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SolaReady: Climate-Responsive and Sustainable Solar Irrigation Upscaling

Solar irrigation is being scaled across the Global South for its potential to reduce GHG emissions associated with groundwater irrigation, strengthen climate resilience, and enhance energy security. Beyond its climate benefits, solar-powered irrigation pumps (SIPs) offer multiple co-benefits—improving farm profitability, boosting food security, and reducing agricultural subsidy burdens. Given significant investments are needed to set up solar irrigation, there is a need for developing context and location specific solar irrigation strategy

The **SolaReady** platform is a spatial decision support tool that supports the deployment of appropriate implementation solar models aligned with local conditions and priorities. By integrating water, energy, climatic, agricultural, and socio-economic indicators, the tool identifies where solar irrigation can deliver the greatest benefits across the Water-Energy-Food (WEF) Nexus—enhancing adaptation, contributing to mitigation, and promoting sustainable groundwater development.

This decision-support tool can support policymakers, investors, and development partners design context-specific, targeted SIP models and roadmaps —maximizing benefits (expanding irrigation, improving crop yields, reducing emissions) while minimizing risks (e.g., models with incentives to reduce groundwater over abstraction). Through integrated WEF approach, the tool recommends evidence-based and context specific solar irrigation models for upscaling solar energy transitions that are climate-responsive, economically viable, and environmentally sustainable.

🔆 What It Is

A spatial decision-support tool that maps the suitability of solar irrigation pumps (SIPs) using water, energy, food, and socio-economic indicators.

🌍 What It Does

Identifies where solar irrigation can deliver the highest adaptation, mitigation, and groundwater sustainability benefits while minimizing risks.

📈 Why It Matters

Enables policymakers, investors, and practitioners to make informed, location-specific decisions—supporting climate-resilient and sustainable SIPs upscaling.

SolaReady: India

SolaReady is a spatial decision-support platform that identifies where solar irrigation can most effectively advance adaptation, mitigation, and groundwater sustainability through deployment of different solar irrigation models with district-level conditions and priorities. SolaReady can strengthen India's demand-driven SIP allocation process, which currently does not fully account for adaptation, mitigation, and groundwater sustainability realities and potential. Integrating such evidence into state and national allocation decisions—including those shaped by MNRE's demand-based, co-funded model—can help ensure that solar irrigation is deployed where it delivers the greatest benefits while avoiding unintended impacts. The tool is designed to complement existing systems used by central and state government agencies, development banks, the private sector, and researchers. It supports informed, location-specific decision-making for scaling solar irrigation in ways that improve farmer livelihoods, build climate resilience, and protect groundwater resources.

Data and Methodology

Data

The methodology uses 17 indicators (Table 1)—drawn from socio-economic, agricultural, hydrological, and climatic datasets—reflecting key dimensions of the Water–Energy–Food (WEF) Nexus. The indicators were shortlisted through a literature review and discussed in stakeholder consultations. Datasets under these categories are:

- **Water**-related datasets comprise of groundwater development stage, groundwater level, irrigation water needs, type of aquifer, and surface water bodies.
- **Energy**-related datasets include number of irrigation pumps, electrical and diesel pumps, electricity tariffs, and solar irradiance.
- **Food**-related datasets relate to share of cultivated land, cropping intensity, irrigation coverage, and source of irrigation.
- **Farmer**-connected datasets are small and marginal holdings, average area per holding, and average number of parcels per holding (depicting land fragmentation).
- **Utility**-related data sets include integrated rating and feeder segregation of the discom utilities.

The data indicators are explained in Annexure 1.

Table 1: Data indicators used for solar irrigation suitability mapping: Sources and duration

Sl	Indicator	Sources	Years
1.	Solar Irradiance	Global Solar Atlas, World Bank. Global Solar Atlas	2018
2.	Cropping Intensity (%)	- **Directorate of Economics and Statistics (DES), Ministry of Agriculture & Farmers Welfare (MoA&FW), Government of India (GoI) (DES | District Level Entry)** - DES, Government of Maharashtra (LUS-2023-24-to-be-printed-Uploaded.pdf) - District Irrigation Plans (DIPs) for 2015-2023 under Pradhan Mantri Krishi Sinchayee Yojana (PMKSY), MoA&FW, GoI (Pradhan Mantri Krishi Sinchayee Yojana)	**2022-2023;** *2021-2022 (Punjab); 2020-2021 (Gujarat, Meghalaya); 2014-2015 (A & N Islands, Manipur,*

