2012	*Bihar Saur Kranti Sichai Yojana*	Bihar
2016	*Mukhyamantri Navin & Navnirman Urja Yojana*	
2014	*Surya Raitha Scheme* (pilot)	Karnataka
2018	*Surya Raitha Scheme*	
2014	Rajasthan Solar Pumps program	Rajasthan
2018	Hi-tech Technology/For Agriculture Solar Powered Pump Scheme	
2015	Madhya Pradesh *Mukhyamantri Solar Pump Yojana*	Madhya Pradesh
2015	Maharashtra Solar Pump Scheme	Maharashtra
2016	*UP Solar Pump Yojna*	Uttar Pradesh
2016	*Saur Sujala Yojana Scheme*	Chhattisgarh
2016	Solar Water Pumping Scheme	Haryana
2017	Tamil Nadu Solar Pump Scheme	Tamil Nadu
2014	Andhra Pradesh Solar PV Water Pumping Programme	Andhra Pradesh
2018	Andhra Pradesh Solar Pump Scheme	

In March 2019, the MNRE initiated *Pradhan Mantri-Kisan Urja Suraksha evam Utthaan Mahabhiyan (PM-KUSUM)* to promote the use of solar energy in agriculture by establishing decentralized solar power plants to replace diesel pumps and facilitate the solarization of grid-connected pumps. State governments have also taken various measures to encourage the use of solar energy in agriculture (see Table 2.4).

2.3 Institutional arrangements for micro-irrigation and solar power

Micro-irrigation is promoted under the PDMC and solar pumps under the PM-KUSUM. These initiatives were intended to contribute directly to achieving the targets enshrined in the National Solar Mission (NSM), National Water Mission (NWM), and National Mission on Sustainable Agriculture (NMSA) under the National Action Plan on Climate Change (NAPCC) (Figure 2.1).

Figure 2.1. Micro-irrigation and solar-powered irrigation under NAPCC



Micro-irrigation systems and solar pumps are provided at subsidized rates. Consequently, the institutional arrangements for their implementation directly influence adoption. Table 2.5 presents a comparison of the key features and institutional arrangements for the PDMC and PM-KUSUM.

Micro-irrigation and solar pumps are complementary technologies; however, they are promoted under two distinct centrally sponsored schemes: PDMC and PM-KUSUM. The PDMC scheme was started in 2015 as part of the PMKSY by the Department of Agriculture and Farmers' Welfare (DA&FW), while PM-KUSUM was launched in 2019 by the MNRE. In 2022-23, the PDMC is a component of the RKVY that provides more flexibility and autonomy to states in the planning and implementation of the scheme. Under RKVY, 70% of the sanctioned budget is spent on the 'Annual Action Plan,' emanating from the District Agricultural Plan (DAP). Transferring the PDMC to RKVY offers scope to integrate the District Irrigation Plan (DIP), thus making micro-irrigation an integral component of agricultural development.

Table 2.5. Comparison of PDMC and PM-KUSUM schemes

Aspect	PM-KUSUM	PDMC
Name	*Pradhan Mantri- Kisan Urja Suraksha evam Utthaan Mahabhiyan*	Per Drop More Crop
Coverage	All India	All India
Year of Initiation	2019	2015 (transferred to RKVY from 2022-23). Earlier, PDMC was part of PMKSY
Objective	Support the agriculture sector through the setting up of decentralized solar power plants, replacement of agriculture diesel pumps with solar-powered pumps, and solarization of existing grid-connected agriculture pumps	Enhance water use efficiency at farm level, improve productivity and income of farmers through adoption of micro-irrigation
Components	• **Component-A**: Install 10 GW solar capacity by setting up solar energy-based power plants with a capacity of up to 2MW. • **Component-B**: Installation of 20 lakh standalone solar-powered agriculture pumps • **Component-C**: Solarization of 15 lakh grid-connected agricultural pumps	Dissemination of micro-irrigation, viz. drip and sprinkler irrigation system

Contd.

Table 2.5 contd.

Aspect	PM-KUSUM	PDMC
Architecture/ Institutional set up	• **Two-tier** • **National Level:** Screening Committee under the chairmanship of Secretary, MNRE • **State level:** State Implementing Agency (SIA)	• **Three-tier** • **National level**: National Stewardship Council (NSC) under the chairmanship of Secretary (DA&FW) • **State level**: State Level Sanctioning Committee (SLSC) of RKVY under the chairmanship of Chief Secretary; Interdepartmental Working Group (IDWG) under the chairmanship of Secretary, Deptt. of Ag/Ag. Production Commissioner/Developmental Commissioner • **District level**: District level Implementation Committee (DLIC) under the chairmanship of District Collector/Magistrate
Planning	• SIA will assess the demand for solar pumps and submit the proposal to MNRE. • MNRE, after approval from the Screening Committee, will sanction and allocate the number of pumps to SIA • SIA installs pumps through empaneled vendors and monitors the progress till at least five years	• State Irrigation Plan (SIP) and District Irrigation Plan (DIP) • DIPs are the cornerstone for planning and implementation of different schemes related to irrigation, which will identify gaps in irrigation infrastructure after taking into consideration District Agricultural Plans (DAPs) prepared for RKVY • Annual Action Plan for PDMC will be drawn from DIPs and implemented in conjunction with the water sources created under convergence with other State/Central schemes.
Nodal Department	**National level**: MNRE **State level**: DISCOMS/State-specific Renewable Energy Development Agency/ Agriculture department/Any other department identified by state government	• **National Level:** DA&FW • **State level:** Agriculture/ Horticulture department. States are, however, free to identify nodal departments
Beneficiaries	Individual farmers/SHGs/JLGs forming groups of farmers/Co-operatives/Panchayats/FPO, WUA.	Individual farmers/ farmers' groups/ cooperatives/ FPO/WUA

Table 2.5 contd.

Aspect	PM-KUSUM	PDMC
Financial assistance (Subsidy)	**Component B&C:** • 60% of benchmark or tender cost, whichever is less, in all states except North Eastern states, J&K, Himachal Pradesh, Uttarakhand, Lakshadweep, and A&N islands, where subsidy assistance is 80%. • If the state government provides a top-up subsidy, farmers' share can be reduced. • Priority will be given to marginal and small farmers and to those with micro-irrigation system	Small and marginal farmers: 55% Other farmers: 45%
Ceiling	• Central Financial Assistance (CFA) will be restricted to 7.5 Hp pumps. However, more than 7.5 Hp pumps may be allowed without CFA. • CFA is available for pumps up to 15 Hp capacity in J&K, Ladakh, Uttarakhand, Himachal Pradesh, and the A& N and Lakshadweep Islands, as well as for cluster/community irrigation projects in high water table areas.	Subsidy is limited to 5 hectares of land per beneficiary. Beneficiaries already availed subsidy would be eligible for subsidy again for the same land after the end of the projected life of the micro-irrigation system, i.e., 7 years
Funding pattern	**Component B&C:** • 100% central government for all UTs • 50:50: Central & state government sharing for all other states (60% subsidy of benchmark cost) • 62.5: 37.5: Central & state government sharing for all other states in NE & Himalayan states, Lakshadweep and A&N Islands (80% subsidy of benchmark cost) • Farmers share: 20% in special category states and 40% in other states. Bank finance may be available up to 10% to 30% of farmers' share.	• 100% central government for all Union Territories • 90:10: Central & State government sharing for North-Eastern & Himalayan states • 60:40: Central & state government for all other states

Table 2.5 contd.

Aspect	PM-KUSUM	PDMC
Installation and maintenance	• Empaneled vendors are responsible for design, supply, installation and commissioning of solar agricultural pumps under close real-time monitoring by SIA. • AMC for 5 years, including insurance coverage for installed systems against natural calamities and theft.	• Empaneled vendors install the system under the supervision of nodal agencies. Third Party Inspection Agencies (TPIAs) inspect and verify the installation and also conduct trial run at site. All land-based interventions are geo-tagged/ geo-fenced and are made available in State Portal. • AMC free of cost for at least 3 years. • Micro-irrigation may be insured for its expected life and premium may be borne by beneficiary/state government depending on decision to be taken by the state government.
Convergence possibility	The guidelines of PM-KUSUM encourage convergence with PDMC. New solar pumps will not be installed in dark zones. Existing pumps in dark zones can be replaced with solar provided they use micro irrigation to save water	Revised guidelines (2023) encourage convergence with PM-KUSUM, *Atal Bhujal Yojana (ABJ)*, watershed development component of PMKSY, CADWM-PMKSY, and other centrally sponsored schemes

Conversely, the PM-KUSUM, in its current structure, aims to enhance economic accessibility to clean energy without considering its implications for groundwater sustainability, except in severely water-scarce regions, where solar pumps are mandatory for micro-irrigation. Existing guidelines for both the PDMC and PM-KUSUM encourage states to explore the feasibility of integrating micro-irrigation and solar pumps; however, such integration is not obligatory. Consequently, the institutional frameworks acknowledge the water-energy nexus but do not fully address it in the dissemination of either of these technologies.

The PDMC is implemented in a three-tier (National>State>District) administrative architecture as opposed to a two-tier (National>State) structure in PM-KUSUM. Thus, the PDMC has a more robust institutional setup than PM-KUSUM. Both schemes offer substantial capital subsidies, and focus on smallholders and disadvantaged farmers. For a broader outreach, there is a ceiling on financial assistance — for a solar pump of up to 7.5 Hp and for micro-irrigation up to 5 hectares. The subsidies for solar pumps are 60-80%, and for micro-irrigation 45-55% of their capital costs, depending on the geographical location and farm size. Nevertheless, small farmers encounter difficulties financing these technologies from their personal savings.

For effective implementation, both schemes advocate a 'cluster approach.' The latest guidelines (2023) of the PDMC recommend a cluster of 50 hectares for mainland states and 20 hectares for northeastern and hilly states. Micro-irrigation is promoted through Water User Associations (WUAs), Farmers Producers Organizations (FPOs), Self-Help Groups (SHGs), and Cooperatives. Individuals for collective action are provided higher financial assistance (55%). The organization can utilize an administrative/institutional charge of 3% of the project cost. Similarly, PM-KUSUM incentivizes a collective approach for the adoption of solar pumps of 15 Hp.

Farmers are provided with post-installation maintenance services for five years for solar pumps, three years for micro-irrigation systems, and insurance against natural calamities and theft.

However, institutional setups vary across states. Gujarat, Andhra Pradesh, and Uttar Pradesh have dedicated agencies for implementing micro-irrigation. Such agencies are absent for solar pumps.

2.4 Adoption of micro-irrigation and solar-powered irrigation

2.4.1 Micro-irrigation

The area under micro-irrigation increased from 0.23 million hectares in 1985 to 15.59 million hectares in 2023 (Figure 2.2) but at an accelerated rate after 2005 (Figure 2.3). Between 2005 and 2010, micro-irrigation was promoted under NHM, CSMI, and RKVY. Efforts to disseminate micro-irrigation technologies intensified later on. In 2015-16, all water management-related schemes converged into the newly launched PMKSY, and micro-irrigation was promoted under its Per Drop More Crop (PDMC) component. This led to a quantum jump in micro-irrigation; between 2015 and 2023, the area under micro-irrigation increased by 10 lakh hectares per annum.

