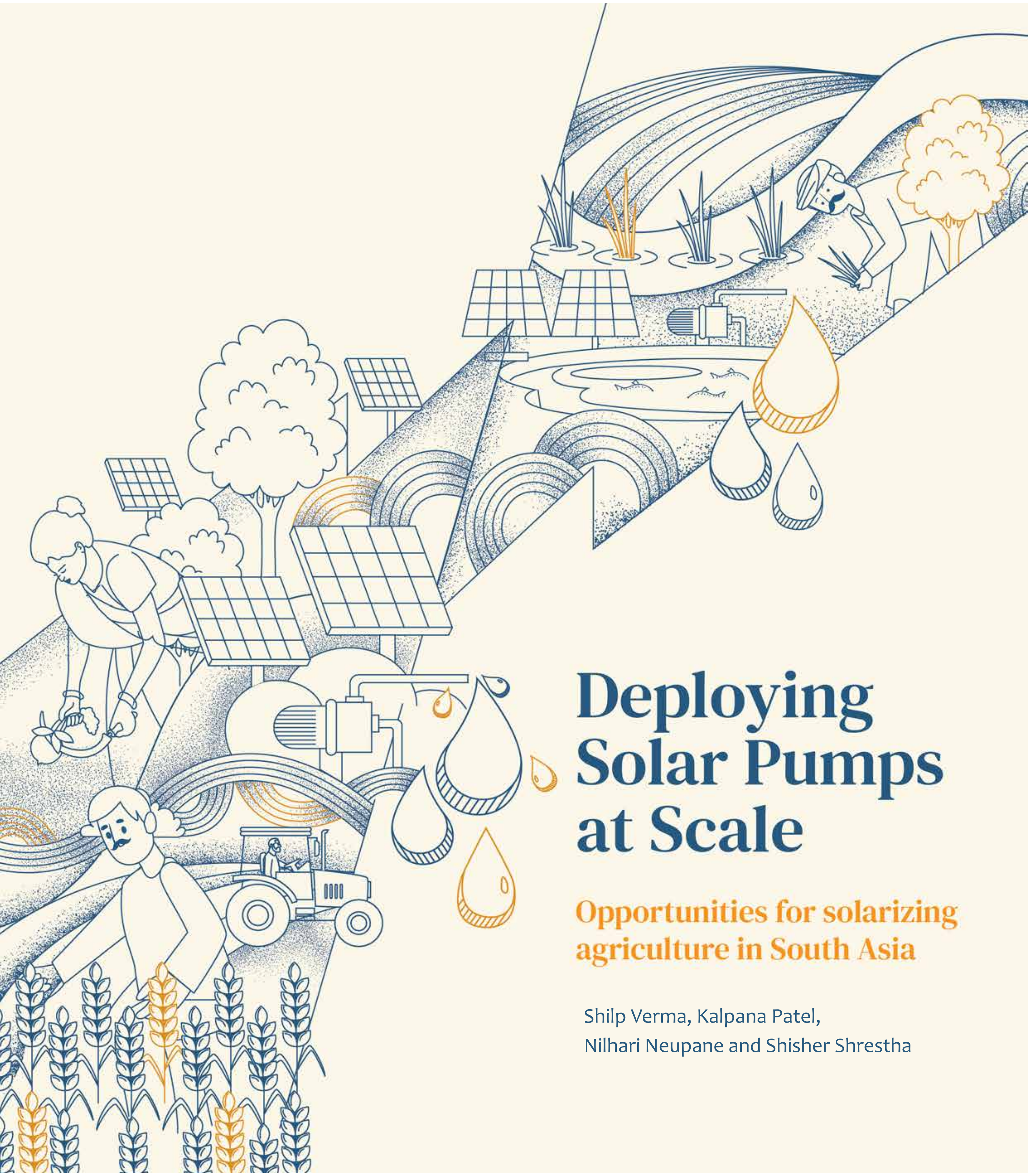

Deploying Solar Pumps at Scale

Opportunities for solarizing agriculture in South Asia

Shilp Verma, Kalpana Patel,
Nilhari Neupane and Shisher Shrestha

INTERNATIONAL SOLAR ALLIANCE
IWMI International Water Management Institute
IWMI-TATA Water Policy Program
SE4RL Solar Energy for Rural Livelihoods
CGIAR CLIMATE ACTION

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Partner Programs

ITP	IWMI-Tata Water Policy Program	
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Executive Summary

The fates of South Asia's water, energy and food sectors are intertwined. No other region in the world pumps as much water as South Asia. Much of this pumping – both from surface and groundwater sources – is for irrigation and food production, and some more for meeting domestic, municipal, and industrial water demand. Estimates vary, but the region has more than 100 million hectares of pumped irrigated cropped area. An estimated 30 million energised minor irrigation structures form the backbone of the irrigated agriculture economy. Deployed almost exclusively through private capital invested by millions of poor farmers, these structures have contributed substantially to ensuring food security for the region's 1.6 billion people. The structures also account for more than half the global groundwater pumped for irrigation, leading to pockets of severe groundwater depletion, and contributing 8-11% of the region's GHG emissions. The structures are also the leading cause for the dismal performance and bankruptcy of the region's electricity utilities.

The six South Asian countries in focus for this report – Bangladesh, Bhutan, India, Maldives, Nepal and Sri Lanka – together have nearly 200 million hectares of agricultural land. Access to electricity, especially in rural areas, is excellent in Bhutan, Maldives and Sri Lanka and rapidly improving in Nepal, Bangladesh, and India. Compared to the global average, per capita energy consumption is quite low; but is rapidly rising. Sunshine is abundantly available with most parts receiving the equivalent of 1,400 – 2,000 peaksunshine hours. The prospect for using solar resource for pumping water is enormous, given the scale of the region's pumped irrigation economy. Not surprisingly, the region is an early leader in off-grid solar capacity deployed for use in agriculture and the 'global epicentre' for solar pumps.

The south Asian economy is predominantly agrarian, with roughly half the population relying on agriculture for livelihoods. Like most developing economies, agriculture contributes relatively little – only about 18% – to the region's Gross Domestic Product (GDP) and is responsible for more than 80% of the annual freshwater withdrawals. Data shows that the global (off-grid) capacity of solar pumps installed for use in agriculture grew from a little over 13 MW in 2009 to nearly 1,339 MW by 2023. This hundred-fold increase has been driven primarily by aggressive promotion of solar pumps. While there is no official count, it would be fair to assert that the region is home to more than a million solar pumps.

With aggressive policy support, India is a distant leader accounting for more than 93% of the global off-grid solar capacity deployed for use in agriculture. But India's potential for solar pumps is much bigger – nearly 200 GWp, as per one estimate. Between 2018 and 2022, Bangladesh has doubled agri-solar capacity, thanks to innovative public-private partnerships. In Nepal, particularly after 2015, solar pumps have picked pace, driven by AEPC and a renewed interest in diversifying the country's energy mix. While the solar economies in Bhutan, Sri Lanka and Maldives are still nascent, the potential to scale and create significant positive impacts on the lives and livelihoods of millions of farmers is enormous.

Our rough estimate suggests that at current market prices (USD 800 per kWp of solar generation capacity), and with an ultimate potential for deployment of ~25 million solar pumps, the potential solar pump market of the region would easily exceed USD 120 billion in value. Our analyses also strongly suggests that solarization of South Asian agriculture is no longer a choice, only the pace at which this will happen is uncertain.

PARTICULARS	BANGLADESH	BHUTAN	INDIA	NEPAL	SRI LANKA
RE share in electricity generation | 2022 %	3.1	99.6	33.7	97.8	58.9
Agricultural Land | '000 Km^2	99.0	5.1	1,790.5	41.2	28.1
PV Installed Capacity | 2025GWp	0.85	0.00	97.04	0.18	1.45
Off-grid Solar Pump Capacity | 2023 MWp	49.331	0.000	1251.704	4.335	0.001
Short-term Target for Solar Pump Deployment	~100,000	-	~2,500,000	~30,000	~2.000
Long-term Potential for Solar Pumps	~1.5 million	NA	~23 million	~350,000	NA
Key Government Stakeholder	IDCOL	DRE	MNRE	AEPC	SLSEA

Our synthesis of the experience of more than a decade of solar pump expansion through numerous field and policy experiments offers some suggestions for carving a practical and pragmatic roadmap. These include creating an enabling policy environment, fitting business models and deployment strategies to the diverse biophysical and socio-economic contexts, reducing unit costs by leveraging economies of scale and scope, right-sizing systems, innovating on financial models and products, investing in optimum utilization, creating awareness and capacity, facilitating south-south learning and knowledge exchange, and focusing on equity and sustainability.

This report also recommends some immediate actions for ADB and ISA that can facilitate this transition. These include detailed first-hand assessments of the potential for solar pumps in Bhutan, Maldives and Sri Lanka, a solar pump innovation fund for encouraging innovations in design and deployment strategies, scaling out the solar pump sizing tool beyond India, and a regional learning platform to catalyse south-south learning and cooperation.