Sl	Indicator	Sources	Years
			Mizoram, Sikkim)
3.	Irrigation Intensity (%)	- DES, MoA&FW, GoI - DES, Government of Maharashtra (https://mahasdb.maharashtra.gov.in/searchReports.do) - DIPs for 2015-2023 under PMKSY, MoA&FW, GoI	**2022-2023;** *2021-2022 (Punjab); 2020-2021 (Gujarat, Meghalaya); 2014-2015 (A & N Islands, Manipur, Mizoram, Sikkim, West Bengal); 2011-2012 (Maharashtra)*
4.	Irrigation Water Use (as % of Crop Water Use)	IWMI's water productivity atlas for India. WP Atlas	2010 – 2020
5.	Share of Electric Pumps (%)	- Sixth Minor Irrigation Census, Ministry of Water Resources, GoI (Minor Irrigation Census)	2017-2018
6.	Groundwater Development Stage (%)	Central Ground Water Board (CGWB), Ministry of Water Resources, GoI (https://cgwb.gov.in/)	2023
7.	Surface Water Area (% of district area)	First Census on Water Bodies in India, Ministry of Water Resources, GoI (https://www.jalshakti-dowr.gov.in/)	2017-2018
8.	Cultivated Land (%)	- Directorate of Economics and Statistics (DES), Ministry of Agriculture & Farmers Welfare (MoA&FW), Government of India (GoI) (DES | District Level Entry) - District Irrigation Plans (DIPs) for 2015-2023 under Pradhan Mantri Krishi Sinchayee Yojana (PMKSY), MoA&FW, GoI (Pradhan Mantri Krishi Sinchayee Yojana)	2022-2023; *2021-2022 (Punjab); 2020-2021 (Gujarat, Meghalaya); 2014-2015 (A &*

Sl	Indicator	Sources	Years
			N Islands, Manipur, Mizoram, Sikkim)
9.	Electricity Subsidy	Electricity Tariff & Duty & Average rates of electricity supply in India, March 2023, Central Electricity Authority, GoI (CEA COVER FINAL 2024.cdr)	2023
10.	Groundwater's Share in Irrigation (% of Total Irrigation Water Use)	- DES, MoA&FW, GoI - DES, Government of Maharashtra (https://mahasdb.maharashtra.gov.in/searchReports.do) - DIPs for 2015-2023 under PMKSY, MoA&FW, GoI	2022-2023; *2021-2022 (Punjab); 2020-2021 (Gujarat, Meghalaya); 2014-2015 (A & N Islands, Manipur, Mizoram, Sikkim, West Bengal); 2011-2012 (Maharashtra)*
11.	Water Table Depth (m)	CGWB, Ministry of Water Resources, GoI (https://cgwb.gov.in/)	2023
12.	Proportion of Small and Marginal Farmers (%)	Input Survey, MoA&FW, GoI (inputsurvey.da.gov.in/districttables.aspx)	2016-2017
13.	Integrated rating of utilities	12th Annual Integrated Rating and Ranking of Power Distribution Utilities, Ministry of Power, GoI. 12 Annual Integrated Report_Print version-compressed2.pdf	2024
14.	Feeder segregation of utilities	Report on Status of Metering in the Country, Feeders, Distribution Transformers & Consumers Metering Status, 31st March 2024, Central Electricity Authority, Report_on_Metering_status_of_Feeders_DTs_and_Consumers__as_on_31st_March_2024-1.pdf	2023
15.	Number of pumps	- Sixth Minor Irrigation Census, Ministry of Water Resources, GoI (Minor Irrigation Census)	2017-2018
16.	Average area per holding	Input survey, 2016-2017, MoA&FW, GoI. inputsurvey.da.gov.in/districttables.aspx)	2016-2017
17.	Average number of parcels	Input survey, 2016-2017, MoA&FW, GoI. inputsurvey.da.gov.in/districttables.aspx)	2016-2017