Figure 2.2. Trend in area under micro-irrigation in India

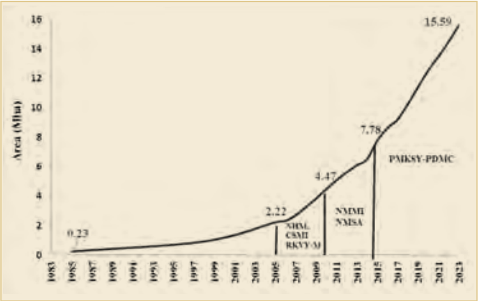
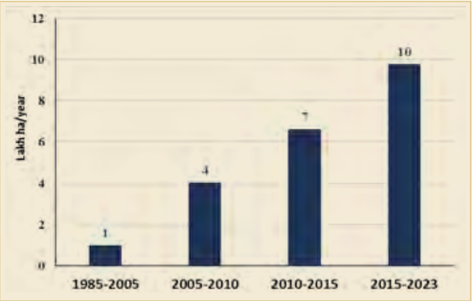


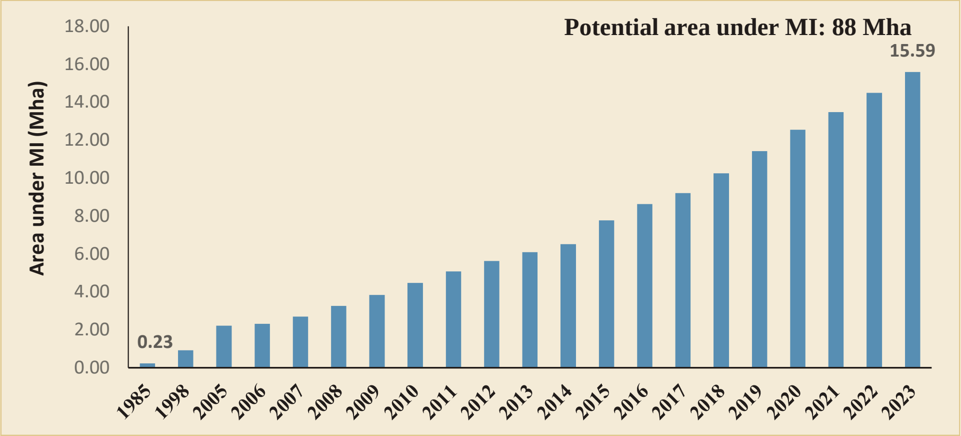
Figure 2.3. Per annum incremental area under micro-irrigation in India



Although the area under micro-irrigation increased at an annual rate over 9% during the past four decades, it currently covers 15.59 million ha, which is substantially less than the estimated potential of 88 million hectares (Figure 2.4). If this rate persists, the potential could be realized within 20 years.

It is estimated that at the current level of adoption, micro-irrigation conserves 11.22 BCM of groundwater. If it increases at a rate of 7% per annum, the entire potential of micro-irrigation will be exploited by 2049, leading to the conservation of 65 BCM of groundwater. Conserved water can be used to irrigate an additional 33 million hectares, or for other purposes.

Figure 2.4. Actual *versus* potential area under micro-irrigation in India



Significant inter-state disparities exist in the adoption of micro-irrigation. 79% of the total micro-irrigated area is concentrated in six states: Karnataka, Rajasthan, Maharashtra, Andhra Pradesh, Gujarat, and Tamil Nadu (Table

2.6). The adoption of micro-irrigation varies from less than 2% in Punjab, Jammu & Kashmir, and Uttar Pradesh to as high as 80% in Andhra Pradesh. States with substantial potential but low adoption rates can be prioritized for micro-irrigation implementation. Uttar Pradesh is such a case, accounting for one-fourth of the total potential area for micro-irrigation, yet exhibiting an adoption rate of only 2%.

It should be noted that the available estimates of micro-irrigation are based on data from publicly funded schemes. Information on micro-irrigated areas using water purchased from private markets is unavailable. Given the limited financial resources but substantial potential, establishing an ecosystem for a self-sustaining market for micro-irrigation is imperative.

Table 2.6. State-wise potential and actual adoption of micro-irrigation in 2022-23

State	Estimated potential area (Lakh ha)	Actual area (Lakh ha)	Share in total area (%)	Adoption (%)
Karnataka	38.6	26.0	17	67
Rajasthan	92.8	22.9	15	25
Maharashtra	45.1	22.1	14	49
Andhra Pradesh	25.2	20.1	13	80
Gujarat	75.2	18.2	12	24
Tamil Nadu	32.0	13.3	9	41
Haryana	49.2	7.2	5	15
Madhya Pradesh	118.1	7.1	5	6
Chhattisgarh	14.1	4.1	3	29
Uttar Pradesh	201.7	3.7	2	2
Telangana	30.8	3.5	2	12
Odisha	7.0	2.0	1	28
West Bengal	35.0	1.4	1	4
Bihar	41.7	1.3	1	3
Punjab	65.5	0.6	0.4	1
Jharkhand	1.9	0.5	0.3	29
Assam	2.3	0.4	0.3	18
Kerala	3.3	0.4	0.2	11
Uttarakhand	4.4	0.3	0.2	8
Himachal Pradesh	0.6	0.1	0.1	24
Jammu & Kashmir	1.6	0.02	0.01	1
India	887	156	100	18

2.4.2. Solar-powered irrigation

Solar energy use has increased faster than micro-irrigation. The number of installed solar pumps has increased from 11626 in 2013 to 501673 in 2022 (Figure 2.5). Nevertheless, they constitute only 2.3% of the total 21.5 million

GEDs (Table 2.7). Utilizing data from the most recent Minor Irrigation Census (2017-19), the potential energy capacity of 21.5 million GEDs is estimated at 102 GW. Realizing this potential by 2030 could contribute 36.6% to the goal of installing 280 GW of solar energy.

Nevertheless, the installed solar power capacity of 2.7 GW for irrigation constitutes merely one percent of the target of 280 GW, owing to the limited adoption (2.6%) of solar pumps.

Figure 2.5. Trend in solar pumps installation in India

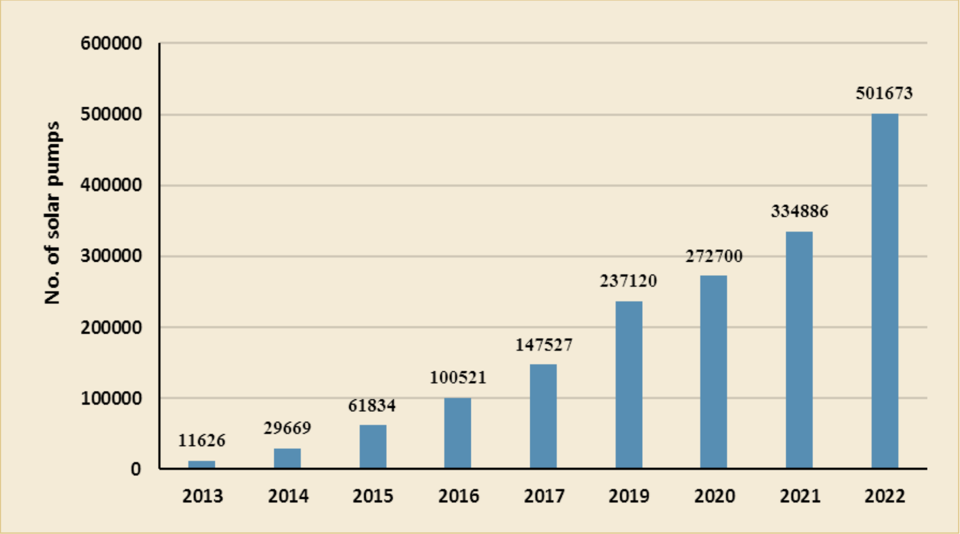


Table 2.7. Potential and adoption of solar-powered irrigation in India

Particulars	Values
Total solar potential (MW)	748990
Targeted installed solar capacity by 2030 (MW)	280000
Estimated solar potential from irrigation (MW)	102438
Installed capacity in PMKSY (till Nov 2023) (MW)	2704
Total number of groundwater extraction devices (no.)	21547401
Solar pumps installed (till Dec 2022) (no.)	501673
Adoption rate based on capacity installed (%)	2.6
Adoption rate based on number of pumps (%)	2.3
Potential contribution of irrigation to targeted solar capacity	
2.64% (existing) adoption	1.0
5% adoption	1.8
10% adoption	3.7
20% adoption	7.3
50% adoption	18.3
100% adoption	36.6

Our estimations indicate that at present, the solarization of diesel/electric wells reduced 1.05 million tons of CO_2 per annum and has the potential to reduce 45 million tons per annum if all diesel/electric-operated wells are solarized. This would require an annual growth of 14.9% for solar pumps by 2050.

Significant regional variations exist in the potential, the installed capacity, and the adoption of solar pumps (Table 2.8). Two-thirds of the total solar power potential for irrigation is concentrated in six states, namely Uttar

Table 2.8. State-wise solar-powered irrigation potential and actual adoption in 2022-23

State	Total solar potential (MW)	Solar potential from irrigation (MW)	Installed capacity in irrigation/ PM-KUSUM (as on November 2023) (MW)	Total number of wells, 2017-19 (no.)	Installed solar pumps as on November 2023 (no.)	Adoption (%)
Uttar Pradesh	22830	20685	218	3935122	41423	1.1
Maharashtra	64320	12011	288	3224475	49036	1.5
Rajasthan	142310	10376	596	1453540	108644	7.5
Punjab	2810	8699	81	1173740	16710	1.4
Tamil Nadu	17670	8203	66	1999607	7927	0.4
Gujarat	35770	7416	54	1350949	12805	0.9
Madhya Pradesh	61660	7008	94	2214089	25138	1.1
Telangana	20410	6853	9	1558342	424	0.0
Karnataka	24700	5789	30	1249845	7734	0.6
Andhra Pradesh	38440	5687	88	1080875	34045	3.1
Haryana	4560	2484	488	219455	42153	19.2
Bihar	11200	2283	21	652903	2813	0.4
West Bengal	6260	1701	13	324409	653	0.2
Chhattisgarh	18270	1029	387	330385	119282	36.1
Odisha	25780	876	28	344436	10689	3.1
Assam	13760	526	9	150027	45	0.0
Jharkhand	18180	311	50	138887	13592	9.8
Uttarakhand	16800	264	14	51769	333	0.6
Kerala	6110	98	23	60942	848	1.4
Himachal Pradesh	33840	51	33	10648	484	4.5
Jammu and Kashmir	111050	37	25	10463	501	4.8
Total	748990	102438	2704	21547401	501673	2.3

Pradesh, Maharashtra, Rajasthan, Punjab, Tamil Nadu, and Gujarat. Notably, the adoption of solar-powered irrigation in these states, with the exception of Rajasthan, remains low. It is imperative to target states with a high potential but limited reliance on solar pumps. Approximately 72% of the solar pumps are located in Chhattisgarh, Rajasthan, Maharashtra, Haryana, and Uttar Pradesh. Chhattisgarh, Haryana, Jharkhand, and Rajasthan have demonstrated superior performance in the adoption of solar pumps.

The adoption of both micro-irrigation and solar pumps has demonstrated a positive trend. However, there remains substantial untapped potential for both technologies. The adoption varies significantly across different states. Notably, states with higher adoption rates of micro-irrigation tend to have lower adoption rates of solar pumps and vice versa. For instance, Chhattisgarh accounts for the largest proportion of solar pumps (23.8%), yet it has only 2.6% of the total area under micro-irrigation (Table 3.5). Conversely, Karnataka leads in the area irrigated through micro-irrigation at 16.6% but comprises only 1.5% of the total solar pumps.

♦♦♦

3 Feasibility of Bundling Micro-irrigation and Solar Power

Micro-irrigation and solar power are complementary technologies that offer numerous economic and environmental benefits. However, these technologies have not yet been promoted or adopted in conjunction. This chapter examines the feasibility of integrating micro-irrigation systems with solar pumps.

3.1. Rationale for bundling micro-irrigation and solar power

Groundwater extracted using solar pumps, when applied as flood irrigation (a widely adopted method), meets the irrigation requirement of a smaller area or fails to fulfill the requirement because of the lower water discharge from solar pumps compared with electric or diesel pumps. This phenomenon is particularly evident in low-capacity (Hp) solar pumps. Micro-irrigation enhances conveyance efficiency and thus mitigates this deficiency.

The Government of India has recently increased the maximum permissible capacity of pumps from 5 Hp to 7.5 Hp. However, there are concerns that this modification may increase the risk of groundwater over-exploitation owing to unlimited access to solar energy.

A combined approach integrating solar power and micro-irrigation systems aligns with the concept of the water-energy nexus. This strategy has the potential to substantially enhance water and energy efficiencies, thereby reducing irrigation costs and increasing agricultural productivity.

Micro-irrigation and solar pumps are promoted under the PDMC and PM-KUSUM, respectively. The operational guidelines of both schemes encourage states to utilize their complementary nature. In regions where groundwater has been significantly overexploited, it is mandatory to implement solar pumps in conjunction with micro-irrigation systems.

3.2. Potential benefits of bundling micro-irrigation and solar power

The solarization of grid-connected irrigation pumps conserves electricity and presents an opportunity for farmers to generate additional revenue from the sale of excess electricity. Moreover, the coupling of micro-irrigation with solar power reduces the energy consumption (owing to water conservation) for irrigation, and surplus power can be sold to utility companies. Farmers utilizing off-grid pumps equipped with a Universal Solar Pump Controller (USPC) can allocate excess power to alternative applications, including the operation of chaff cutters, flour mills, cold storage facilities, driers, and battery recharging.