Prashanth Vishwanathan/IWMI

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Abbreviation list

ABhY	Atal Bhujal Yojana
AC-PVWP	Accelerated Commercialization of Solar Photovoltaic Water Pumping project
ADB	Asian Development Bank
AEPC	Alternative Energy Promotion Centre, Government of Nepal
AKRSP-I	Aga Khan Rural Support Programme (India)
B2G	Business-to-Government
BADC	Bangladesh Agricultural Development Corporation, Government of Bangladesh
BARI	Bangladesh Agricultural Research Institute, Government of Bangladesh
BCM	Billion Cubic Meters
BEA	Bhutan Electricity Authority, Royal Government of Bhutan
BISA	Borlaug Institute for South Asia
BMDA	Barind Multipurpose Development Authority, Government of Bangladesh
BPC	Bhutan Power Corporation Ltd, Royal Government of Bhutan
BREB	Bangladesh Rural Electrification Board, Government of Bangladesh
COP26	26th UN Climate Change Conference
CREDA	Chhattisgarh State Renewable Energy Development Agency, Government of India
CSP	Concentrated Solar Power
CUF	Capacity Utilization Factor
DAE	Department of Agricultural Extension, Government of Bangladesh
DGPC	Druk Green Power Corporation, Royal Government of Bhutan
DHMS	Department of Hydromet Services, Royal Government of Bhutan
DHPS	Department of Hydropower Systems, Royal Government of Bhutan
DRE	Department of Renewable Energy, Royal Government of Bhutan
DWRI	Department of Water Resources and Irrigation, Government of Nepal
FAO	Food and Agriculture Organization of the United Nations
FiT	Feed-in-tariff
GCF	Green Climate Fund
GDP	Gross Domestic Product
GESI	Gender Equity and Social Inclusion
GERMI	Gujarat Energy Research and Management Institute
GGGI	Global Green Growth Institute
GHG	Greenhouse Gases
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH
GoN	Government of Nepal
GW	GigaWatt
GWp	GigaWatt-peak
GWSSB	Gujarat Water Supply and Sewerage Board
HP	Horse power
HYV	High Yielding Varieties
ICAR	Indian Council of Agricultural Research, Government of India
ICED	India Climate and Energy Dashboard, NITI Aayog, Government of India
ICIMOD	The International Centre for Integrated Mountain Development
IDCOL	Infrastructure Development Company Limited
iDE	International Development Enterprises
INGOs	International Non-Governmental Organizations
IRENA	International Renewable Energy Agency
IRMA	Institute of Rural Management, Anand
ISA	International Solar Alliance
IWMI	International Water Management Institute
ITP	IWMI-Tata Water Policy Program
kWp	Kilowatt-peak
kWh/m^2	Kilowatt-hour per square metre

LPG	Liquefied Petroleum Gas
MNRE	Ministry of New and Renewable Energy, Government of India
MoAFW	Ministry of Agriculture and Farmers' Welfare, Government of India
MoEA	Ministry of Economic Affairs, Government of India
MoEWRI	Ministry of Energy, Water Resources and Irrigation, Government of Nepal
MoPEMR	Ministry of Power, Energy and Mineral Resources, Government of Bangladesh
MoPID	Ministry of Physical Infrastructure Development, Government of Nepal
MRP	Maximum Retail Price
MSKVY	Mukhyamantri Saur Krushi Vahini Yojana
NDC	Nationally Determined Contributions
NEC	National Environment Commission, Royal Government of Bhutan
NGOs	Non-Governmental Organizations
NMSA	National Mission for Sustainable Agriculture, Government of India
NO_x	Nitrous Oxides
NPC	National Planning Commission, Government of Nepal
NPR	Nepalese Rupee
NSEFI	National Solar Energy Federation of India
PAYGO	Pay-as-You-Go
PMFBY	Pradhan Mantri Fasal Bima Yojana
PMKSY	Pradhan Mantri Krishi Sinchai Yojana
PM-KUSUM	Pradhan Mantri Kisan Urja Suraksha evam Utthan Mahabhiyan
PPP	Public Private Partnership
PV	Photovoltaic
PVOUT	Photovoltaics Power Output
RDA	Rural Development Academy, Bangladesh
RE	Renewable Energy
RTO	Rent-to-Own
SDGs	Sustainable Development Goals
SDC	Swiss Agency for Development and Cooperation
SE4ALL	Sustainable Energy for All
SHS	Solar Home System
SIPs	Solar Irrigation Pumps
SKY	Suryashakti Kisan Yojana
SNA	State Nodal Agencies (India)
SPaRC	Solar Power as Remunerative Crop
SPIPA	Strategic Partnership for the Implementation of the Paris Agreement
SREDA	Sustainable and Renewable Energy Development Authority, Government of Bangladesh
STW	Shallow Tubewell
SLSEA	Sri Lanka Sustainable Energy Authority, Government of Sri Lanka
USAID	United States Agency for International Development
UNDP	United Nations Development Programme
WEF Nexus	Water-Energy-Food Nexus

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South Asia's Solar Landscape

A. South Asia's Solar Landscape

1. Water-Energy-Food Nexus

The fates of South Asia's water, energy and food sectors are intertwined. No other region in the world pumps as much water as South Asia. Much of this pumping is for food production and irrigation – both from surface and groundwater sources – and some more for meeting domestic, municipal, and industrial water demands. Estimates vary but the region has roughly 100 million hectares of pumped irrigated area – and a lion's share of this is serviced by pumped irrigation. With small land holdings and limited coverage from gravity-based canal irrigation systems, an estimated 30 million energised minor irrigation structures form the backbone of the agrarian economy. In India – home to 21 million of these structures, this accounts for nearly a fifth of annual energy use. All these structures, deployed almost exclusively through private capital invested by millions of poor farmers, have contributed substantially to ensuring food security for the region's 1.6 billion people. But they also account for more than half the world's groundwater pumped for irrigation, have led to pockets of severe groundwater depletion, contribute 8-11% of the region's GHG emissions, are one of the key factors responsible for bankrupt electricity utilities.

In this report, we map the region's water and energy resources – including solar irradiation patterns and solar energy generation potential, water resource availability, current patterns of surface and groundwater use and the prospects for solar pumps. Based on these, we offer a first-cut assessment of the potential size of the solar pumps market in the region. For the purpose of this assessment, we focus primarily on four countries – Bangladesh, India, Nepal and Sri Lanka.

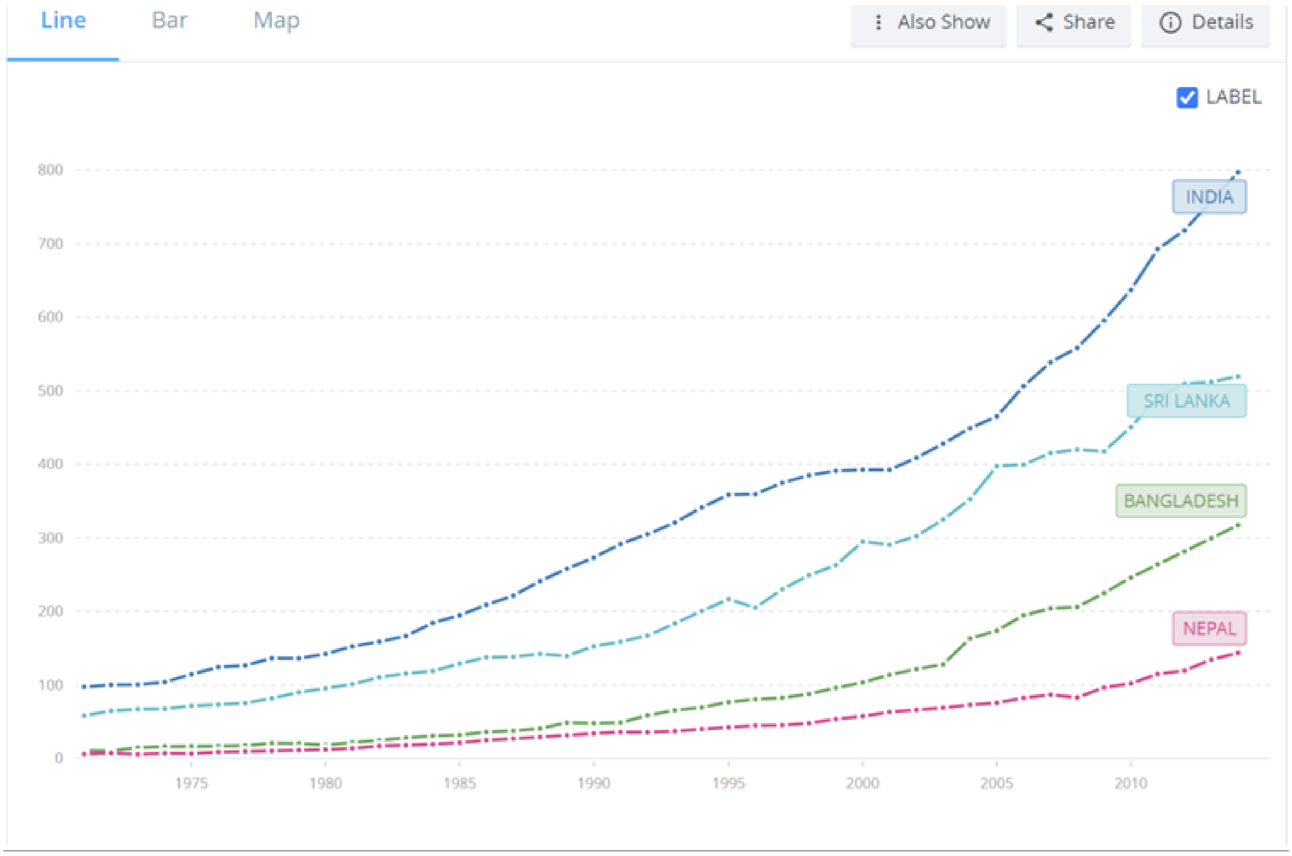
Thus, South Asian agriculture is trapped in a perverse nexus between water and energy use for food production. With poorly defined water rights, the price of energy (used for pumping water) can act as a precious surrogate for water price and should signal relative resource scarcity. However, thanks to the political economy of energy and food policies, irrigating with groundwater is cheap and lucrative where the resoure is scarce and costly and unattractive where groundwater is plentiful. The advent of solar pumps adds a new dimension to this nexus – offering an opportunity to fix some of the perverse incentives, but also posing new challenges, including further exaggerating the threat of groundwater depletion.

2. Energy and Renewable Energy

The six focus countries in South Asia – Bangladesh, Bhutan, India, Maldives, Nepal and Sri Lanka – together have nearly 200 million hectares of agricultural land. Access to electricity, especially in rural areas, is excellent in Bhutan, Maldives and Sri Lanka and rapidly improving in Nepal, Bangladesh, and India. Compared to the global average, per capita energy consumption is quite low throughout the region, but rising (Table 1; Figure 1). Likewise, compared to the global average of 4.7 tonnes of CO_2 per person, emissions are lower in the region and range from 0.51 (Nepal) to 4.62 (Maldives) (Table 1; Figure 2).