Sl	Indicator	Sources	Years
	per holding		

Goal: Adaptation, Mitigation and Groundwater Sustainability

Using a multi-criteria evaluation framework, tool combines indicators and identifies where solar irrigation can deliver the greatest benefits across the Water-Energy-Food (WEF) Nexus—enhancing:

- **Adaptation**: Districts where the priority is irrigation expansion to manage weather extremes and climate change. These are characterised by low cropping intensity and irrigation coverage with underdeveloped groundwater and shallow water tables. High use of diesel pumps that increases cost of irrigation.
- **Mitigation**: Districts where pumping emissions are high due to high irrigation water requirements coupled with significant share of groundwater irrigation and diesel pumps with higher preference for districts where groundwater is safe so that standalone SIPs doesn't lead to groundwater risk
- **Groundwater Sustainability**: Districts where incentive for upscaling solar is to manage groundwater depletion, caused by high irrigation requirement and high subsidies for pumping, through introducing incentive mechanisms via SIPs

Composite index for adaptation, mitigation and sustainability aspects

District-level values for each selected indicator are grouped into four categories, from 1 (low) to 4 (high), to show how suitable each district is for solar irrigation under the three goals: adaptation, mitigation, and groundwater sustainability. A category value of 1 means low suitability, while a value of 4 means high suitability. In simple terms, a higher category value means that a higher value of that indicator makes a district more suitable for solar irrigation for that specific goal.

Table 1 presents the 12 indicators used to assess adaptation, mitigation, and groundwater sustainability. The threshold values used for classification for each indicator uis based on expert judgement and can be used in the platform. Each indicator is classified into four suitability levels—least suitable, moderately suitable, highly suitable, and very highly suitable—assigned the values 1, 2, 3, and 4. For example, solar irradiance below 3.75 kW/m^2 is marked as "least suitable" (value 1), while values above 5.25 kW/m^2 fall into the "very highly suitable" category (value 4) for all three goals.

Cropping intensity works differently across the goals. A higher cropping intensity is less suitable for adaptation but more suitable for mitigation and groundwater sustainability. For mitigation and sustainability, cropping intensity below 140% is "least suitable" (value 1), while the same value is considered "very highly suitable" (value 4) for adaptation. Low cropping intensity suggests more room for improving adaptation through expanded irrigation. In contrast, high cropping intensity offers more potential for mitigation and sustainability because solar pumps can reduce emissions and can be used as incentive (e.g. on grid solar) for more efficient irrigation.

Table 3: Classification of key indicators for adaptation, mitigation and sustainability suitability of solar irrigation pumps

S. No.	Data indicator	Adaptation, mitigation, sustainability aspects	Less Suitable (1)	Moderately Suitable (2)	High Suitable (3)	Very Highly Suitable (4)
1.	Solar Irradiance	Adaptation Mitigation Sustainability	<3.75 Kw/m^2	3.75-4.5 Kw/m^2	4.5-5.25 Kw/m^2	>5.25 Kw/m^2
2.	Cropping Intensity (%)	Adaptation	>220%	180-220%	140-180%	<140%
		Mitigation Sustainability	<140%	140-180%	180-220%	>220%
3.	Irrigation Intensity (%)	Adaptation	>75%	75-50%	50-25%	<25%
		Mitigation Sustainability	<25%	50-25%	75-50%	>75%
4.	IWU (% of CWU)	Adaptation Mitigation Sustainability	<28.5%	28.5-48%	48-67.5%	>67.5
5.	Electric pumps (%)	Adaptation Mitigation	>75%	75-50%	50-25%	<25%
		Sustainability	<25%	50-25%	75-50%	>75%
6.	GW development stage (%)	Adaptation Mitigation	>100%	100-70%	70-50%	<50
		Sustainability	<50	70-50%	100-70%	>100%
7.	Surface water area (%)	Adaptation Mitigation Sustainability	<1%	1-3%	3-5%	>5%
8.	Cultivated land (%)	Adaptation Mitigation Sustainability	<25%	50-25%	75-50%	>75%
9.	Electricity tariff net of subsidy	Adaptation Mitigation	<Rs 70/unit	Rs 70-150/unit	Rs 150-300/unit	>Rs 300/unit
		Sustainability	>300/unit	Rs 150-300/unit	Rs 70-150/unit	<Rs 70/unit
10.	Water level depth	Adaptation	>20 m	10 -20 m	5 - 10 m	< 5 m
		Mitigation Sustainability	<5	5-10 m	10 - 20 m	> 20 m
11.	GW Share in % (% of IWU)	Adaptation	>75%	50 - 75%	25 - 50%	< 25%
		Mitigation Sustainability	<25%	25 - 50%	50 - 75%	> 75%
12.	Small & Marginal % Holdings	Adaptation Mitigation Sustainability	<35%	35 - 60%	60 - 80%	> 80%