High-capacity solar pumps increase the likelihood of groundwater over-extraction owing to unrestricted energy access. The integration of micro-irrigation systems with solar pumps can mitigate this risk substantially. Consequently, micro-irrigation contributes to the reduction of negative externalities associated with solar power on groundwater sustainability.

Solar-powered micro-irrigation provides dual benefits: lower energy costs (particularly for farmers using diesel-operated pumps) and higher crop yields. Nevertheless, farmers may incur additional costs of approximately 20% when coupling solar power with micro-irrigation. However, incremental benefits outweigh incremental costs. Thus, bundling micro-irrigation and solar pumps reduces the time lag in recovering the capital cost of installing solar pumps, owing to the higher incremental returns from micro-irrigation.

Furthermore, the solarization of one fossil-fuel (electricity/diesel)-based GED can conserve 2875 units of electricity, 911 liters of diesel, and reduce CO2 emissions by 2.1 tons annually. This is accompanied by a 15-50% reduction in water consumption due to micro-irrigation. Moreover, solar-powered micro-irrigation mitigates the fiscal burden of electricity subsidies, thereby improving the financial health of DISCOMS. In 2020-21, irrigation accounted for 64.7% of the total electricity subsidies, amounting to Rs 724.14 billion. Additionally, solarization has the potential to reduce expenditures on diesel imports.

3.3. Challenges in bundling micro-irrigation and solar power

While bundling micro-irrigation and solar-powered irrigation technologies offers several benefits, there are numerous technical, economic, and institutional challenges associated with their integration.

***Technical challenges*:** Solar pumps, owing to their dependence on solar radiation, have low discharge pressure, resulting in inconsistent water flow for irrigation, whereas micro-irrigation systems, particularly sprinklers, require a steady water supply. The efficacy of micro-irrigation is contingent on the water discharge from solar pumps. Consequently, solar-powered micro-irrigation systems must be tailored to specific locations, considering factors such as the water head and other relevant parameters. Experts recommend augmenting the pump size by 20-25 feet of head to achieve the necessary pressure. Furthermore, the system may require automation to compensate for variable water flow at different times of the day.

***Economic challenge*:** The high initial capital cost is a significant factor impeding the adoption of solar-powered micro-irrigation systems. The PM-KUSUM has fixed benchmark cost for a 7.5 Hp solar pump (without USPC) at Rs 3,49,566. The benchmark cost of a micro-irrigation system under PDMC is Rs 69,218 for a farm size of 1.08 hectares (Table 3.1). The government provides a 60% subsidy for the capital cost of solar pumps and 45-50% for micro-irrigation systems. Farmers are responsible for the remaining cost, estimated at Rs 1,70,975 for smallholders and Rs 1,77,896 for others. Of this, 18-21% were for micro-irrigation systems. For small farmers, financing marginal money from personal savings is a challenge. Commercial banks are supposed to finance up to 75% of this amount. Some states (e.g., Uttar Pradesh) also offer additional subsidies for micro-irrigation, further reducing the cost of solar-powered micro-irrigation systems.

Table 3.1. Average cost of solar and micro-irrigation at national level, 2023

Particulars	Micro-irrigation*		Solar pump (7.5Hp)	Solar-powered micro-irrigation	
	Marginal & small farmers	Other farmers		Marginal & small farmers	Other farmers
Benchmark cost (Rs)	69218		349566	418784	
Subsidy (%)	55	45	60	-	-
Margin money (Rs)	31148	38070	139826	170975	177896

*for 1.08-hectare land (all-India average)

Table 3.2. presents the installation costs of different-sized solar-powered micro-irrigation systems. In the absence of capital subsidy, the cost of a solar-powered micro-irrigation system ranges from Rs 1.68 lakh to Rs 7.66 lakh, contingent upon the capacity of solar pumps and the area coverage under micro-irrigation. With a 60% subsidy on solar pumps and 55% on micro-irrigation, farmers are required to invest Rs 0.70 to Rs 3.80 lakh.

Table 3.2. Cost of installing solar-powered micro-irrigation systems, 2023

Lakh Rs

Particulars		Area under micro-irrigation (Ha)									
		1 ha	2 ha	3 ha	4 ha	5 ha	1 ha	2 ha	3 ha	4 ha	5 ha
		Without capital subsidy					With capital subsidy *				
Pump capacity	1 HP	1.68	2.32	2.96	3.60	4.25	0.70	0.99	1.28	1.57	1.86
	2 HP	1.92	2.56	3.20	3.84	4.49	0.80	1.09	1.38	1.67	1.95
	3 HP	2.32	2.96	3.60	4.24	4.88	0.96	1.25	1.53	1.82	2.11
	5 HP	3.22	3.86	4.50	5.14	5.78	1.32	1.61	1.90	2.19	2.47
	7.5 HP	4.14	4.78	5.42	6.06	6.70	1.69	1.98	2.26	2.55	2.84
	10 HP	5.10	5.74	6.38	7.02	7.66	2.65	2.93	3.22	3.51	3.80

*60% solar subsidy + 55% MI subsidy. The subsidy for solar pumps is restricted to 7.5 Hp.

Return on investment is a significant factor in farmers' decision-making processes regarding the adoption of solar-powered micro-irrigation. An analysis of the savings in diesel and electricity costs from adopting solar-powered micro-irrigation was conducted (Table 3.3). For operating a 6.34 Hp electric pump for an average of 605 hours annually, a farmer incurs an expenditure of Rs 8,251 at a subsidized tariff of Rs 2.87/KWh. The operational cost of a diesel pump of equivalent capacity for the same duration is tenfold, amounting to Rs 81,894. The implementation of solar-powered micro-irrigation can reduce these costs.

Furthermore, the increase in water-use efficiency attributable to micro-irrigation (20%) is converted into an energy equivalent and valued at the prevailing price. Consequently, the total savings (including energy savings from micro-irrigation) on substituting an electric pump of 7.5 Hp are estimated at Rs 9,901, and a diesel pump at Rs 98,273 for an average farm of 1.08 hectares. It is noteworthy that additional benefits, such as yield improvements and a reduction in the cost of other inputs, have not been considered in the calculation of economic returns from the solarization of fossil fuel-based pumps.

Table 3.3. Parameters for economic analysis of solar-powered micro-irrigation system

Particulars	Value	Source
Benchmark cost of 7.5 Hp solar system and micro-irrigation system for 1.08 ha (Rs)	418784/- (without subsidy) 170975/- (with subsidy)	PM-KUSUM and PDMC
Average Hp of electric/ diesel pumps	6.34	Weighted average from 6th MI census
Annual operating hours (Hours)	605	
Life of the solar-powered micro-irrigation system (years)	25 : Solar pump 7 : Micro-irrigation	Assumed
Power tariff (subsidized) for estimating savings in power bill (Rs)	2.87 / KWh +50/Hp/ month	Estimated using data from Power Finance Corporation Ltd.
Power tariff (unsubsidized) for estimating savings in power bill (Rs)	6.30/ KWh +50/Hp/ month	
Diesel price for estimating savings in fuel cost (Rs)	85/lit	Assumed
Discount factor (%)	6	Assumed

Table 3.4 presents the internal rate of return (IRR) and payback period for solar-powered micro-irrigation systems under various pump capacities and capital subsidy scenarios. The subsidy scenarios represent combinations of capital subsidies on solar pumps (i.e., 20 basis point increments on the existing 60% subsidies), subsidies on micro-irrigation systems (45%, 55%, and 90% for different farm classes and supplementary subsidies by state governments), and electricity subsidies.

Table 3.4. Economics of replacement of an electric/diesel-operated pump by solar-powered micro-irrigation system under different subsidy scenarios

Capital subsidy regime	Electricity subsidy				Diesel pumps	
	No power subsidy		Subsidized power			
	IRR (%)	Payback period (years)	IRR (%)	Payback period (years)	IRR (%)	Payback period (years)
No subsidy	4	-	-1	-	23	~5
60% on solar+ 45% on MI	14	11	6	-	55	<2
60% on solar+ 55% on MI	15	10	7	-	57	<2
60% on solar+ 90% on MI	18	7	9	18	67	<2
80% on solar+ 45% on MI	24	5	13	14	91	<2
80% on solar+ 55% on MI	26	5	14	12	97	<2
80% on solar+ 90% on MI	34	4	19	7	128	<1

The Internal Rate of Return (IRR) from investment in a solar-powered micro-irrigation system replacing a diesel pump is estimated at 55-67% with existing capital subsidies and 23% without subsidies. This indicates that investment in solar-powered micro-irrigation may be recovered in approximately two years (or approximately five years without capital subsidies) through savings in diesel costs alone.

Nevertheless, the Internal Rate of Return (IRR) from investment in solar-powered micro-irrigation to replace an electric pump is not economically viable. The IRR remains low (6-9%), even with capital subsidies on solar pumps and micro-irrigation. This is attributable to subsidies on electricity for irrigation. This finding suggests that as long as the electricity for irrigation remains subsidized, investment in solar-powered micro-irrigation is not economically advantageous.

Suppose that there is no subsidy for electricity (Rs 6.4 /KWh); the IRR increases to 4%, and with capital subsidies for solar pumps and micro-irrigation it increases to 14-18%. At current subsidy levels for solar power and micro-irrigation systems, break-even can be achieved in 7-11 years.

The economic viability of solar-powered micro-irrigation systems can be improved by reducing electricity subsidies and increasing capital subsidies for solar-based micro-irrigation. Suppose that capital subsidies for solar pumps are increased by 20 basis points. The IRR improves, and the payback period reduces to less than two years if it replaces diesel pumps and 4-5 years if it replaces electric pumps without electricity subsidies. These findings suggest the rationalization and reallocation of electricity subsidies for solar pumps to improve the economic viability of solar-powered micro-irrigation systems.

In summary, (i) replacement of diesel pumps by solar-powered micro-irrigation is economically feasible, even without subsidies on solar pumps and micro-irrigation systems; and (ii) investment in solar-powered micro-irrigation systems to replace electric pumps is not financially feasible from the savings in electricity bills without heavily subsidizing solar pumps. Even at the existing levels of subsidies for solar pumps and micro-irrigation, investment is unlikely to be recovered if electricity for irrigation remains subsidized. Repurposing electricity subsidies as capital subsidies for solar pumps will improve the economic feasibility of solar-powered micro-irrigation.

***Institutional challenges*:** As previously indicated, solar pumps and micro-irrigation are promoted independently under two distinct schemes: solar pumps under PM-KUSUM, and micro-irrigation under PDMC. The guidelines of both schemes explicitly delineate the potential for synergy between solar pumps and micro-irrigation; however, they lack specificity regarding institutional arrangements and strategic plans for convergence. The National Stewardship Council (NSC) of the PDMC, the apex committee responsible for providing strategic directions and planning, does not include representatives from the MNRE, and the converse is also true. To facilitate effective convergence, apex committees must include representatives from their respective ministries.

At the state level, PDMC and PM-KUSUM are implemented independently in most states, with the exception of Rajasthan, where the Department of Horticulture serves as the nodal agency for both schemes. However, a state has the discretion to select implementing agencies (SIA) for their convergence, either by assigning both schemes to the same SIA or through institutional arrangements (e.g., inter-departmental working groups) for their co-implementation. Andhra Pradesh and Gujarat have established dedicated Special Purpose Vehicles (SPVs) to implement PDMC. The implementation of PM-KUSUM can be entrusted to these SPVs.

The PDMC is now a component of the RKVY, which provides greater autonomy and flexibility to states in the planning and implementation of micro-irrigation. This provides an opportunity to integrate micro-irrigation as a fundamental component of the comprehensive agricultural development strategy at the district level by incorporating it into the District Agricultural Plan (DAP). However, PM-KUSUM lacks this provision. The DAPs can be re-evaluated to align the PM-KUSUM with the PDMC.

Synchronizing the activities of these two schemes presents a significant challenge for the joint promotion. For successful convergence, processes such as vendor empanelment, supply order, system design, delivery, and installation of solar pumps and micro-irrigation must be completed concurrently. This can only be achieved when both schemes are implemented by the same SIA or combined as a single scheme. This also necessitates collaboration among manufacturers of solar pumps and micro-irrigation systems. Nevertheless, manufacturers and vendors supplying equipment are distinct entities that operate independently.