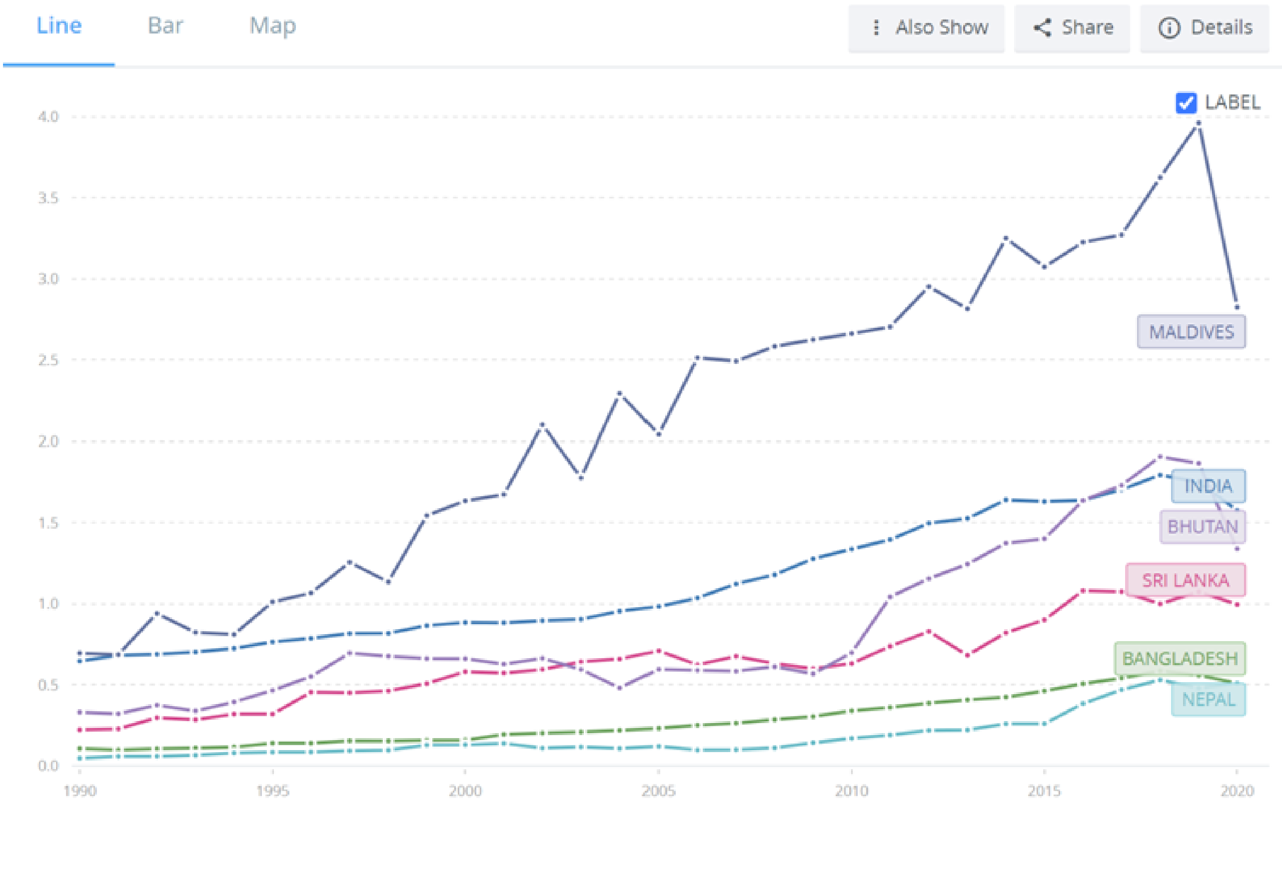
Sunshine is abundantly available in the region with most parts getting 1,400 – 2,000 peak-hour equivalent of sunshine hours. As discussed above, the prospect for using this energy for pumping water is also enormous, given the scale of the region's pumped irrigation economy. Not surprisingly, therefore, the region is an early leader in off-grid solar capacity deployed for use in agriculture (IRENA 2022) and can be termed as the 'epicentre' for solar pumps.

The Global Solar Atlas 2.0 maps daily and annual long-term average photovoltaic potential around the world (Figure 3) and shows that most parts of South Asia have moderate to high solar energy generation potential. Among the six countries of interest, the average (*theoretical*) potential estimated in kWh/m^2 ranges from 3.940 in Bhutan to 5.593 in Maldives. The average practical potential estimated in kWh/kWp ranges from 3.881 in Bangladesh to 4.442 in Maldives. The PVOUT Seasonality Index for all countries in the region is below well below the widely accepted threshold of 2.0 and ranges from 1.34 in Maldives to 1.75 in India (Table 1; Figure 4).



Source: World Development Indicators | https://wdi.worldbank.org/

Figure 1: Per capita energy consumption (KWh/person/year)



Source: World Development Indicators | https://wdi.worldbank.org/

Figure 2: Per capita CO_2 emissions

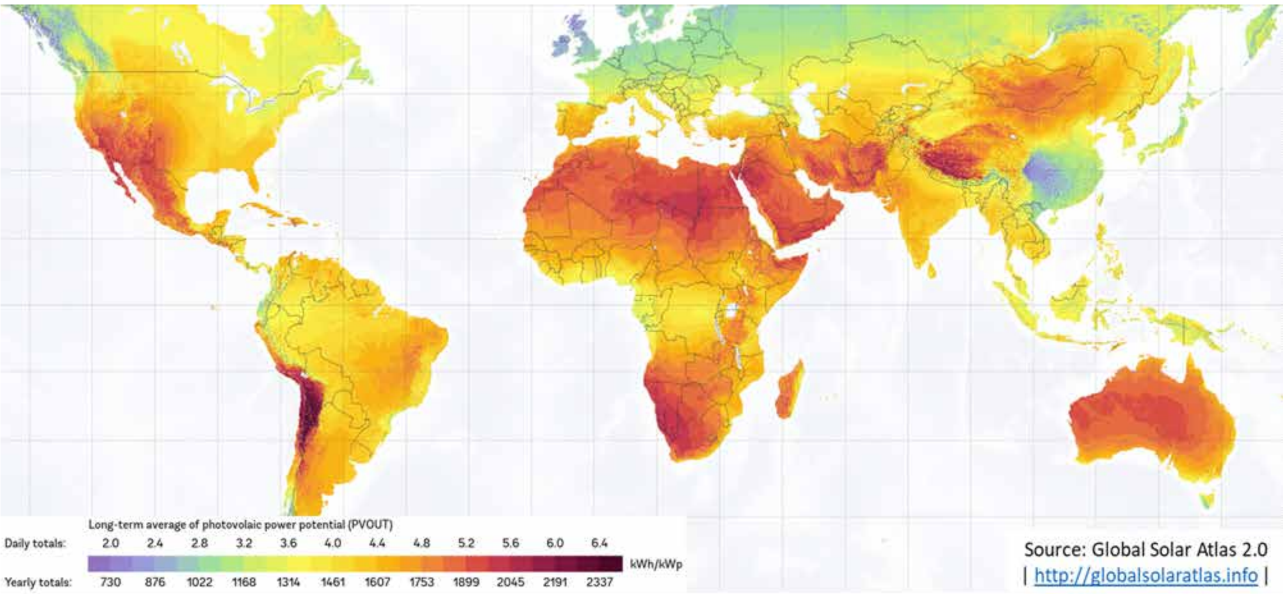


Figure 3: Daily and Annual Photovoltaic Potential across the world

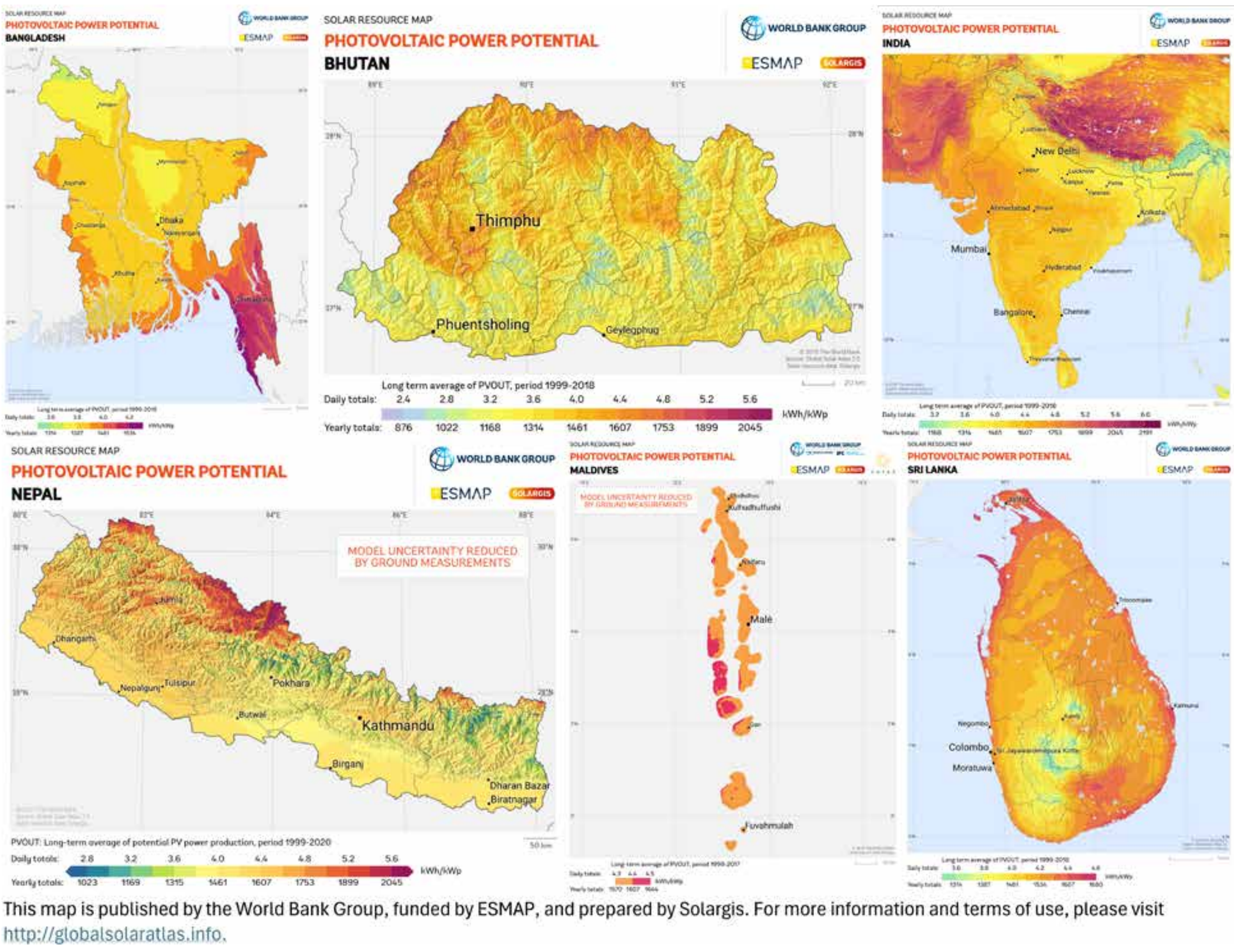


Figure 4: PV Potential in Bangladesh, Bhutan, India, Nepal, Maldives and Sri Lanka

India dominates the region in terms of total PV installed capacity as well in agriculture. In fact, according to estimates by IRENA, South Asia is home to more than 97% of the world's off-grid PV capacity deployed for use in agriculture, mostly in India and Bangladesh.