Source: Authors

The 12 data-indicators, each categorised into four groups depicting levels of suitability for solar irrigation, are combined to form a composite index, for adaptation, mitigation and sustainability aspects, for each district. The solar suitability index (SSI) is defined as

$$SSI = \sum_{i=1}^{n} w_i \times X_i$$

where, w_i denotes weight assigned to indicator i and X_i represent the respective classification category value, i.e., 1 to 4, of indicator i. The current analysis gives all indicators equal weight for simplicity, but these weights can be adjusted in the online SolarReady platform.

Districts are ranked based on their SSI scores for adaptation, mitigation, and sustainability, and then placed into five solar irrigation suitability categories: very high, high, moderate, low, and very low. Districts above the 80th percentile are classified as very high suitability, while those between the 60th and 80th percentiles are high. Districts falling between the 40th and 60th percentiles are moderate, those between the 20th and 40th percentiles are low, and districts below the 20th percentile are categorized as very low suitability. In total, 655 districts are mapped, excluding 11 districts for which data on any one of the 12 indicators is not available.

District model recommendation

SolarReady also identifies the most appropriate solar irrigation model for each district under India's PM-KUSUM scheme, helping planners and practitioners align technology deployment with local contexts. While the 12 indicators are involved in ranking districts for adaptation, mitigation and sustainability suitability (Table 1), additional indicators related to integrated rating and feeder segregation of utilities, total number of pumps, share of diesel pumps, average area per holding, and average number of parcels per holding, are used for district-level insights on water, energy, food, farmers, and utility categories, and identifying suitable model or component of solar pump under PM KUSUM scheme.

The platform identifies districts for their suitability for (a) various models under components B and C of the PM KUSUM scheme, (b) community-based model of solar irrigation pump, and (c) groundwater versus surface water irrigation sources.

A. *Models under components B and C of the PM KUSUM scheme*

PM-KUSUM Component B focuses on installing standalone solar pumps in areas dominated by diesel pumps for irrigation, while component C relates to solarization of grid-integrated pumps in areas with large share of electric pumps, with high feeder segregation and discom rating.

- **Model component B** for districts dominated by diesel pumps
- For districts with both diesel and electric pumps, but weak DISCOM rating and/or low feeder segregation
    - Strengthen **DISCOM performance** and **feeder segregation** to qualify for Component C.
    - Meanwhile, continue with **Component B**.
- **Model component C** for Districts dominated by electric pumps with strong DISCOM rating and high feeder segregation
    - In groundwater-stressed areas: use **Individual Pump Solarization (IPS)** only. The IPS model motivates farmers for efficient use of water and energy by provisioning transfer of surplus energy to the grid.
    - In districts with safe groundwater: adopt **both IPS and Feeder-Level Solarization (FLS)**.

B. Community vs Individual Solar Irrigation Pumps

- **Community-based (cooperative) solar irrigation systems** in districts with small and highly fragmented landholdings. By pooling resources, farmers can invest in off-grid solar systems or solar feeders collectively, enabling them to access solar irrigation technology and improve agricultural productivity.

- **Individual SIPs** in Districts with larger, less fragmented landholdings

C. Surface Water vs Groundwater Solar Irrigation

- Prioritize **surface water–based solar irrigation** in Districts facing groundwater stress or declining groundwater levels
- Using **groundwater-based solar irrigation** in Districts with stable and sufficient groundwater availability

The analysis, thus, helps in developing context and location specific solar irrigation strategy. The analysis is useful as the off-grid and on-grid solar irrigation pumps have distinct implications for the water, energy and food (WEF) nexus and equity, necessitating nuanced approaches to their deployment.