Table 3.5. Distribution of installed solar pumps and area under micro-irrigation across states in 2022-23

Area under micro-irrigation		Installed solar pumps	
State	**Share in total area (%)**	**State**	**Share in total installed solar pumps (%)**
Karnataka (KA)	16.65	Chhattisgarh	23.78
Rajasthan (RJ)	14.67	Rajasthan	21.66
Maharashtra (MH)	14.16	Maharashtra	9.77
Andhra Pradesh (AP)	12.91	Haryana	8.40
Gujarat (GJ)	11.64	Uttar Pradesh	8.26
Tamil Nadu (TN)	8.51	Andhra Pradesh	6.79
Haryana (HR)	4.62	Madhya Pradesh	5.01
Madhya Pradesh (MP)	4.52	Punjab	3.33
Chhattisgarh (CG)	2.60	Jharkhand	2.71
Uttar Pradesh (UP)	2.36	Gujarat	2.55
Telangana (TG)	2.27	Odisha	2.13
Odisha (OD)	1.27	Tamil Nadu	1.58
Bihar (BR)	0.81	Karnataka	1.54
Punjab (PB)	0.37	Bihar	0.56
Jharkhand (JH)	0.35	Telangana	0.08
Assam (AS)	0.26	Assam	0.01
India	100.00 (15.59)	India	100.00 (501673)

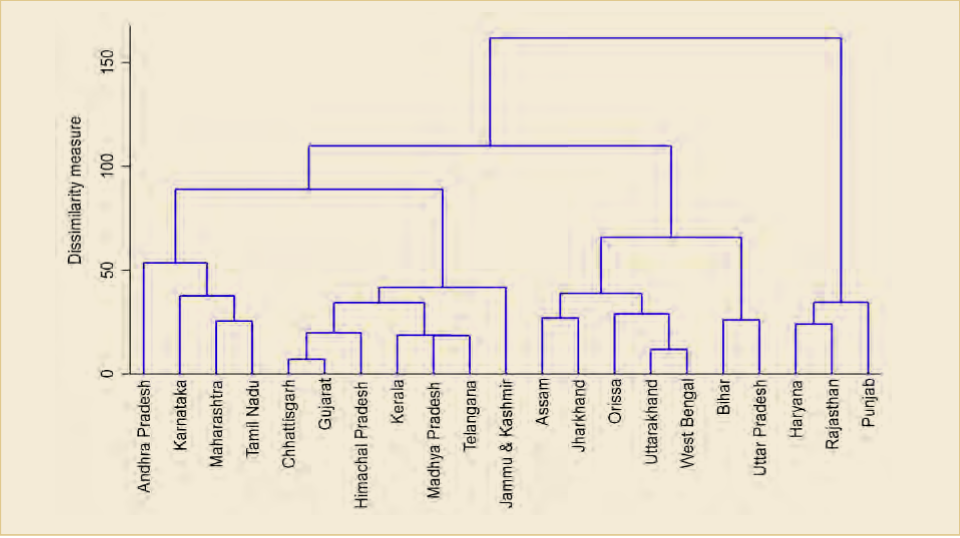
The parentheses in Col. 2 show the total area under micro-irrigation in million hectares, and in Col 4 is the number of solar pumps installed until 2022-23.

Another major challenge in the convergence of the two schemes is their prioritization. In regions experiencing over-exploitation of groundwater, the micro-irrigation is encouraged and not the solar energy, perhaps because of the increased risk of over-extraction of groundwater due to unrestricted access to solar power. Furthermore, spatial heterogeneity exists in the adoption of solar pumps and micro-irrigation. States with better adoption of micro-irrigation lag in adopting solar pumps and *vice-versa* (Table 3.5). For instance, Chhattisgarh has approximately one-fourth of the total solar pumps, but it shares only 2.6% of the total area under micro-irrigation. The correlation coefficient between the states' shares in solar pumps and the area under micro-irrigation is only 0.25. Rajasthan and Maharashtra are among the top five states that have adopted micro-irrigation and installed solar pumps. If we exclude these, the correlation coefficient is marginally negative (-0.058). This means that the adoption of micro-irrigation and solar pumps is independent of each other. This is a challenge as well as an opportunity for solar-powered micro-irrigation. The poor adoption of a scheme in a state may adversely affect companion scheme adoption. Conversely, a better-performing scheme may improve the performance of the other schemes. For strategic planning, it is essential to understand the differences in the performance of schemes in different states.

3.4. Prioritizing states for bundling micro-irrigation and solar pump

States for bundling solar pumps and micro-irrigation have been identified based on four indicators: share of the actual area in the potential area for micro-irrigation (%), share of horticultural crops in the gross cropped area (%), share of diesel-operated wells in the total wells (%), and stage of groundwater utilization (%). States with low penetration of micro-irrigation but higher adoption of horticultural crops demonstrate significant potential for promoting micro-irrigation. Conversely, solar pumps can be effectively promoted in states where the groundwater level is low and is predominantly extracted using diesel pumps. States exhibiting homogeneous characteristics are categorized into clusters, as illustrated in Figure 3.1.

Figure 3.1. Complete Linkage Hierarchical Clustering (CLHC)



The states of Assam, Jharkhand, Odisha, Uttarakhand, West Bengal, Bihar, and Uttar Pradesh exhibit comparatively low levels of micro-irrigation, higher areas under horticultural crops, higher proportions of diesel pumps, and low levels of groundwater development. Consequently, these states should be prioritized for the promotion of solar-powered micro-irrigation systems.

Table 3.6. Categorization of states based on CLHC technique

Cluster	States	Share of actual to potential area under MI (%)	Share of horticulture area in GSA (%)	Share of diesel wells in total wells (%)	Groundwater utilization stage (%)
1	AP, KA, MH, TN,	59.35	8.73	3.00	57.25
2	CG, GJ, HP, KL, MP, TG, JK	17.57	8.83	1.78	45.40
3	AS, JH, OD, UK, WB, BR, UP	9.80	6.95	58.49	42.66
4	HR, RJ, PB	12.35	1.40	9.58	150.40

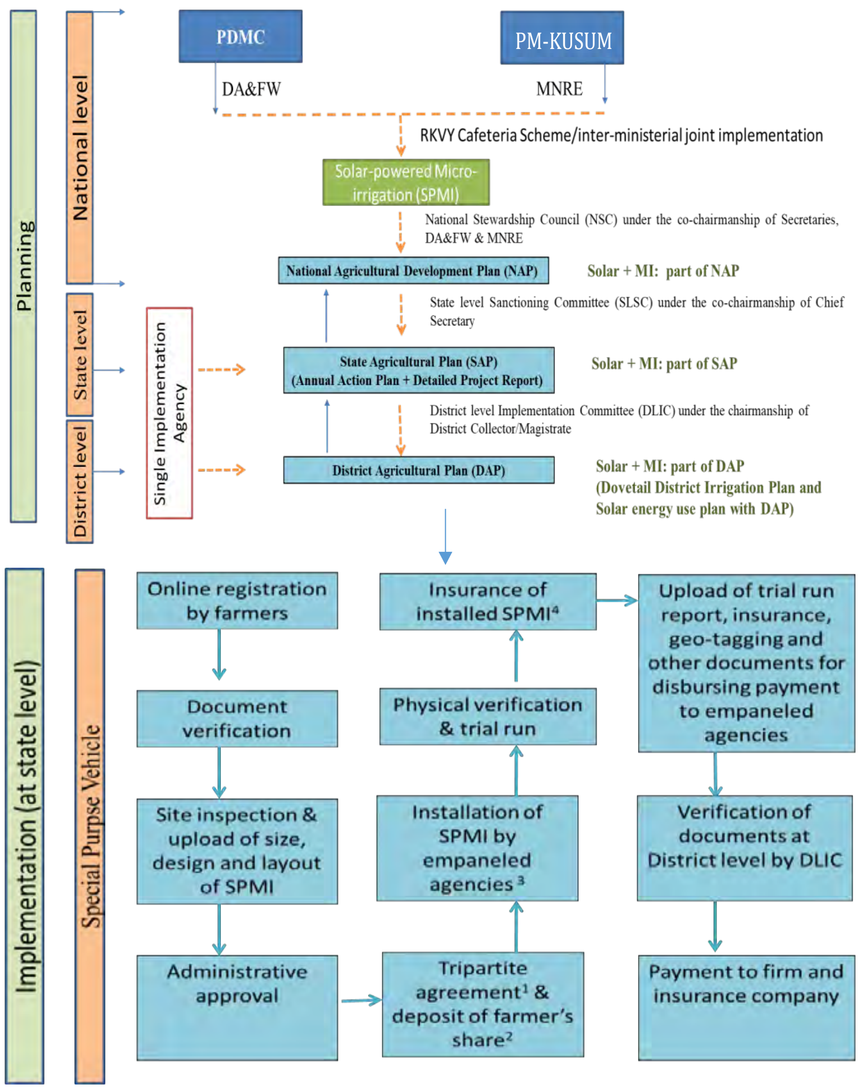
3.5. Institutional framework for convergence

An institutional framework to leverage the synergy between solar pumps and micro-irrigation is proposed in Figure 3.2. It addresses the planning and implementation aspects of the PMKSY and PM-KUSUM. RKVY (micro-irrigation) has a three-tier planning and implementation process: agricultural development plan at the district level (DAP), consolidation of DAPs into state agricultural plans (SAP), and integration of SAPs into the National Agricultural Development Plan (NAP). It also includes provisions for the promotion of solar pumps. Consequently, PM-KUSUM (components B and C) implemented by the MNRE can be transferred to RKVY or implemented collaboratively as an inter-ministerial scheme. In the latter case, the existing National Stewardship Council (NSC) could be expanded to include a representative from the MNRE.

For joint implementation, a plan for solar power for irrigation should be prepared at the district level by the District Level Implementation Committee (DLIC) of RKVY, dovetailing with existing DAPs. Similarly, SAPs and NAP can be revisited to include solar pumps. If the PDMC and PM-KUSUM are jointly implemented by DA&FW and MNRE, a Single Implementation Agency (SIA) should be in place.

Special Purpose Vehicles (SPVs) have demonstrated efficacy in promoting micro-irrigation in Andhra Pradesh and Gujarat. These mechanisms can be expanded to include solar pumps. In addition, we propose a comprehensive digitization of the implementation procedure, encompassing the registration of beneficiaries through post-verification.

Figure 3.2. Proposed institutional framework for the convergence of solar and micro-irrigation.



Notes: [1]Tripartite agreement including farmers, empaneled agency, and SPV; [2]Deposit farmer's contribution and subsidy in Escrow account; [3]Inter-industry (solar and MI) convergence [4]Insurance fee by state or farmer or included in the tender cost of SPMI

♦♦♦

4 Insights from Micro-irrigation and Solar Energy Use in Select States

This chapter examines the implementation processes of micro-irrigation and solar pump schemes in Rajasthan and Uttar Pradesh. In Rajasthan, PDMC and PM-KUSUM are implemented by the Department of Horticulture, and it is mandatory for farmers who avail themselves of subsidies for solar pumps to have a micro-irrigation system to mitigate the perceived threat of groundwater over-extraction due to unrestricted access to solar energy. This has resulted in an increase in the adoption of micro-irrigation. Conversely, Uttar Pradesh has the maximum potential for micro-irrigation, but has minimal adoption.

4.1. Micro-irrigation and solar power use in Rajasthan

4.1.1. Status of groundwater irrigation

Agriculture is the predominant economic activity in Rajasthan. It contributes 27% to the gross state domestic product (GSDP) and employs 62% of the total workforce. Approximately half of the net sown area is irrigated, primarily using groundwater (Table 4.1). The current state of groundwater development is 149% (CGWB 2023), compared to the national average of 59%. In other words, groundwater withdrawal exceeded its recharge by 49%. Over 72% of the groundwater assessment units (blocks/tehsils) have been overexploited, and 68% of the wells have a depth exceeding 10 mbgl. Thus, farmers rely on high-power submersible pumps to extract groundwater, thereby placing groundwater resources at risk of depletion.

The state government has been promoting micro-irrigation to prevent falling groundwater levels. By 2022-23, approximately 2.3 million hectares have been brought under micro-irrigation — 86% through sprinklers and 14% through drippers. The adoption rate is higher (25%) than the national average (18%). The government has also been trying to harness solar energy for irrigation. By 2022-23, more than 100 thousand solar pumps have been installed, and the adoption rate is more than three times the national average. Because groundwater is under severe stress, bundling micro-irrigation and solar pumps are mandatory.