3. Water Resources

The south Asian economy is predominantly agrarian with roughly half the population dependent on agriculture for livelihoods although, like most developing economies, agriculture contributes relatively little, only about 18% to the region's Gross Domestic Product (GDP) and is responsible for more than 80% of the annual freshwater withdrawals. Along with China and South-East Asia, the region is sometimes referred to as *'Monsoon Asia'* due to its high dependence on the north-west monsoon, which means that bulk of its precipitation occurs in 3-4 months while the rest of the year is almost completely dry. The centrality of agriculture and monsoon makes water storage, irrigation and management critical to life and livelihoods in the region.

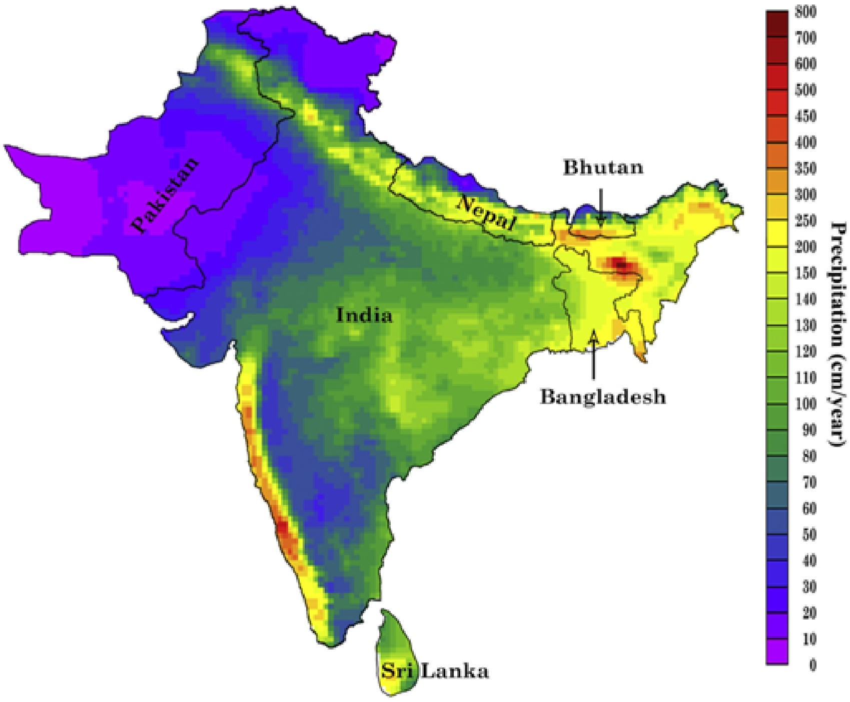
The precipitation map (Figure 5) shows the range of mean annual precipitation in the region, from less than 100 mm/year in western Pakistan to more than 5,000 mm/year in north-east and the western coast of India. The total annual precipitation volume – a function of mean rainfall and geographical area – ranges between less than 1 billion cubic meters (BCM) for Maldives to more than 3,500 BCM for India (Table 2).South Asia is not only home to the world's largest contiguous surface irrigation system (Indus irrigation system), it also accounts for a quarter of the world's groundwater use. Some estimates suggest that every year, 250-300 BCM of groundwater is pumped, mostly for irrigation, through a dense network of 30 million wells, tubewells and lift irrigation schemes running on diesel, electric or even muscle power, broadly classified as 'minor irrigation systems' (Figure 6). With growing municipal and industrial water demand and rising income levels, compounded by climate-induced uncertainties, water stress is increasing in the region. This is particularly true for large parts of India and pockets in Nepal, Bangladesh and Sri Lanka. Per capita water availability is also extremely low in Maldives and can seriously hamper economic activities and growth.

Table 1: Country profiles and Solar PV potential in South Asia

	UNITS	B'DESH	BHUTAN	INDIA	MALDIVES	NEPAL	S. LANKA
Geographical Area	'000 Km^2	147.6	38.4	3287.3	0.3	147.2	65.6
Agricultural Land	'000 Km^2	99.0	5.1	1790.5	0.1	41.2	28.1
Population | 2024*e*	Million	172.95	0.79	1428.63	0.52	30.90	21.89
GDP per Capita | 2022	USD	2,734	3,562	2,466	15,097	1,293	3.293
HDI Rank | 2019	-	134	131	130	98	143	73
Electricity Access (%rural population) | 2021	%	99	100	99.6	100	89.9	100
Electricity Consumption per Capita | 2014	kWh/year	317	-	797	-	144	520
CO_2 emissions per capita | 2022	Tons/year	0.63	2.01	1.91	4.62	0.51	0.87
Total RE Installed Capacity | 2022	MWp	775	2,335	162,963	37	2,342	2,857
RE share in electricity capacity | 2022	%	3.1	99.6	33.7	6.6	97.8	58.9
Solar PV Installed Capacity | 2022	MWp	537	-	62,804	36	117	714
Off-grid PV Capacity in Agriculture | 2022	MWp	49.331	-	1251.704	-	3.247	0.001
Average (theoretical) Potential	kWh/m^2	4.596	3.940	5.098	5.593	4.534	5.277
Average (practical) Potential	kWh/kWp	3.881	3.916	4.322	4.442	3.996	4.212
PVOUT Seasonality Index	-	1.47	1.61	1.75	1.34	1.59	1.43
Levelized Cost of Electricity (LCOE)	USD	0.11	0.11	0.07	0.10	0.11	0.10
Approx. Electricity Tariff | 2019	USD	0.092	0.054	0.17	0.449	0.114	0.169

Source: Data compiled from IRENA (2023), World Bank Open Data, World Development Indicators and Global Solar Atlas 2.0[1]

[1]The Global Solar Atlas 2.0 is a free, web-based application developed and operated by the company Solargis s.r.o. on behalf of the World Bank Group, utilizing Solargis data, with funding provided by the Energy Sector Management Assistance Program (ESMAP). For additional information: https://globalsolaratlas.info



Source: Mukherjee et al. (2015)

Figure 5: Mean annual precipitation in South Asia

Table 2: Country profiles and Water Resources in South Asia

	UNITS	B'DESH	BHUTAN	INDIA	MALDIVES	NEPAL	S. LANKA
Geographical Area	'000 Km^2	147.6	38.4	3287.3	0.3	147.2	65.6
Agricultural Land	'000 Km^2	99.0	5.1	1,790.5	0.1	41.2	28.1
Population | 2018	Million	161.36	0.75	1,352.62	0.52	28.09	21.67
Population Density | 2020	per Km^2	1,116	20	424	1,715	205	354
GDP per capita | 2020	USD	2,001	3,218	1,931	6,924	1,135	3,768
Contribution of agriculture to GDP	%	19	18	17	5	34	13
Long-term Average Precipitation – Depth	mm/year	2,320	2,200	1,170	-	1,500	1,712
Long-term Average Precipitation – Volume	BCM/year	393.42	84.46	3,560.10	0.59	220.77	112.32
% cultivated area equipped for irrigation | 2020	%	54.30	27.68	41.74	-	48.76	24.03
Total Renewable Groundwater	BCM/year	21	8	432	0.03	20	7.8
Total Renewable Surface Water	BCM/year	1,206	78	1,869	-	210	52
Total Renewable Water Resource	BCM/year	1,227	86	1,910	0.03	210	52.8
Total Renewable Water Resource per capita	m^3/person	7,451	101,087	1,385	55	7,214	2,466
Water Withdrawal – Agriculture	BCM/year	31.5	0.3	688.0	-	9.6	11.3
Water Withdrawal – Municipal	BCM/year	3.6	0.0	56.0	-	0.1	0.8
Water Withdrawal – Industrial	BCM/year	0.8	0.0	17.0	-	0.0	0.8
Water Withdrawal – TOTAL	BCM/year	35.9	0.3	761.0	-	9.8	13.0

Source: Data compiled from FAO AQUASTAT, World Bank (2016), Shah and Verma (2017)