Annexure 1

A.1 The data indicators employed in the study are defined as below:

1. Solar Irradiance: It is the amount of solar energy received per unit area at a given location over a specific time. It is measured in kilowatt-hours per square meter (kWh/m^2). It is critical for assessing the potential of solar energy applications, including solar-powered irrigation systems.

2. Cultivated Land (%): Cultivated land refers to the proportion of total area of a district or region that is used for agricultural cultivation. It represents a combined share of net sown area and total fallow land in the total area reported for land utilization in a region. It is a key indicator of agricultural activity and land use intensity in a region. A larger proportion of cultivated land generally means greater demand for irrigation and associated energy needs.

3. Cropping Intensity (%): It refers to number of crops grown on the same piece of land during a year. It is calculated as ratio of gross cropped area to net sown area, multiplied by 100. It is a key indicator of agricultural productivity and land use efficiency.

4. Irrigation Intensity (%): Irrigation intensity measures how much of the gross cropped area is irrigated during a year and shows the proportion of land under irrigation, highlighting regions dependent on water inputs. It is calculated as the ratio of gross irrigated area to gross cropped area, multiplied by 100.

5. Irrigation Water Use (as % of Crop Water Use): represents the proportion of total crop water demand that is met through irrigation. It expresses how reliant a cropping system is on irrigation. It is especially useful for understanding water and energy needs for irrigation.

6. Groundwater's Share in Irrigation (% of Total Irrigation Water Use): It is the proportion of groundwater in the total irrigation water used in a region. It is calculated as the percentage share of gross irrigated area from groundwater in the gross cropped area, in a region. Areas heavily dependent on groundwater are strong candidates for solar-based pumping.

7. Groundwater Development Stage (%): Groundwater Development Stage indicates the extent to which the available groundwater resources in an area are being utilized. It is a critical indicator for assessing groundwater sustainability.

8. Surface Water Area (% of district area): It is the proportion of geographical area of a district that is covered by surface water bodies such as rivers, lakes, tanks, ponds and reservoirs. It provides a relative measure of surface water availability at the district level and helps in understanding regional water resource distribution.

9. Water Table Depth (m): Water level refers to the depth at which groundwater is found below the surface, usually measured in meters from the ground level or the surface of a reference point such as a well or borehole. It indicates the availability and accessibility of groundwater in a particular area. Shallow groundwater requires less energy for pumping and vice-versa.

10. Share of Electric Pumps (%): It is the proportion of electricity-powered irrigation pumps in total number of irrigation pumps. A high share of electric pumps signals a high potential to establish grid connected solar pumps, replacing existing irrigation system.

11. Electricity tariff after subsidy: Electricity subsidy for irrigation refers to the financial support provided by governments to farmers, reducing or eliminating the cost of electricity used for operating irrigation pumps. While it helps reduce input costs for farmers, it also has significant implications for energy use, groundwater sustainability, and the adoption of Solar Irrigation

Pumps (SIPs). The presence of subsidies may influence the financial attractiveness of switching to solar.

12. Proportion of Small and Marginal Farmers (%): It is the proportion of farmers owning less than 2 hectares of land in any region in India. Farmers with less than 1 hectare land are called as marginal farmers while those having 1 to 2 hectares of land are considered as small farmers in India. High percentages of smallholders may require tailored or community-based solar approaches. Farmers average area and land fragmentation are also key indicators for community-based SIP.

13. DISCOM Utility rating: It is the rating given to the power distribution companies by Ministry of Power (MoP), Government of India, based-on their financial and operational performance as well as their regulatory environment and the government support. It is an integrated rating that involves 15 parameters and 9 disincentives, together providing a comprehensive score out of 100 to evaluate each utility's performance holistically. The parameters for rating relate to financial sustainability, performance excellence, and external environment. The disincentives include auditor's adverse opinion, availability of audited accounts and default to banks, that contribute to the negative scores. Based-on the rating scores, the utilities are graded between A+ and D, where A+ and D indicate exceptionally strong and very low financial and operational performance, respectively.

14. Feeder segregation: It refers to a separate supply of electricity to agricultural consumers and non-agricultural consumers through dedicated feeders by a distribution utility. The separation of feeders facilitates a regulated supply of electricity to the agricultural consumers and a continuous power supply to the non-agricultural consumers. Here, we consider a utility as feeder segregating if it segregates 70% or more of the electricity distributed by it, and vice-versa.