Table 4.1. Status of irrigation and groundwater in Rajasthan

Particulars	Rajasthan	India
Irrigation coverage (%) : 2021-22	49.22	55.26
Share of groundwater in NIA (%): 2021-22	74.10	60.45
Area under micro-irrigation (Lakh ha): 2022-23	22.90	15.59
Sprinkler (% of total)	85.75	53.10
Drip (% of total)	14.25	46.90
Share of area in potential area under MI (%): 2022-23	24.64	17.59
No. of installed solar pumps (no.): 2022-23	108644	501673
Share of solar pumps in total pumps (%)	7.47	2.30
Stage of groundwater utilization (%): 2023	148.77	59.26
Categorization of assessment units (no): 2023	302	6553
Semi-critical (% of total)	7.28	10.65
Critical (% of total)	7.61	3.04
Over-exploited (% of total)	71.52	11.23
Depth to water level (mbgl): May 2019	0.52 to 128.15	-
Wells with > 10 mbgl water level (%): May 2019	68.66	-

4.1.2. Impact of micro-irrigation on groundwater level

Although micro-irrigation enhances water-use efficiency, leading to savings in groundwater at the farm level, it does not necessarily translate into savings at a higher geographical scale, that is, the regional/basin level. Adopting micro-irrigation leads to an increase in irrigated areas and a shift in cropping patterns towards water-intensive crops (Singh and Gandhi 2024; Sears et al. 2018), leading to an increase in total water demand and a further decline in groundwater level.

The impact of micro-irrigation on the groundwater level at the macro level has been assessed by employing the difference-in-difference (DID) technique, an econometric tool that provides differential effect of a treatment on a 'treatment group' against a 'control group.' There is considerable spatial heterogeneity in the adoption of micro-irrigation. Thus, we used this heterogeneity to identify the treatment and control groups to assess the impact of micro-irrigation (treatment) on the groundwater level (outcome).

Table 4.2. Inter-district variation in penetration of micro-irrigation and stage of groundwater utilization in Rajasthan

District	Cumulative area under micro-irrigation (ha): 2020-21	Gross irrigated area (ha)	Adoption of micro-irrigation (%)	Stage of groundwater utilization (%)
Sikar	258640	271356	95	161
Jhunjhunu	238495	277686	86	217
Jaipur	281115	358004	79	226
Jalore	318584	411785	77	181
Barmer	346808	461930	75	132
Jodhpur	654800	980271	67	257
Nagaur	238551	393566	61	182
Churu	172150	322427	53	126
Bikaner	437161	923555	47	137
Jaisalmer	141519	531973	27	362
Alwar	131483	532723	25	183
Sirohi	26909	139459	19	192
Chittorgarh	41672	274947	15	156
Dausa	20954	157705	13	233
Bhilwara	19948	270241	7	163
Ajmer	10836	148445	7	143
Rajsamand	3129	52089	6	123
Tonk	17790	355842	5	102
Sawai Madhopur	11618	247661	5	117
Pratapgarh	6566	142375	5	129
Hanumangarh	22992	835350	3	61
Banswara	3416	139136	2	67
Bundi	7144	308662	2	102
Jhalawar	7206	322012	2	117
Udaipur	2183	109254	2	102
Dungarpur	1138	59537	2	60
Pali	2406	188970	1	159
Kota	3697	297776	1	105
Karoli	1558	146655	1	158
Ganganagar	10040	1142291	1	40
Baran	2384	351116	1	129
Bharatpur	1813	365360	0	121
Dholpur	389	135068	0	136

The share of micro-irrigated area in the gross irrigated area is negligible for Bharatpur and Dholpur and as high as 95% for Sikar. In our analysis, we considered districts with homogenous agro-climatic conditions and groundwater development of more than 100%. These are Sikar, Jhunjhunu, Jaipur, Bharatpur, Dholpur, Karoli, Pali, Tonk, Sawai Madhopur, Ajmer, Chittorgarh, Dausa, Alwar, Nagaur, Churu. Further, of those with micro-irrigation adoption rate of more than 50% comprise the 'treated' group (i.e., Sikar, Jhunjhunu, Jaipur, Nagaur, and Churu), and the remaining serve as a 'control' group. The adoption of micro-irrigation accelerated after 2015; hence, we considered 2015 as the cutoff or treatment year (Figure 4.1). Groundwater level is the outcome variable.

Figure 4.1. Trends in groundwater level in treated and control groups

Without covariates **With covariates**

The macro impact of micro-irrigation on the groundwater level was assessed with and without covariates (i.e., cropping intensity, share of groundwater in the net irrigated area, and rainfall) to control their effect on groundwater demand and supply (recharge). Table 4.3 presents the average treatment effect on treated (ATT). The ATT is negative in both cases, indicating that micro-irrigation could not prevent the groundwater levels from falling. We expected that the negative impact of micro-irrigation on the groundwater level at the macro-level could be due to an increase in the overall demand for water for irrigation. Surprisingly, none of the covariates representing water demand are positive and significant. In other words, there is no evidence of an increase in the total demand for groundwater, which is counterintuitive, as micro-irrigation is expected to cause a rise in the demand for water at the aggregate level.

Table 4.3. Average treatment (ATT) effect on pre-monsoon groundwater level

Dependent Variable	ATT
Groundwater level (mbgl)	-4.134* (2.240) (without covariates) -4.061* (2.085) (With covariates)
Cropping intensity (%)	-10.182*** (3.662)
Groundwater share (%)	-0.461[ns] (1.286)
Rainfall (mm)	24.058[ns] (56.898)

The figures in parentheses are the standard errors of the coefficients.

Further analysis indicates a decrease in groundwater demand for irrigation in the 'treated group' and an increase in the 'control group' (Table 4.4). Conversely, the groundwater demand for domestic and industrial purposes increased in both the groups. The observed decline in groundwater levels in districts with enhanced micro-irrigation can be attributed to the increasing demand for domestic and industrial purposes. This observation leads to the conclusion that micro-irrigation conserves water; however, its sustainability is contingent on its utilization for various purposes.

Table 4.4. Change in availability and extraction of groundwater for different uses

Particulars	Groundwater availability (ha-m)			Groundwater extraction (ha-m)			Stage of groundwater extraction
	Recharge	Natural discharge	Net availability	Irrigation	Domestic and industrial	Total	
Treated districts							
2013	204225	18977	185247	294482	70737	365219	179
2020	208034	19978	188056	287570	91531	379101	185
Change(Ha-m)	3809	1000	2809	-6913	20794	13881	6
Change (%)	1.87	5.27	1.52	-2.35	29.40	3.80	3.36
Control districts							
2013	434628	40010	394618	489894	55569	545464	135
2020	383794	36493	347302	517286	59014	576300	163
Change (Ha-m)	-50834	-3517	-47316	27392	3445	30837	28
Change (%)	-11.70	-8.79	-11.99	5.59	6.20	5.65	20.70

Source: Central Groundwater Board

The concurrent installation of solar pumps and micro-irrigation systems suggests that micro-irrigation effectively mitigates the potential negative externalities of solar pumps on groundwater resources.

4.1.3. Farm-level evidence on use of solar power for micro-irrigation

A primary survey of 300 farm households was conducted in Jaipur and Sikar districts to assess the adoption of micro-irrigation and solar energy use in agriculture. Sprinkler irrigation is widely adopted in these districts because of the acute scarcity of groundwater and predominance of sandy soils, which are unsupportive of flood irrigation. Most farmers who own sprinklers are willing to adopt solar pumps, as it makes them eligible to avail subsidies on solar pumps. Once they opt for solar pumps, the beneficiaries must surrender their electricity connections compulsorily. However, there is moral hazard. Despite the installation of solar pumps, most farmers retain their electricity connections. There are three issues here. First, the government provides tariff-free electricity of 2000 units for irrigation. Second, electric pumps have high and stable discharge of water. Third, land ownership is divided among family members; hence, a family member who owns land but has no electricity connection can avail the benefits of a solar pump. Thus, farmers supplement electricity by maintaining their consumption below the tariff-free threshold level of electricity consumption. Thus, instead of replacing electricity, solar energy has become a supplementary source of energy.

4.1.4. Institutional aspects of micro-irrigation and solar power

The PM-KUSUM and PDMC schemes are implemented by a single agency, namely the Rajasthan Horticulture Development Society (RHDS) under the Directorate of Horticulture. However, there is no convergence between the two schemes. Farmers are required to apply separately to avail the benefits of these schemes, even if they have an inclination for their joint adoption.

There is a potential for streamlining the convergence process between the two schemes. The convergence initiation point is the eligibility criteria under PM-KUSUM for obtaining subsidies for solar pumps by farmers who have previously installed micro-irrigation systems (i.e., drip/sprinkler/micro-sprinkler/mini-sprinkler/raingun) and possess a minimum of 0.4 hectares of land (0.2 ha for farmers of scheduled tribes). The subsidy is 60% for a solar pump of 7.5 Hp. A 10 Hp pump is permitted for those owning at least 1.5 ha; however, the subsidy is limited to 7.5 Hp.

Under the PDMC scheme, farmers are eligible for a 70% subsidy for micro-irrigation systems (27% from the central government, 18% from the state government, and a top of 25% by the state government). For marginal, small, women, and scheduled caste/tribe farmers, the subsidy is 75% (33% from the central government, 22% from the state government, and an additional 20% from the state government).

Despite the implementing agency for the PM-KUSUM and PDMC being the same, the timing of the implementation of their activities is not synchronized. Thus, the joint installation of micro-irrigation and solar pump systems is not guaranteed.

4.2. Micro-irrigation and solar power use in Uttar Pradesh

4.2.1. Farm-level evidence on micro-irrigation and solar power

A survey of 300 farm households was conducted in the Jalaun district in the Bundelkhand region of Uttar Pradesh to gather evidence on the economic potential of solar pumps and micro-irrigation and improve water-use efficiency. The district has a normal rainfall of 786 mm and cropping intensity of 118%.

4.2.1.1. Cropping pattern and access to irrigation

Approximately half of the sample households have a farm size ranging from 4 to 10 hectares. The average landholding of the sample households is 4.41 hectares, with a cropping intensity of 125%. Green pea is the main crop, occupying 53% of the gross cropped area, followed by wheat, sesamum, paddy, mentha (mint), and pulses (Figure 4.2). Green pea is a high-value commercial crop and is grown by approximately 87% of households. It is also being promoted under the 'One District One Product (ODOP)' scheme of the Ministry of Food Processing Industries (MoFPI), Government of India.

Irrigation methods differ across crops (Table 4.5). Flood irrigation is common in paddy and mustard, and sprinkler irrigation is common in green peas. For wheat, both flood and sprinkler methods are used.

Figure 4.2. Cropping pattern on sample farms, 2023

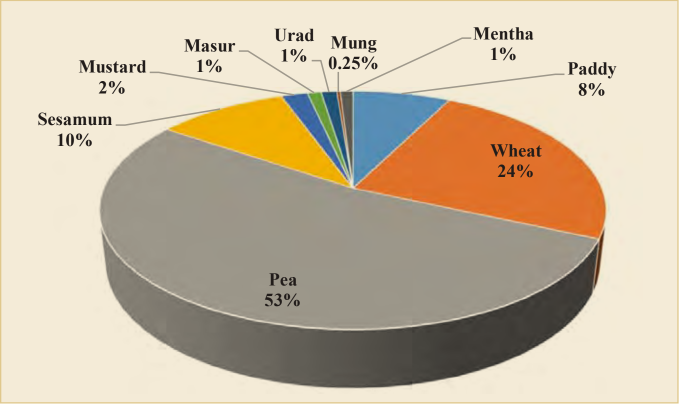


Table 4.5. Irrigation methods for major crops

Percent

Crop	Electric			Solar			Farmers (no.)
	Flood	Sprinkler	Flood+ sprinkler	Flood	Sprinkler	Flood+ sprinkler	
Paddy	89.33			10.67			75
Wheat	6.03		81.91	11.35		0.71	282
Pea	6.13	86.21		6.90	0.77		261
Mustard	100.00						38

4.2.1.2. Irrigation water requirement and use

Table 4.6 presents the estimated water requirements of the major crops. The requirement is lowest for green peas (2761 m3/ha) and highest for paddy (9410 m3/ha). Approximately 43% of the water requirement for paddy and 84% of that for sesame are met through rainfall. Winter season crops such as wheat and green peas are entirely dependent on irrigation.