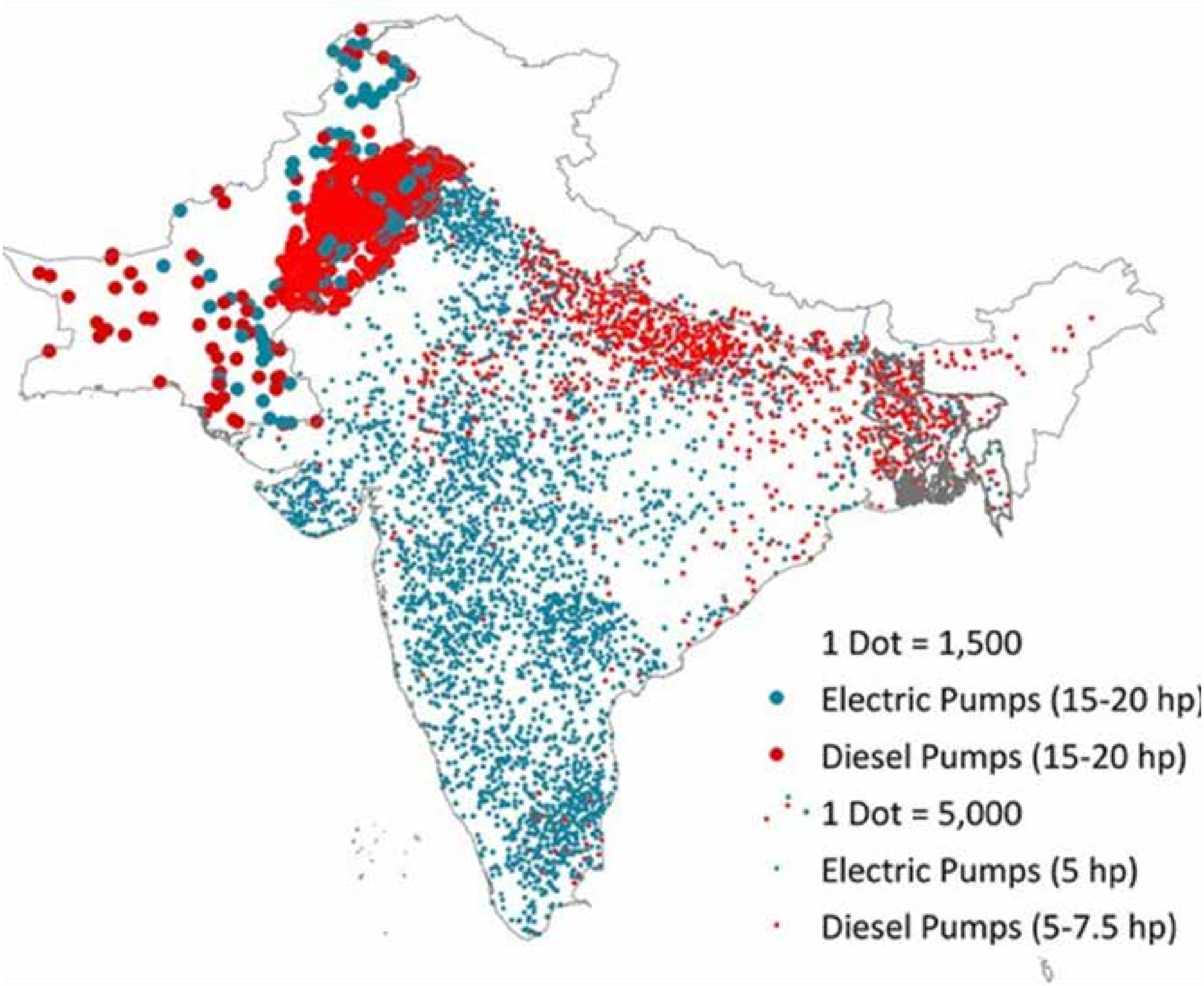


Figure 6: South Asia's Minor Irrigation Economy

4. Potential for Solar Pumps

IRENA (2023) data shows that the global (off-grid) capacity of solar pumps installed for application in agriculture grew from a little over 13 MW in 2009 to nearly 1,355 MW by 2022. This hundred-fold increase has been driven primarily by aggressive promotion of solar pumps in South Asia – with India leading and Bangladesh a distant but significant second. Of the 1355 MW of off-grid solar capacity estimated to be deployed for agricultural use, 1,252 MW is attributed to India and 49 MW to Bangladesh; about 36 MW is in Africa while the remaining is sparsely spread around the world. While there is no official count, it may be surmised that the number of solar pumps in the region now exceeds half a million.

India started early and has scaled-up solar pump numbers to more than 400,000 by 2022. One early estimate (ITP-GERMI-Greenpeace 2018) suggests that solarizing all of India's irrigation pumps can account for more than 150 GW of solar capacity. India's solar pump economy is a small but growing part of the larger pump irrigation ecosystem and a politically entrenched water-energy-food nexus (Figure 7). With an estimated annual pumping of 250-300 BCM, India is the world's largest user of groundwater. Much of this is for agriculture through her 21 million irrigation pumps. Of these, about 15-16 million are electric while the rest run on diesel. Farmers in most Indian states receive free or highly subsidised farm power to run their electric pumps and this account for an annual farm power subsidy burden of USD 18-20 billion. A key driver of agri- solarization in India is this growing annual farm power subsidy burden, which has also contributed to pockets of severe groundwater depletion all over western and peninsular India.

Almost every state in India has been offering 70-95% capital subsidies to encourage farmers to adopt solar pumps. In 2017, the government of India announced PM-KUSUM (*Pradhan Mantri Kisan Urja Suraksha evam Utthan Mahabhiyan*), an ambitious campaign with a (revised) target of deploying 3.5 million solar pumps by 2026. The aggressive subsidy support, growing farmer interest and the resultant decline in unit costs have all contributed to solar pump expansion in India.

In **Nepal**, the first solar pumping system was introduced in 1993 but the program got accelerated after a 2015 USAID program that has installed about 200 systems. The 2016 Renewable Energy Subsidy Policy anointed the Alternate Energy Promotion Centre (AEPC) as the nodal agency responsible for mainstreaming solar pumps. So far, AEPC has supported the deployment of about 2,000 solar pumps – largely for irrigation – and has a target of 6,500 installations by 2024. The country's solar pump landscape has two distinct segments – in Upper and Middle Himalayas, the remoteness of habitations and the need to lift water make multiple use solar pumping systems attractive. In Nepal *Terai*, abundant shallow groundwater, intensive cultivation, poor farm power supply and the rising cost of diesel offer tremendous opportunity for solar irrigation pumps.

IRENA data shows that between 2018 and 2022, **Bangladesh** managed to double the off-grid solar capacity deployed for use in agriculture. This has – to a large extent – been possible thanks to an innovative model of solar irrigation enterprises being scaled by IDCOL (Infrastructure Development Company Limited) that has been financing solar pumps. By encouraging private enterprises and NGOs to invest in village-scale solar irrigation systems (that combine solar panels and pumps with a network of buried pipes) and offer 'solar-irrigation-as-a-service'. So far, IDCOL has implemented 1,523 solar irrigation enterprises with installed capacity of 42.1 MW through their 50% grant, 35% credit and 15% equity model (Mitra *et al*. 2023). ADB (2023) used multi-criteria suitability mapping to identify upazilas suitable for surface and groundwater based solar irrigation expansion (see Figure 8). IWMI's recent work shows that besides the obvious mitigation benefits, solar pumps also reduce farmers' irrigation expenditure, save time and labour, and enable supplemental irrigation during late monsoons (Mitra *et al.* 2023). By 2030, Bangladesh aims to generate 10% of electricity from renewable sources and solarization of the country's 1.24 million diesel and 0.34 million electric pumps (BADC 2020) can contribute significantly to this target. With a tourism economy still recovering from the effects of CoViD-19 and the economic crisis that followed immediately after, **Sri Lanka** has been able to make little progress on solarization. A (draft) pre-feasibility report done for ISA includes detailed mapping of solar and water resources and projects a demand for 2000 small-capacity solar pumps. The solar pump economy in **Bhutan** and **Maldives** is nascent, with little reported progress and even less information on plans.

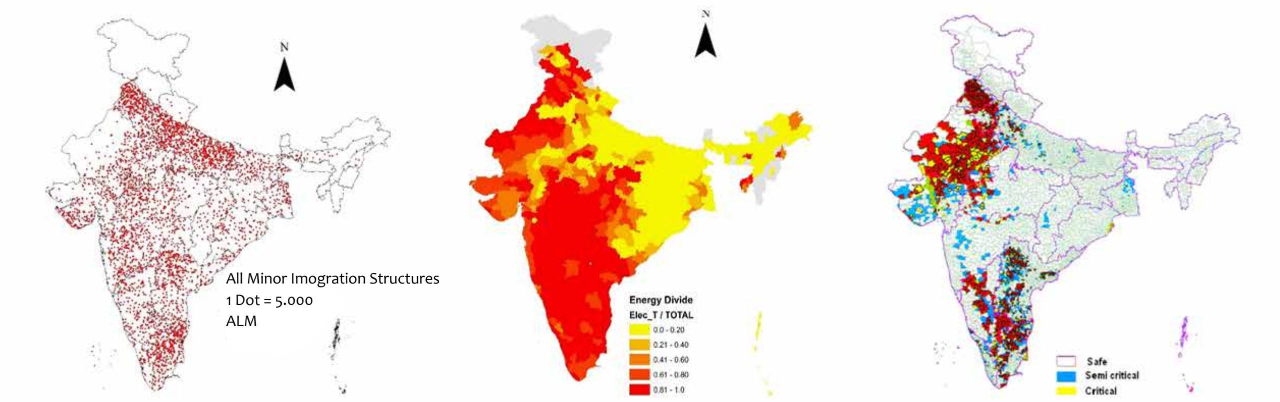
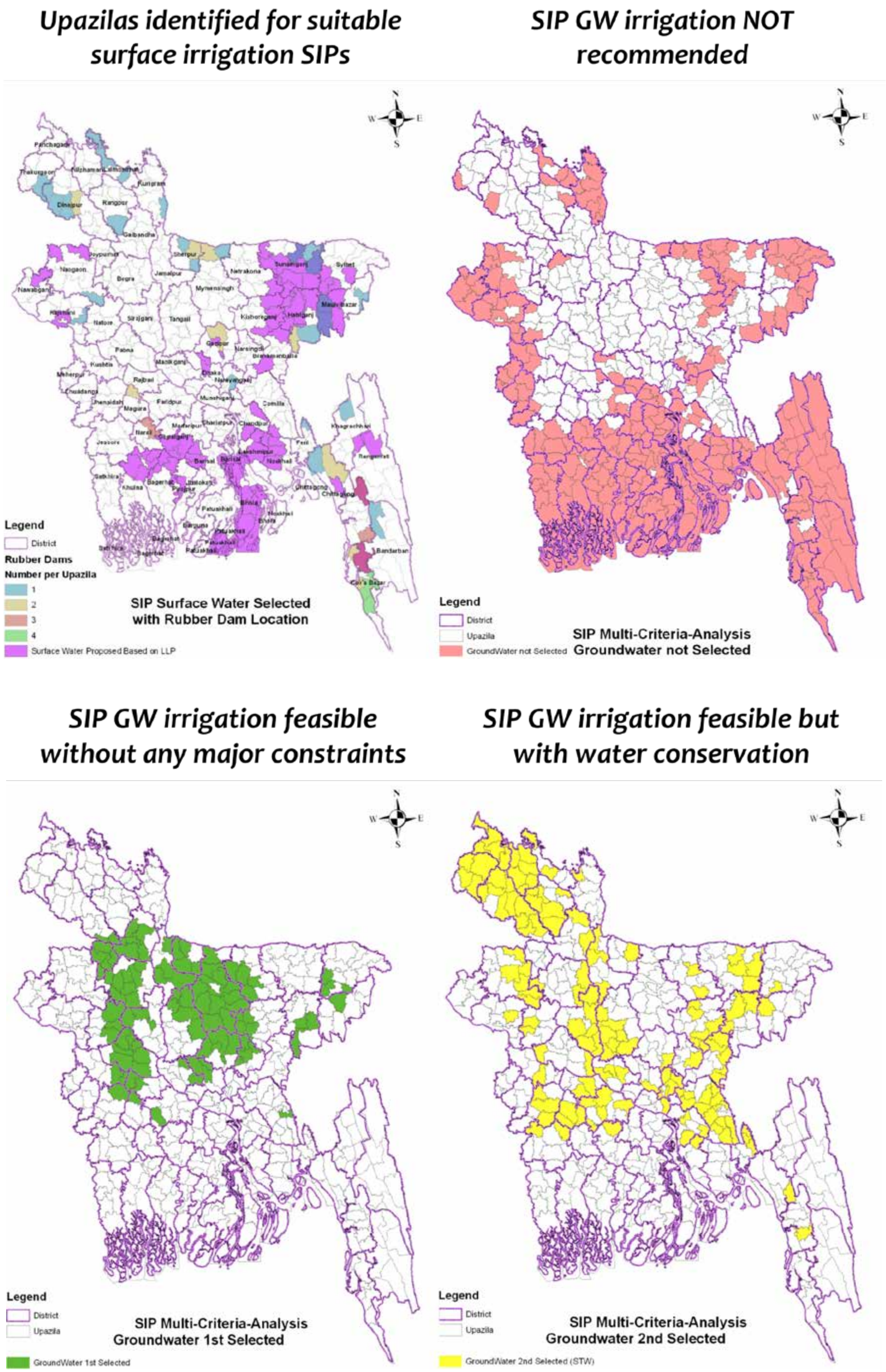


Figure 7: The Water-Energy-Food Nexus in India



Source: ADB (2023)

Figure 8: Multi-criteria suitability mapping for scaling solar pumps in Bangladesh.

5. Solar Pump Economy of South Asia: A Rough Estimate

With a large and still growing minor irrigation economy increasingly being put under pressure by rising diesel costs, unsustainable farm power subsidies and growing public and private ambition and support for Renewable Energy, solar pumps have a bright future in South Asia.

We use existing public data and a simple method to estimate the overall potential size of the solar pump economy in South Asia. This economy is likely to be driven by the demand for solar irrigation pumps, which exceed 30 million in the region. Some estimates also suggest that each year, 1-1.5 million new pumps are added – although there is no reliable data on this.

We also know that the size of irrigation pumps varies from region to region, depending on several factors including average land holding, irrigation command area, cropping and irrigation intensity, groundwater depth, pumping head and irrigation method and techniques. For instance, pump sizes are much larger (20-60 HP) in north-western India where farmers are pumping groundwater from 1000-1500 feet. On the other hand, average pump size in water-abundant Nepal Terai and eastern India's Gangetic plains is much smaller (3-5 HP); some farmers also use sub-HP micro solar pumps to deliver protective irrigation to small land parcels. In Bangladesh, where each solar pump is deployed to service scores of farmers, average pump size is again larger (25 HP), even though groundwater is shallow and land holdings are small.

India's PM-KUSUM campaign, which aims to deploy 3.5 million solar pumps and roughly 30 GWp of solar generation capacity for irrigation by 2026, is estimated to require an investment (both public and private) of about USD 20-25 billion. If we assume that each new solar pump will replace an existing electric or diesel pump then it would be safe to assume an average pump size of 5 HP, combined with a 5 kWp solar array. At the current market prices in India (~ USD 800 per kWp), the potential size of the solar irrigation pump economy can be estimated to be approximately **USD 120 billion**. Further, we can add roughly 1-1.5 million solar drinking water systems, with an average size of 1-2 kWp. At current costs of about USD 2500 each, this would amount to roughly **USD 3.5 billion**.

Current trends suggest that solarization of agriculture in South Asia is no longer a choice, only its pace is. And this pace can be accelerated through smartly designed initiatives and programs by ADB and ISA.

Nabin Baral/IWMI

Bangladesh

Determined to Ditch Diesel

B. Bangladesh: Determined to Ditch Diesel

Bangladesh stands out as one of the world's largest delta nations and is among the most densely populated. The country's economic foundation is predominantly agrarian, with agriculture contributing a significant 11% to its GDP and engaging around 45% of the workforce (GoB, 2023). With a substantial population and comparatively limited arable land, ensuring and sustaining food security remains one of the foremost concerns for the government. Consequently, Bangladesh has experienced consistent agricultural expansion, aiming to attain self-sufficiency in cereal production.

The GDP of Bangladesh has steadily increased over the last 20 years. As a result, demand for energy is rising quickly. Bangladesh announced ambition to expand the proportion of RE in its energy mix to 10% by 2030 through the first RE Policy, published in 2014. The goal to raise the nation's peak RE output was revised recently and is now expected to reach 40 GW by 2041 (Talut *et al.* 2022).

Bangladesh's per capita land availability is one of the lowest globally (Talut *et al.* 2022) and is still declining (Figure 10). Despite these challenges, solar energy has emerged as the most easily harvestable renewable energy resource, necessitating considerable land space for large-scale power generation.

Fortuitously, significant land stretches exist in regions where population density is notably lower (Figure 11). These lands, characterized by minimal arability due to heightened salinity, hold potential for solar power generation. Nevertheless, the deployment of solar farms on such landmasses poses a significant challenge. Widespread land price inflation and legal disputes over ownership pervade, exacerbating the difficulty in establishing solar energy installations.

During the 1980s and 1990s, Bangladesh grappled with persistent food shortages, necessitating imports and foreign assistance. This state of affairs persisted until 1999-2000 when the country achieved food self-sufficiency, marking the end of dependence (Rahman and Rahman, 2009). The subsequent two decades witnessed Bangladesh's successful attainment of food self-sufficiency, with the total food grain production meeting domestic requirements. Nonetheless, some food grains, particularly wheat, continue to be imported. The pivotal role played by extensive groundwater irrigation in driving Bangladesh's agricultural growth is extensively documented (Hossain, 2010; Mottaleb *et al.*, 2019; Rahman and Rahman, 2009).

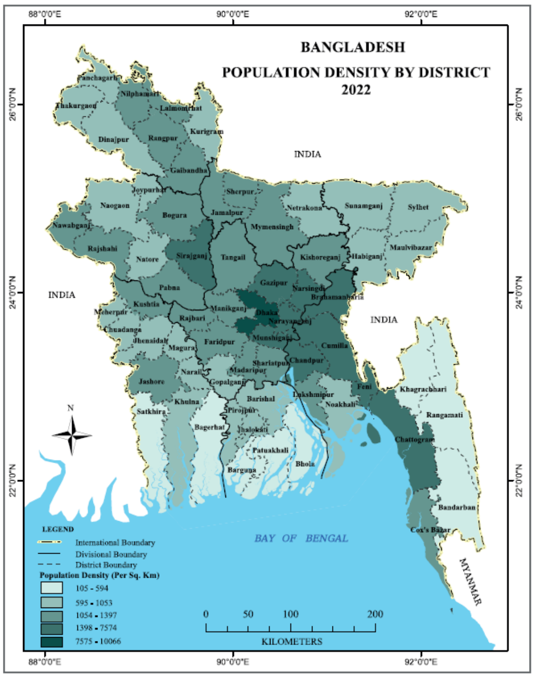
Source: https://www.un.org/geospatial/file/1739 download?token=u3wQt770

Figure 9: UN Geospatial map of Bangladesh

Data source: World Bank (2021)

Figure 10: Declining per person arable land, Bangladesh.