Table 4.6. Irrigation water requirement and actual use of groundwater

Crop	Crop water requirement (m^3/ha)	Irrigation water requirement (m^3/ha)	Irrigation hours (hrs/ha)		GW use (m^3/ha)		Yield(qtl/ha)	
			E	S	E	S	E	S
Rice	9410	5370	109.59	213.91	7172	5252	46.07	48.42
Sesame	3280	540	-	-	-	-	4.56	-
Wheat	3970	3940	48.01	104.93	3142	2576	49.43	46.26
Pea	2760	2760	36.12	80.92	2364	1984	83.76	80.06

Note: E: Submersible pump(Electric), S: Submersible pump(Solar)

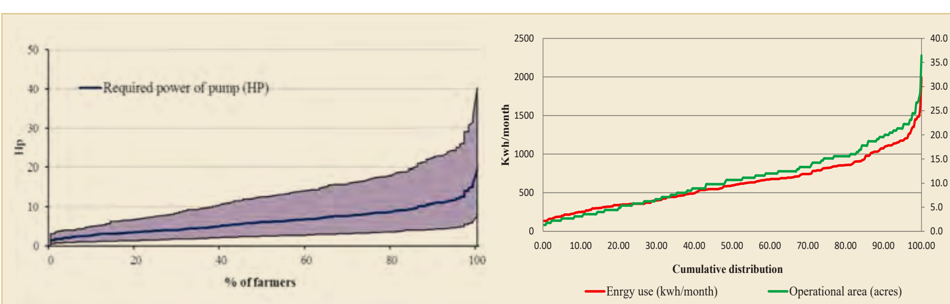
A comparative analysis was conducted on the number of irrigations using electric submersible pumps and solar-powered pumps. The irrigation duration is higher on farms equipped with solar pumps, but water supply is lower because of the low pumping capacity (average Hp = 4.76) compared with electric pumps (average Hp = 10.23). Notably, the actual volume of water utilized is less than that required for all the crops.

4.2.1.3. Energy requirement for irrigation

To satisfy the irrigation water requirements of the existing cropping pattern, the optimal pump size was arrived at various groundwater levels. The mean groundwater depth in Jalaun is 9.89 mbgl, with a range from 0.81 to 26.4 mbgl. The requisite pump size is estimated at 6.33 Hp for the average water depth. However, it varies from 1.51 Hp to 19.38 Hp depending on the irrigated area and cropping pattern (Figure 4.3). The optimal pump size is estimated at 2.55 Hp and 13.02 Hp at the minimum and maximum water depths, respectively.

For an average farm size of 4.41 hectares, a pump of 6.33 Hp (~6.5 Hp), as opposed to the existing size of 10.23 Hp, is sufficient to meet the irrigation requirements of the current cropping patterns. The primary factors for installing higher-capacity pumps include the irrigation method employed, electricity subsidies, anticipated groundwater depletion, and insufficient awareness regarding the judicious use of energy. Through the reduction of water demand, micro-irrigation has the potential to influence farmers' behavior towards optimizing the pump size and enhancing energy efficiency.

Figure 4.3. Required pump size (Hp) and actual energy use



Furthermore, the supply of 600 units of electricity per month is found sufficient to meet the irrigation water demand. Note that in 2023, electricity for irrigation was made free in Uttar Pradesh, a disincentive to adopt micro-irrigation and solar pumps. As discussed earlier, a solar pump of 7.5 Hp permitted under PM-KUSUM is sufficient for pumping the required water. Coupling solar pumps and micro-irrigation can improve both water and energy use efficiency.

4.2.1.4. Economic feasibility of solar-powered micro-irrigation

Solar-powered sprinkler irrigation yields net returns of Rs 1,48,762 per hectare from green peas, which exceeds the average cost of a 7.5 Hp solar pump (Rs 1,46,236, with a 60% subsidy for solar pumps and 90% for micro-irrigation). This indicates that the investment in solar pumps and sprinklers is economically viable and recoverable within a year. Moreover, the physical (Kg/m3) and economic productivities of water (Rs/m3) are 13% and 22% higher, respectively, for solar pumps than for electric pumps.

4.2.2. Institutional aspects of solar-powered micro-irrigation

In Uttar Pradesh, the PDMC scheme is implemented by the Department of Horticulture and PM-KUSUM (Component B) by the Department of Agriculture. Recently, the government launched an accelerator program called the Uttar Pradesh Micro-Irrigation Project (UPMIP) in collaboration with the World Bank and Gujarat Green Revolution Company Ltd. (GGRC) to implement the PDMC scheme. This is expected to accelerate the adoption of micro-irrigation.

The PDMC scheme comprises two components: micro-irrigation and other interventions, with expenditures allocated in a ratio of 4:1. The Department of Horticulture implements micro-irrigation under UPMIP, whereas the Department of Agriculture implements other interventions. The latter includes the construction of Farm Ponds (*Khet Talab Nirman*) with mandatory installation of a micro-irrigation system. Both the Department of Agriculture and the Department of Horticulture (UPMIP) are involved in the construction of farm ponds and installation of micro-irrigation systems. This collaborative approach of pond-based micro-irrigation can be utilized to integrate the PDMC and PM-KUSUM.

Capital subsidies of 90% (33% by the central government, 22% by the state government, and a top up of 35% by the state government) are provided to marginal and small farmers, and 80% (27% by central, 18% by the state, and an additional 35% by the state government) to other categories of farmers. The subsidy for solar pumps is 60% and is shared equally by the central and state governments. In case, solar pumps and micro-irrigation are implemented jointly, the expenditure on the latter does not exceed 5%

of the total cost of Rs 1,46,748 (7.5 Hp solar pump and micro-irrigation for 1.08 ha). Thus, coupling micro-irrigation with solar pumps requires a small incremental expenditure.

After the initiation of the accelerator program, the costs and implementation time for micro-irrigation have reduced (personal discussion with the implementing agency). According to recent guidelines, GST is included in the benchmark cost; otherwise, it must be borne by farmers. This has reduced farmers' costs. Further, under the UPMIP, payments to suppliers of micro-irrigation systems are made from an escrow account where the government and farmers contribute their shares in advance. This reduces the delay in payment to suppliers. Note that these provisions are not present in PM-KUSUM.

Given the complementary relationship between micro-irrigation and solar energy, the PM-KUSUM scheme can be integrated with UPMIP.

- Component B of PM-KUSUM can be shifted to RKVY, and both schemes can be implemented under a common institutional framework, as shown in Figure 3.2. The RKVY allows the dissemination of solar pumps under its 'Farm Machinery' component. This requires revisiting District Agricultural Plans (DAPs) and integrating them with District Irrigation Plans (DIP).
- Water-lifting devices are not provided to the farm ponds. The possibility of integrating Farm-Pond (Department of Agriculture), micro-irrigation (Department of Horticulture), and solar pump schemes (Department of Agriculture) must be explored.
- 'Special Purpose Vehicles (SPVs)' can be established for coordinating with implementation agencies of PM-KUSUM and PDMC.

♦♦♦

5

Conclusions and Implications

The Government of India has been actively promoting micro-irrigation and solar power in agriculture to ensure water and energy security and to reduce greenhouse gas emissions. Micro-irrigation and solar pumps are complementary technologies. However, these are promoted independently under different schemes — micro-irrigation is implemented under the Per Drop More Crop (PDMC) component of the *Pradhan Mantri Krishi Sinchayee Yojana (PMKSY)* by the Ministry of Agriculture and Farmers Welfare, and solar pumps by the Ministry of New and Renewable Energy under the *Pradhan Mantri- Kisan Urja Suraksha evam Utthaan Mahabhiyan Yojana (PM-KUSUM)*. In this study, we examined (i) the progress in micro-irrigation and solar power, (ii) the economic feasibility of their integration, and suggested institutional frameworks for their convergence.

The adoption of micro-irrigation has accelerated over the past two decades, from an annual 4 lakh hectare from 2005 to 2010 to 10 lakh hectares from 2015 to 2023, reaching 15.59 million hectares in 2023, equivalent to 12.95% of the total irrigated area. India has the potential to bring 88 million hectares under micro-irrigation, and if the current trend in its utilization continues, 20 years may be required to reach this potential. However, significant regional disparities exist, with six states, Rajasthan, Maharashtra, Andhra Pradesh, Gujarat, and Tamil Nadu, accounting for 79% of the total micro-irrigated area. States, such as Uttar Pradesh and Punjab, have less than 2% of their irrigated area under micro-irrigation.

The adoption of solar pumps is faster. The number of solarized pumps increased more than 40 times, from 11626 in 2013 to 501673 in 2022. However, their adoption is low; solar irrigation pumps comprise only 2.33% of the total 21.5 million electric- and diesel-operated GEDs. If all the electric- and diesel-operated GEDs are replaced by solar pumps, approximately 102 gigawatts of solar power can be generated. Similar to micro-irrigation, solar pumps are concentrated in a few states: Chhattisgarh, Rajasthan, Maharashtra, Haryana, and Uttar Pradesh, and there is no significant correlation between the adoption of micro-irrigation and solar pumps. States with a higher adoption of micro-irrigation have a lower adoption of solar pumps and *vice versa*.

The coupling micro-irrigation with solar power has numerous economic and environmental benefits. Solar-powered micro-irrigation systems conserve both energy and water resources. Micro-irrigation enhances water-use efficiency by 15-50% and contributes to increased crop yields. The solarization of one fossil-fuel (electric/diesel)-based GED results in annual savings of 911 liters of diesel and 2875 units of electricity, consequently reducing CO_2 emissions by 2.1 tons. Therefore, there is a significant potential to mitigate the fiscal burden associated with electricity subsidies and diesel imports.

The bundling of solar energy and micro-irrigation although is costlier, the incremental benefits are sufficient to outweigh the incremental costs. The substitution of diesel pumps with solar-powered micro-irrigation systems is a more economically viable option, even in the absence of capital subsidies for such systems. The cost can be recovered in less than five years without capital subsidies for solar pumps and in two years with capital subsidies from the savings in diesel costs alone. Conversely, replacing an electric pump with a solar-powered micro-irrigation system is not economically feasible because of the provision of electricity at a heavily subsidized tariff.

In light of these findings, the following recommendations warrant consideration for integration of micro-irrigation and solar energy technologies:

First, it is necessary to prioritize states/regions for promoting the bundled approach to micro-irrigation and solar energy. States with high potential but low adoption of micro-irrigation and solar pumps should receive higher priority. Furthermore, solar-powered irrigation should be targeted in areas where groundwater extraction is heavily dependent on diesel pumps.

Second, the continued provision of subsidized electricity for irrigation by states significantly impedes the adoption of solar-powered micro-irrigation systems as alternatives to electric-operated pumps. Therefore, it is advisable to reallocate electricity subsidies as capital subsidies for the solarization of irrigation. This reallocation would effectively reduce the financial burden of electricity subsidies on state governments.

Third, although the guidelines for the implementation of PDMC and PM-KUSUM at the central government level explicitly mention harnessing synergy between the two, these are rarely adhered to by the states. Consequently, there is a necessity to reevaluate institutional mechanisms for enhanced synergy between solar power and micro-irrigation schemes.

Fourth, financial institutions should develop innovative mechanisms for financing the joint implementation of solar power and micro-irrigation schemes. One potential approach is to make financing contingent upon joint implementation.

Fifth, the solar-powered micro-irrigation system is capital-intensive. Consequently, it should be targeted towards crops, particularly vegetables and fruits, which are more economically viable than the widely cultivated staple food crops. This also indicates the necessity of modifying the system to accommodate the requirements of diverse cropping systems.

Sixth, Indian agriculture is dominated by small farms. Solar-powered micro-irrigation is a capital-intensive indivisible technology; hence, a cluster or community approach is warranted to conserve water and energy resource, reduce costs to individuals, and improve inclusiveness.

♦♦♦

References

Bahinipati, C. S. & P.K. Viswanathan. 2019. Can micro-irrigation technologies resolve India's groundwater crisis? Reflections from dark-regions in Gujarat. *International Journal of the Commons* 13(2): 848–858.

Bassi, N. 2017. Solarizing groundwater irrigation in India: a growing debate. *International Journal of Water Resources Development* 34 (1):132-145.

Bhamoriya, V. & S. Mathew. 2014. *An analysis of resource conservation technology: a case of micro-irrigation system (drip irrigation)*. Final report of Centre for Management in Agriculture, Indian Institute of Management, Ahmedabad. https://desagri.gov.in/wp-content/uploads/2024/04/2014-15-An-Analysis-of-Resource-conservation-Technology-A-Case-of-Micro-Irrigation-System.pdf.