1. Food and Energy Scenario



Source: BBS (2022)

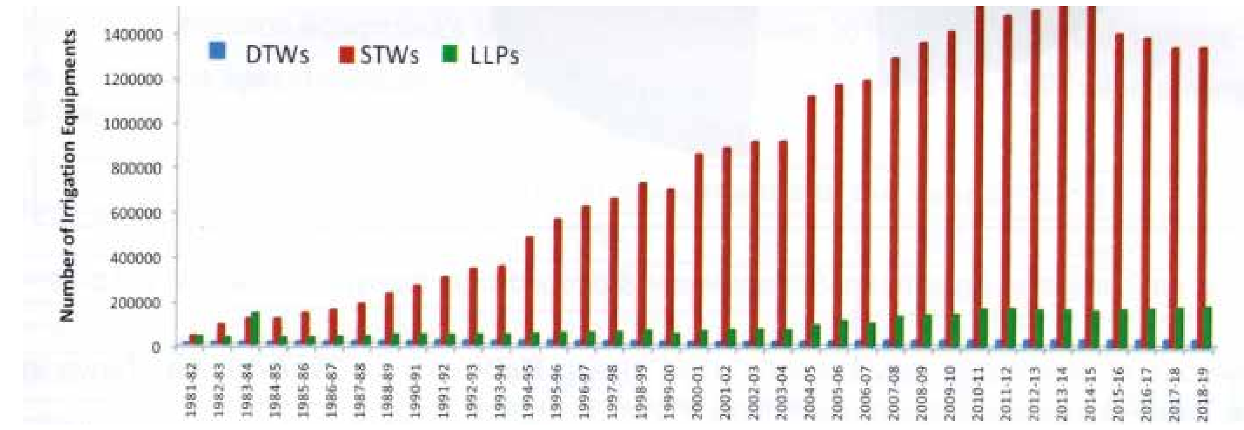
Figure 11: District wise population density in Bangladesh

While the monsoon brings ample rainfall to Bangladesh, the period from January to May, crucial for cultivating boro paddy, witnesses minimal precipitation. Following independence, the government's emphasis on expanding minor irrigation through groundwater and surface water was executed via the Bangladesh Agricultural Development Corporation (BADC). The BADC facilitated the leasing of low-lift pumps to farmers, subsidized diesel, and managed deep tube wells (Mottaleb *et al.*, 2017). However, limitations on importing diesel engines and regulations regarding tubewell spacing hindered the rapid expansion of groundwater irrigation. Subsequent to catastrophic floods of 1988 and cyclones in early 1990s, the government eased restrictions on importing irrigation equipment, aiming to invigorate the agricultural sector (BADC, 2020). This policy shift led to an influx of affordable diesel-powered shallow tube wells (STWs) (Hossain, 2010), resulting in an increase in the number of STWs from 0.4 million in 1993 to 1.2 million in 2006, and around 1.4 million by 2018 (Figure 12). These economical STWs were not only straightforward to install and maintain but also gained popularity among farmers (BADC, 2020).

The production of food grains exhibited a remarkable ascent, surging from around 10 million metric tonnes during 1971-72 (Chen and Chaudhury, 1975) to 25 million metric tons in 1999-2000, and further to an impressive 46 million metric tons by 2021-22 (GoB 2023). This notable progress was achieved through an expansion in total cultivated area and increased paddy yields facilitated by widespread adoption of high-yielding and stress-tolerant varieties coupled with expansion of small-scale groundwater irrigation (from 0.4 million hectares in 1971-72 to 5.6 million hectares in 2018-19) (BADC, 2020; Mottaleb *et al.*, 2019). At present, rice comprises a dominant 85% share of the total food grain production in Bangladesh, with *boro* rice emerging as the most crucial variety at 46% (GoB 2023). The significance of boro rice lies in its role in maintaining Bangladesh's food security, as it demonstrates greater resilience against floods and other natural disasters compared to *Aman* or *Aus rice*.

This diesel-pump revolution saw 73% of irrigated land being watered with groundwater, with almost 87.5% of total groundwater withdrawal directed towards irrigation. Although heavy monsoon rains recharge aquifers in most regions, some areas like Barind and north-central regions near Dhaka experience secular decline in groundwater tables (BADC, 2020; Dey *et al.*, 2017; Rahman *et al.*, 2016). The agricultural sector's success is also evident in the swift expansion of the boro cultivation area, which grew from 2.6 mha (1993) to 4.3 mha (2006) and 4.8 mha (2014-15).

Rapid STW growth has made the irrigation sector highly reliant on imported diesel. This dependence is expected to escalate with economic growth, with an estimated annual diesel consumption of around 4.6 billion liters for groundwater extraction, costing ~USD 4 billion (Qureshi *et al.*, 2014). Moreover, using 'dirty' diesel for power generation conflicts with Bangladesh's commitment to lowering Greenhouse Gas (GHG) emissions for its Nationally Determined Contributions (NDCs). Despite the high cost, and environmental and health risks associated with diesel, farmers still use diesel pumps where grid-connected electricity is absent. Diesel exhaust, containing harmful nitrogen oxides (NO_x) and particulate matter (PM) known as 'black smoke', poses health hazards and has been classified as carcinogenic by the International Agency for Research on Cancer (Frondel and Vance, 2014; IARC, 2012).



Source: BADC (2020)

Figure 12: Historical Development of different types of pumps in Bangladesh

To ensure energy security and reduce GHG emissions, Bangladesh's Renewable Energy Policy, 2008 (GoB, 2008) aimed to achieve a minimum of 10% of energy production from renewable sources by 2020, encompassing solar, hydropower, wind energy, biomass, and biogas plants. However, according to USAID (2023), as of 2022, less than 4% of the country's installed capacity comes from RE (including large hydro). At COP26, Bangladesh committed to producing 30% of electricity from renewable sources by 2030 and 40% by 2041 – elucidated in the Mujib Climate Prosperity Plan, 2022-2041 (GoB 2022).

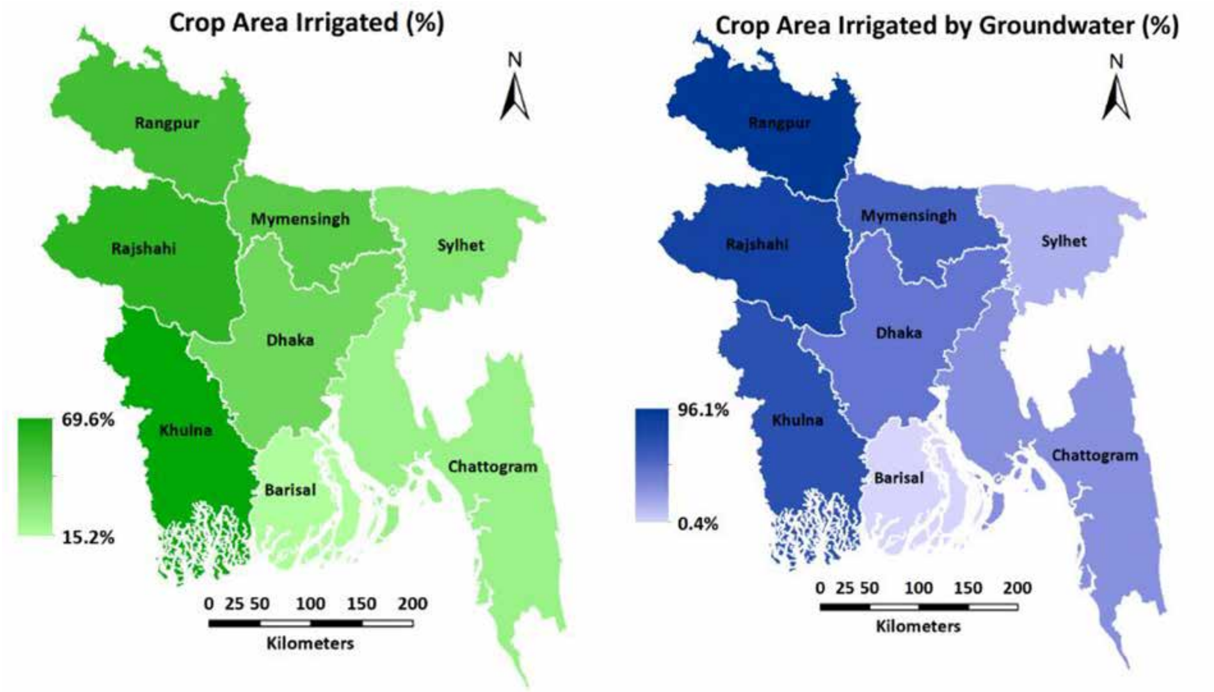
2. Water Resources and Irrigation

Across much of Bangladesh, the prevailing aquifers consist of unconsolidated, near-surface sediments deposited by the Ganges-Brahmaputra-Meghna (GBM) river system. These sediments serve as prolific aquifers, frequently tapped for groundwater extraction. The annual abstraction of groundwater is estimated at approximately 32 km^3, with 90% directed towards irrigation and the remaining 10% serving domestic and industrial needs combined (Shamsudduha *et al*., 2020).

The utilization of groundwater for irrigation has been particularly intensive, notably gaining momentum in the 1960s and 70s alongside the introduction of High Yield Varieties (HYV) seeds. This strategy aimed to meet the escalating food requirements of a burgeoning population. Groundwater-intensive irrigation, coupled with high-yield crop varieties, has significantly contributed to Bangladesh's self-sufficiency in rice production. Consequently, the nation's rice output has surged by more than 15 million tonnes over the past two decades, playing a pivotal role in rural poverty reduction by generating employment and small-scale business opportunities (GED, 2018).

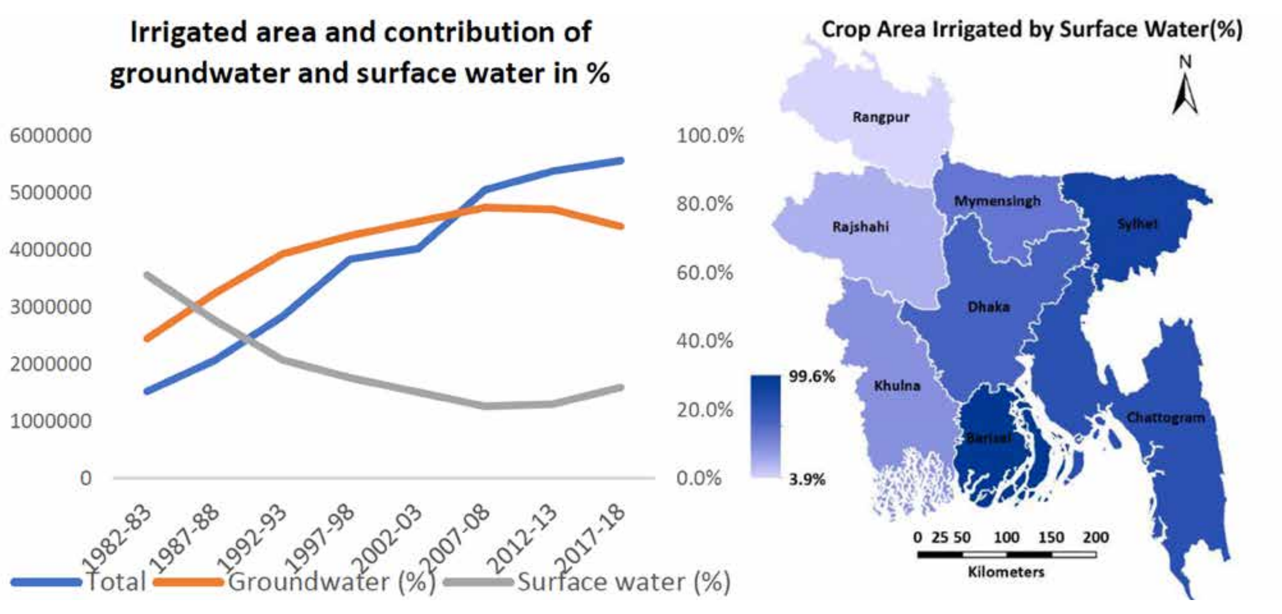
Approximately half of the total cropped area is equipped with irrigation, with heightened irrigation prevalence observed in the north-central and western divisions, including Dhaka, Mymensingh, Rajshahi, Rangpur, and Khulna (Figure 13). These regions exhibit higher cropping intensity, ranging from 199% to 219%. Groundwater irrigation encompasses around 80% of the overall irrigated area, while the remainder is sourced from surface water sources. The extensive use of groundwater is prominent in the north-central and north-west divisions, specifically Dhaka, Mymensingh, Rajshahi, Rangpur, and Khulna, where roughly 94% of the irrigated area relies on groundwater. Boro rice accounts for a substantial portion of groundwater-based irrigation in most divisions, ranging from 70% to 87%. However, in certain western divisions such as Khulna, Rajshahi, and Rangpur, there is greater agricultural diversification, allocating 42% to 54% of irrigation to boro rice and the remainder to various crops, including vegetables and wheat.