Bhaskar, K.S., M.R.K. Rao, P.M. Mendhe, & M.R. Suryavanshi. 2005. *Micro irrigation management in cotton*. Technical Bulletin-31. Central Institute for Cotton Research Nagpur. https://krishi.icar.gov.in/jspui/bitstream/123456789/7877/1/CICR_micro_irrigation.pdf.

Birthal, P. S. & J. Hazrana. 2019. Crop diversification and resilience of agriculture to climatic shocks: evidence from India. *Agricultural Systems* 173: 345–354.

Birthal, P.S., T. Khan, D.S. Negi, & S. Agarwal. 2014. Impact of climate change on yields of major food crops in India: implications for food security. *Agricultural Economics Research Review* 27 (2): 145-155.

Biswas, S.K., A.R. Akanda, M.S. Rahman, & M.A. Hossain. 2015. Effect of drip irrigation and mulching on yield, water-use efficiency and economics of tomato. *Plant, Soil and Environment* 61(3): 97-102.

CGWB. 2023. *National Compilation on Dynamic Groundwater Resources of India, 2023*. Central Groundwater Board, Department of Water Resources, River Development and Ganga Rejuvenation, Ministry of Jal Shakti, Government of India.

Chakravarty, S. & L.B. Singh. 1994. *Water Economy through Drip Irrigation.* In Proceedings of the 20th WEDC Conference, Colombo, Sri Lanka. http://www.lboro.ac.uk/departments/cv/wedc/papers/20/sessiong/chakrava.pdf.

Chand, S., P. Kishore, & S.K. Srivastava. 2019. Pressurized irrigation system: policies and implications in India. *Indian Journal of soil conservation* (Conference issue): 42-50.

Chand, S., P. Kishore, S. Kumar, & S.K. Srivastava. 2020. *Potential, Adoption and Impact of Micro Irrigation in Indian Agriculture*. Policy Paper 36, ICAR-National Institute of Agricultural Economics and Policy Research (NIAP), New Delhi.

Chandrakanth, M.G., C.N. Priyanka, P. Mamatha, & K.K. Patil. 2013. Economic benefits from micro irrigation for dry land crops in Karnataka. *Indian Journal of Agricultural Economics* 68 (3):426-338.

Chandran, M.K. & U. Surendran. 2016. Study on factors influencing the adoption of drip irrigation by farmers in humid tropical Kerala, India. *International Journal of Plant Production* 10 (3): 347-364.

Choudhary, D., B. Lal, O.M. Cheeta, R.S. Jakhar, & K. Singh. 2022. Constraints in adoption of solar pumps by the farmers in Jodhpur District of Rajasthan. *The Pharma Innovation* 11(1): 623-625.

Devineni, N., S. Perveen, & U. Lall. 2022. Solving groundwater depletion in India while achieving food security. *Nature Communication* 13: 3374.

FAO. 2017. Does Improved Irrigation Technology Save Water? A Review of the Evidence. *FAO Discussion Paper*. Food and Agriculture Organization. http://www.fao.org/policysupport/resources/resources-details/en/c/897549/.

Gautam, Y. & O.P. Singh. 2020. Empirical analysis of economic viability and cost of installation of 3 hp solar irrigation pump in Jaipur, Rajasthan. *Asian Journal of Agricultural Extension, Economics & Sociology* 38 (12): 60-67.

Goel, S., R. Murali, A. Rahman, P. Swain, B. Viswanathan, S. Agrawal, C. Beaton, M. Govindan, A. Jain, & D. Palit. 2021. *Implementing Solar Irrigation Sustainably: A Guidebook for State Policy-Makers on Maximizing the Social and Environmental Benefits from Solar Pump Schemes*. International Institute for Sustainable Development (IISD). https://www.iisd.org/publications/implementing-solar-irrigation-sustainably.

GoI. 2017. *Report of the Committee on Doubling Farmers' Income: Sustainability Concerns in Agriculture (Volume V)*. Department of Agriculture, Cooperation and Farmers' Welfare, Ministry of Agriculture & Farmers' Welfare, Government of India. http://farmer.gov.in/imagedefault/DFI/DFI%20Volume%205.pdf.

GoI. 2024. *Land Use Statistics- At a Glance*. Economics, Statistics and Evaluation Division, Department of Agriculture & Farmers Welfare, Ministry of Agriculture and Farmers Welfare, Government of India. https://desagri.gov.in/document-report-category/land-use-statistics-at-a-glance/ (online accessed on 09.07.2024).

Gupta, E. 2019. The impact of solar water pumps on energy-water-food nexus: evidence from Rajasthan, India. *Energy Policy* 129 (February):598–609.

IEA. 2015. *India Energy Outlook-Special Report*. International Energy Agency. https://www.iea.org/reports/india-energy-outlook-2015.

Jha, G., O.P. Choudhary, & R. Sharda. 2017. Comparative effects of saline water on yield and quality of potato under drip and furrow irrigation. *Cogent Food and Agriculture* 3: 1369345.

Kapur, R., S. Gulati, & S. Chouhan. 2015. *Future prospects of micro irrigation in India.* In Accelerating Growth of Indian Agriculture: Micro Irrigation an Efficient Solution. Strategy Paper. Federation of Indian Chambers of Commerce & Industry (FICCI).

Kishore, A., T. Shah, & N.P. Tewari. 2014. Solar irrigation pumps: farmers' experience and state policy in Rajasthan. *Economic and Political Weekly* 49(10):55-62.

Kishore, P., S. Chand, & S.K. Srivastava. 2022. Potential area of micro-irrigation and its outreach across Indian states. *Indian Journal of Agricultural Sciences* 92 (9): 1056-1060.

Kishore, P., D. Roy, P. S. Birthal, & S.K. Srivastava. 2024. *Regulation and Policy Response to Groundwater Preservation in India.* Policy Paper-43, ICAR-National Institute of Agricultural Economics and Policy Research (NIAP), New Delhi. https://niap.icar.gov.in/pdf/PP43.pdf.

KPMG. 2014. *Feasibility analysis for solar agricultural water pumps in India.* KPMG, India. https://shaktifoundation.in/wp-content/uploads/2014/02/feasibilityanalysis-for-solar-High-Res-1.pdf.

Kumar, D.M. 2002. *Integrated water management in the face of growing scarcity and threatened groundwater ecology: Constraints and opportunities.* Discussion paper, IWMI-TATA Water Policy Research programme.

Kumar, R., H. Trivedi, R. Yadav, B. Das, & A.S. Bist. 2016. Effect of drip irrigation on yield and water use efficiency on brinjal (Solanum Melongena) Cv. Pant Samrat. *International Journal of Engineering Sciences & Research Technology* 5(10): 7-17.

Lobell, D., G. Bala, A. Mirin, T. Phillips, R. Maxwell, & D. Rotman. 2009. Regional differences in the influence of irrigation on climate. *Journal of Climate* 22(8): 2248-2255.

Malik, R.P.S., M. Giordano, & M.S. Rathore. 2016. The negative impact of subsidies on the adoption of drip irrigation in India: evidence from Madhya Pradesh. *International Journal of Water Resources Development* 34 (1): 66-77.

MNRE. 2023. *Annual Report-2022-23*. Ministry of New and Renewable Energy, Government of India. https://mnre.gov.in/annual-reports-2022-23/.

MNRE. 2024. *Solar Overview.* Ministry of New and Renewable energy. Government of India. (mnre.gov.in) .

Nagaraj, N. 2020. *Whether Micro-irrigation is a Panacea for Groundwater Scarcity and Sustainable Use in Indian Agriculture? Policy Imperatives*. Policy Brief-32, Institute for Social and Economic Change (ISEC), Bangalore. http://www.isec.ac.in/PB%2032%20-%20Micro-Irrigation_Final.pdf.

Namara, R.E., R.K. Nagar, & B. Upadhyay. 2007. Economics, adoption, determinants, and impacts of micro-irrigation technologies: empirical results from India. *Irrigation Science* 25:283-297.

Narayanamoorthy, A. & R.S. Deshpande. 1997. *Efficient Water Management through Drip Irrigation: Some Evidences from Western India.* In ICID, The Tenth Afro-Asian Regional Conference Proceedings: Water and land resources development and management for sustainable use, Denpasar, Bali, Indonesia, 19-24 July.

Narayanamoorthy, A. 1997. Economic viability of drip irrigation: an empirical analysis from Maharashtra. *Indian Journal of Agricultural Economics* 52(4):728–739.

Narayanamoorthy, A. & R.S. Deshpande. 1998. *Economics of Drip Irrigation: A Comparative Study of Maharashtra and Tamil Nadu,* Mimeograph Series No. 47, Agro-Economic Research Centre, Gokhale Institute of Politics and Economics, Pune, Maharashtra.

Narayanamoorthy, A. 2003. Averting water crisis by drip method of irrigation: a study of two water-intensive crops. *Indian Journal of Agricultural Economics* 58(3):427.

Narayanamoorthy, A. 2005. Economics of drip irrigation in sugarcane cultivation: case study of a farmer from Tamil Nadu. *Indian Journal of Agricultural Economics* 60(2):235-248.

Narayanamoorthy, A. 2006. *Potential for Drip and Sprinkler Irrigation in India*. Gokhale Institute for Politics and Economics, Pune.

Narayanamoorthy, A. 2008. Drip irrigation and rainfed crop cultivation nexus: the case of cotton crop. *Indian Journal of Agricultural Economics* 63 (3):487-501.

Narayanamoorthy, A., M. Bhattarai, & P. Jothi. 2018. An assessment of the economic impact of drip irrigation in vegetable production in India. *Agricultural Economics Research Review* 31 (1): 105-112.

NCPAH. 2014. National Committee on Precision Agriculture & Horticulture. Ministry of Agriculture and Farmers Welfare, Government of India.

NITI Aayog. 2024. *Working Group Report on Crop Husbandry, Agriculture Inputs, Demand and Supply*. NITI Aayog, Government of India. https://www.niti.gov.in/sites/default/files/2024-02/Working%20Group%20Report%20on%20Demand%20%26%20Supply%20Final_V9.pdf.

Palanisami, K. 2015. Micro-irrigation neglected. *Economic and Political Weekly* 50(51): 5.

Palanisami, K., K. Mohan, K.R. Kakumanu, & S. Raman. 2011. Spread and economics of micro-irrigation in India: evidence from nine states. *Economic and Political Weekly* 46(26&27): 81-86.

Panigrahi, B., D.P. Roy, & S.N. Panda. 2010. Water use and yield response of tomato as influenced by drip and furrow irrigation. *International Agricultural Engineering Journal* 19(1): 19-30.

Paul, J.C., J.N. Mishra, P.L. Pradhan, & B. Panigrahi. 2013. Effect of drip and surface irrigation on yield, water-use-efficiency and economics of capsicum. Grown under mulch and non-mulch conditions in eastern coastal India. *European Journal of Sustainable Development* 2(1) 99-108.

Perez, N., V. Singh, C. Ringler, H. Xie, T. Zhu, E.H. Sutanudjaja, & K.G. Villholth. 2024. Ending groundwater overdraft without affecting food security. *Nature Sustainability* 7:1007-1017.

PIB. 2015. *Revision of Cumulative Targets under National Solar Mission from 20,000 MW by 2021-22 to 1,00,000 MW*. June 17, 2015. https://pib.gov.in/newsite/PrintRelease.aspx?relid=122567.

PIB. 2022. *Renewable Energy in India*. September 09, 2022. www.pib.gov.in.

Polak, P. & R.K. Sivanappan. 1998. *The Potential Contribution of Low Cost Drip Irrigation to the Improvement of Irrigation Productivity in India,* India - Water Resources Management Sector Review, Report on the Irrigation Sector. The World Bank in Cooperation with the Ministry of Water Resources, Government of India.

Postel, S., P. Polak, F. Gonzales, & J. Keller. 2001. Drip irrigation for small farmers: a new initiative to alleviate hunger and poverty. *Water International* 26(1): 3-13.

Priyan, K. & R. Panchal. 2017. Micro-Irrigation: an efficient technology for India's sustainable agricultural growth. *International Conference on Research and Innovations in Science, Engineering &Technology* 1: 398-402.

Pullabhotla, H.K., C. Kumar, & S. Verma. 2012. *Micro-irrigation Subsidies in Gujarat and Andhra Pradesh: Implications for Market Dynamics and Growth.* Water Policy Research Highlight-43. IWMI-Tata water Policy Programme. https://www.iwmi.cgiar.org/iwmi-tata/PDFs/2012_Highlight-43.pdf?galog=no&iwmi=1.

Purohit, P. 2007. Financial evaluation of renewable energy technologies for irrigation water pumping in India. *Energy Policy* 35(6): 3134-3144.

Quevenco, R. 2015. Bountiful crop with every drop: using drip irrigation to increase yields and conserve water. *International Atomic Energy Agency Bulletin* March: 24-25.

Rajan, A., K. Ghosh, & A. Shah. 2020. Carbon footprint of India's groundwater irrigation. *Carbon Management* 1(3): 265-280. doi:10.1080/17583004.2020.1750265.

Rao, K.V.R., S. Gangwar, R. Keshri, L. Chourasia, A. Bajpai, & K. Soni. 2017. Effects of drip irrigation system for enhancing rice (Oryza Sativa L.) Yield under system of rice intensification management. *Applied Ecology and Environmental Research* 15 (4): 487-495.

Raymond, A. & A. Jain. 2018. *Solar for Irrigation: A Comparative Assessment of Deployment Strategies.* CEEW Report. Council on Energy, Environment, & Water. https://www-ceew-in.webpkgcache.com/doc/-/s/www.ceew.in/sites/default/files/CEEW-Solar-for-Irrigation-Deployment-Report-17Jan18_0.pdf.

Reddy, K.Y.V., S. Adamala, & B.B. Harish. 2017. Case study on performance evaluation of drip irrigation systems in selected villages of Guntur District, Andhra Pradesh, India. *International Journal of Current Microbiology and Applied Sciences* 6(2): 437-445.

Reddy, V.V., H. Nagarajan, & D. Vishwanath. 2023. *Assessing Skill Gap in Micro-irrigation across India.* Center for Management in Agriculture, Indian Institute of Management, Ahmedabad. https://www.iima.ac.in/sites/default/files/2023-07/3.%20Micro%20Irrigation_Final%20Report_2023_final_compressed.pdf.

Roberts, J. C. & S.W. Styles. 1997. Drip irrigation technology: a resource management tool for farmers. *Irrigation Journal* 47(7):14-16.

Sarkar, N.A. & S. J. Hanamashet. 2002. Financial viability of drip irrigation system for sugarcane and grapes cultivation in Maharashtra. *Asia Pacific Journal of Rural Development* 12(1):1–31.

Schnetzer, J. & L. Pluschke. 2017. *Solar-Powered Irrigation Systems: A Clean Energy, Low Emission Option for Irrigation Development and Modernization*. Practice Brief: Climate Smart Agriculture. Global Alliance for Climate-Smart Agriculture (GACSA), Food and Agriculture Organization of the United Nations (FAO). https://www.fao.org/3/bt437e/bt437e.pdf.

Sears, L., J. Caparelli, C. Lee, D. Pan, G. Strandberg, L. Vuu, & C.L. Lawell. 2018. Jevons' Paradox and Efficient Irrigation Technology. *Sustainability*, 10:1590.

Shah, T. & A. Kishore. 2012. *Solar-Powered Pump Irrigation and India's Groundwater Economy*. IWMI-TATA Water Policy Research Highlight. http://www.iwmi.cgiar.org/iwmitata/PDFs/2012_Highlight-26.pdf.

Shah, T., N. Durga, S. Verma, & R. Rathod. 2016. *Solar Power as Remunerative Crop*. Water Policy Research Highlight- 10. IWMI-TATA Water Policy Program, Gujarat, India. Available from: http://iwmitata.blogspot.it/2016/12/2016-itp-highlight-10.html.

Shirsath, P.B., S. Saini, N. Durg, D. Senoner, N. Ghose, S. Verma, & A. Sikka. 2020. *Compendium on Solar Powered Irrigation Systems in India*. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). https://ccafs.cgiar.org/resources/publications/compendium-solar-powered-irrigation-systems-india.

Singh, D. R., P. Kumar, A. Kar,G.K. Jha, & A. Kumar. 2017. Solar energy use in agriculture for enhancing farmers' income: a case of solar tubewell in northwestern Rajasthan. *Agricultural Economics Research Review* 30 (Conference Number): 269-277.

Singh, G. & V. Gandhi. 2024. Micro-Irrigation Adoption and Indication to Jevons' Paradox: a Case from Four States of India. http://dx.doi.org/10.2139/ssrn.4797296.

Srivastava, S.K., S. Ghosh, A. Kumar, & P.S.B. Anand. 2014. Unravelling the spatio-temporal pattern of irrigation development and its impact on Indian agriculture. *Irrigation and Drainage* 63(1):1-11.

Suman, S. 2018. *Evaluation and Impact Assessment of the Solar Irrigation Pumps Program in Andhra Pradesh and Chhattisgarh.* https://www.ssael.co.in/images/Library/files/Solar-Pumps-Impact--SSAEL-Report.pdf.

Suresh, A., K.S. Aditya, G.K. Jha, & S. Pal. 2018. Micro-irrigation development in India: an analysis of distributional pattern and potential correlates. *International Journal of Water Resources Development* 1-16. doi: 10.1080/07900627.2018.1504755.

Tiwari, K.N., M. Kumar, D.T. Santosh, V.K. Singh, M.K. Maji, & A.K. Karan. 2014. Influence of drip irrigation and plastic mulch on yield of sapota (Achraszapota) and soil nutrients. *Irrigation and Drainage Systems Engineering* 3(1): 1-8.

Upreti, P., D.R. Singh, N.R. Kumar, & P. Venkatesh. 2023. Feasibility analysis of solar-powered tubewells in arid and sub-humid regions of Rajasthan. *Indian Journal of Extension Education* 59(3):126-131.

Vanitha, K. & S. Mohandass. 2014. Effect of humic acid on plant growth characters and grain yield of drip fertigated aerobic rice. *The Bioscan* 9: 45-50.

Verma, S., S. Tsephal, & T. Jose. 2004. Pepsee systems: grassroot innovation under groundwater stress. *Water Policy* 6:1–16.

Wolff, P. 1987. *On the Development Status of Micro-irrigation*. Report No. 19. Department of Irrigation, Drainage and Soil Conservation, Faculty of International Agriculture, University of Kassel, Witzenhausen, Germany.

Wrachienb, D., M. Medicia, & Lorenzinia. 2014. The great potential of micro-irrigation technology for poor-rural communities. *Irrigation and Drainage Systems Engineering* 3(2): 1-2.

Yashodha, Y., A. Sanjay, & A. Mukherji. 2021. *Solar Irrigation in India: A Situation Analysis Report*. International Water Management Institute (IWMI). doi: https://doi.org/10.5337/2021.217.

♦♦♦

Publications

Policy Papers

32. Singh, N.P., A. Ashok, S. Pavithra, S.J. Balaji, B. Anand, and M. A. Khan. 2017. *Mainstreaming Climate Change Adaptation into Development Planning.*
33. Saxena, R. and R. Chand. 2017. *Understanding the Recurring Onion Price Shocks: Revelations from Production-Trade-Price Linkages.*
34. Saxena, R., R.K. Paul, S. Pavithra, N.P. Singh, and R. Kumar. 2019. *Market Intelligence in India, Price Linkages and Forecasts.*
35. Singh, N. P., B. Anand, and S. Singh. 2020. *Impact of Climate Change on Agriculture in India: Assessment for Agro-Climatic Zone.*
36. Chand, S., P. Kishore, S. Kumar, and S.K. Srivastava. 2020. *Potential, Adoption and Impact of Micro Irrigation in Indian Agriculture.*
37. Subash, S.P., A. Jhajharia, and S. Pal. 2020. *Trade and Investment Policy for Overseas Acquisition of Fertilizers and Raw Materials: Role of the Government.*
38. Birthal, P.S., J. Hazrana, and R. Saxena. 2023. *Livestock Farmers' Information Needs, Search Behaviours, and Their Impact: Lessons for Extension Policy.*
39. Saxena, R., S.K. Srivastava, S.J. Balaji, A. Jhajhria, and M. A. Khan. 2023. *Changes in Indian Agriculture: Household-level Evidence.*
40. Nikam, V., H. Veesam, T.M. Kiran Kumara, and P. Chand. 2023. *Farmer Producer Organizations in India: Challenges and Prospects.*
41. Birthal, P.S., J. Hazrana, D. Roy, and K.J.S. Satyasai. 2024. *Can Finance Mitigate Climate Risks in Agriculture? Farm-level Evidence from India.*
42. Chand, P., T.M. Kiran Kumara, S. Pal, and K. Naik. 2024. *A Spatial Assessment of Sustainability in Indian Agriculture.*
43. Kishore, P., D. Roy, P.S. Birthal and S.K. Srivastava. 2024. *Regulation and Policy Response to Groundwater Preservation in India.*
44. Kandpal, A., P.S. Birthal and S. Mishra. 2024. *From Research to Impact: Payoffs to Investment in Agricultural Research and Extension in India.*
45. Sharma, P., M. Yeasin, R. K. Paul, D.C. Meena and M. E. Anwer. 2024. *Food Price Volatility in India.*

Policy Brief

42. Singh, N.P and J.P. Bisen. 2017. *Goods and Services Tax: What it holds for Agricultural Sector?*
43. Subash, S.P, P. Chand, S. Pavithra, S.J. Balaji, and S. Pal. 2018. *Pesticide Use in Indian Agriculture: Trends, Market Structure and Policy Issues.*
44. Singh, N.P, S. Singh, and B. Anand. 2019. *Impact of Climate Change on Indian Agriculture: An Agro-Climatic Zone Level Estimation.*
45. Pal, S., R. Saxena, and S.J. Balaji. 2020. *Market and Innovation-led Agricultural Transformation.*
46. Roul, C., P. Chand, and S. Pal. 2020. *Developing Agricultural Sustainability Index for the Indo-Gangetic Plains of India.*
47. Birthal, P.S., J. Hazrana, D.S. Negi, and A. Mishra. 2022. *To Insure or Not to Insure: What Explains Low Uptake of Crop Insurance?*
48. Birthal, P.S. 2022. *Managing Climate Risks in Indian Agriculture: What do We Need to Know?*
49. Balaji, S.J., P. Sharma, P. Venkatesh, and K. Shreya. 2022. *Technology and Policy Options for Reducing India's Import Dependence on Edible Oils.*
50. Saxena, R., R.K. Paul, S.J. Balaji, and R. Kumar. 2022. *India's Agricultural Exports during the Covid-19 Pandemic.*
51. Kumar, S., P. Kishore, S.K. Srivastava, and S. Chand. 2023. *Potential of Micro-Irrigation for Sustainable Intensification of Agriculture.*
52. Kingsly, I.T., S. Kumar, P. Shinoj, and S. Pal. 2023. *Outlook for Rice and Wheat to 2030-31.*
53. Sharma, P., B.D. Pal, and P.S. Birthal. 2023. *Technology and Policy Options for Sustaining Pulses Revolution.*
54. Kumar, S, P.S. Birthal, P. Chand, and Kingsly I.T. 2024. *Technology and Policy Options for Efficient Use of Fertilizers in India Agriculture.*
55. Srivastava, S.K., P. Kishore, P.S. Birthal, and P.B. Shirsath. 2024. *Enabling Policies for Solar-powered Micro-irrigation.*
56. Mandal, S., S. Kumar, J. Singh, R. Jain and A. Kandpal. 2024. *Economic Impact of Salt-Tolerant Mustard Varieties.*
57. Chand, K., P.S. Birthal and S. Kachhawaha. 2024. *Impact of Prophylactic Vaccination in Cattle against Lumpy Skin Disease.*
58. Vatta, K., B.K. Sidana, R. Jain, L. Priscilla, A. Kandpal and G. Kaur. *2024. Is DSR Economically Viable?*

भाकृअनुप–राष्ट्रीय कृषि आर्थिकी एवम् नीति अनुसंधान संस्थान
ICAR - NATIONAL INSTITUTE OF AGRICULTURAL ECONOMICS AND POLICY RESEARCH
(Indian Council of Agricultural Research)
Dev Prakash Shastri Marg, Pusa, New Delhi - 110 012, INDIA
Ph: +91(11) 2584 7628, 2584 8731 Fax: +91 (11) 2594 2684
Email : director.niap@icar.gov.in, Website : www.niap.icar.gov.in