Despite the availability of abundant surface water resources, only about 20% of the irrigated area is served primarily by surface water, as indicated by the data from BBS (2020). In fact, there has been a consistent downward trend in the proportion of irrigated area relying on surface water, decreasing from around 60-65% during 1983-82 to a range of 20-25% in the late 2010s. In contrast, the prevalence of groundwater irrigation has shown a notable increase, rising from 40% to nearly 80% during the same period (Figure *14* – left). Regions in the north-eastern and south-central parts of the country exhibit a comparatively higher extent of land under surface water irrigation. However, the degree of irrigation intensity remains lower than that of groundwater irrigation, particularly in the north-western regions (Figure *14* – right).



Source: Mitra et al. (2021)

Figure 13: Crop area irrigated (left) and groundwater irrigated (right)



Source: Mitra et al. (2021)

Figure 14: Time series of irrigated area by source (left); and share of surface water (right).

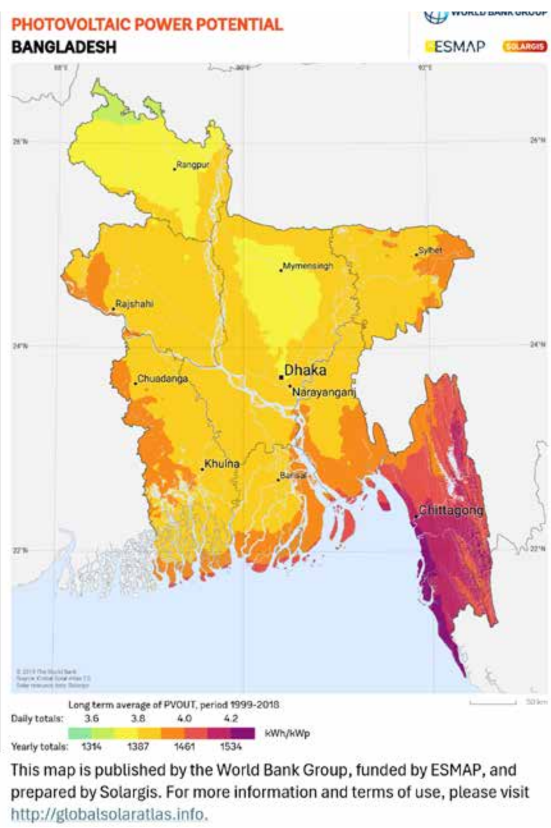
3. Solar Landscape

Due to its geographical location, Bangladesh possesses significant potential for harnessing solar irradiation. The country receives an average daily solar radiation of 4–6.5 kWh/m^2 (Figure 15), which translates to a considerable energy yield of 1018×1018 J. Approximately 0.11% of this energy holds the capacity to fulfill the primary energy consumption of the nation (Hil Baky, Md. Abdullah, *et al*, 2017). The monthly average solar radiation in various cities across Bangladesh is presented in Table 3.

The peak solar radiation occurs during the months of March to April, while the minimum is observed in December to January (Table 3). Notably, Rajshahi district experiences the highest solar radiation levels, presenting a significant opportunity for harnessing solar energy. Rajshahi boasts an annual average direct natural insolation of 1900 kWh/m^2, a value deemed sufficient for the implementation of concentrating solar power (CSP) technology. Utilizing this technology within a 2 m^2 area with an annual average radiation of 2000 kWh/m^2 could generate a total of 100 MW of electricity (Hil Baky, Md. Abdullah, *et al*, 2017).

While CSP technology is still emerging, other technologies are rapidly expanding across Bangladesh. Among these, the solar home system (SHS) has achieved remarkable success. The country has seen the installation of 3.6 million solar home systems, collectively providing a capacity of nearly 150 MW (Hil Baky, Md. Abdullah, *et al*, 2017). Playing a pivotal role in this sector, the Infrastructure Development Company Limited (IDCOL) embarked on SHS initiatives since 2003, aiming to deliver sustainable energy to rural communities lacking electricity access. IDCOL is working towards a goal of installing 6 million solar home systems, with an estimated combined capacity of 220 MW by the year 2017.Bangladesh's aim to achieve 10% renewable energy by 2020 necessitated an installed capacity of around 2000 MW. Yet, data from the Sustainable & Renewable Energy Development Authority (SREDA) indicates that by the end of 2020, only 650.53 MW of renewable energy had been installed, comprising a mere 2.93% of total electricity generation (SREDA, 2020), illustrating that the country fell short of its 2020 target. Within the overall renewable capacity, solar contributes 64%, while hydropower accounts for 35%.

As per the National Database of Renewable Energy, up to 2020, 1969 solar irrigation pumps were established across 5 Divisions and 25 districts, boasting a combined installed capacity of 46.98 MW (Figure 16). Despite this progress, it remains below the 500 MW solar generation capacity envisioned in the 2012 500 MW Solar Power Generation Plan, which aimed for 150 MW of capacity from solar irrigation systems by 2016. In December 2020, the SREDA database indicates a solar installed capacity of 416.6 MW, still falling short of the 500 MW target (SREDA, 2020). To put this in context, Bangladesh's count of solar pumps pales in comparison to the approximately 1.24 million diesel pumps that irrigate about 3.0 million hectares and the 0.34 million electric pumps covering 2.3 million hectares in 2018-19 (BADC, 2020). While electricity pump usage has grown over the years, challenges have historically hindered farmers' grid access, including inadequate production, operational practices, transmission capacity, grid stability, and dispatch efficiency. Nevertheless, the government aimed to provide universal electricity access by 2021 as part of its 'Vision 2021' for Bangladesh (Taheruzzaman and Janik, 2016), and presently, 96% of the population has access to electricity (GoB 2020).



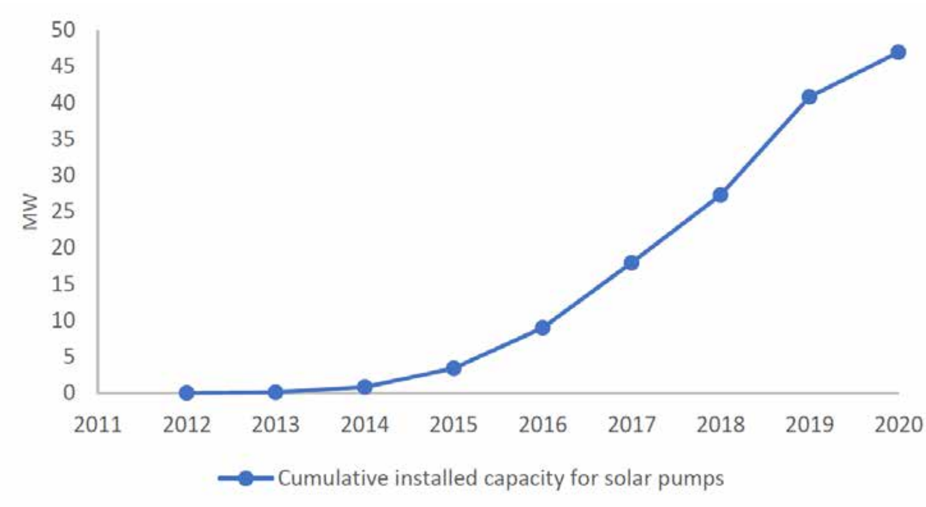
Source: Global Solar Atlas 2.0

Figure 15: Daily and Annual PV Potential in Bangladesh

Table 3: Average monthly solar insolation (kWh/m²/day) at different cities in Bangladesh

Month	Rajshahi	Jessore	Bogra	Dhaka	Barisal	Sylhet
January	3.96	4.25	4.01	4.03	4.17	4.00
February	4.47	4.85	4.69	4.78	4.81	4.63
March	5.88	4.50	5.68	5.33	5.30	5.20
April	6.52	6.23	5.87	5.71	5.94	5.24
May	6.17	6.09	6.02	5.71	5.75	5.37
June	5.25	5.12	5.26	4.80	4.39	4.53
July	4.79	4.81	4.34	4.41	4.20	4.14
August	5.16	4.93	4.84	4.82	4.42	4.56
September	4.96	4.57	4.67	4.41	4.48	4.07
October	4.88	4.68	4.65	4.61	4.71	4.61
November	4.42	4.24	4.35	4.27	4.35	4.32
December	3.82	3.97	3.87	3.92	3.95	3.85
Average	5.00	4.85	4.85	4.73	4.71	4.54

Source: Baky et al, (2017)



Source: Mitra et al. (2021)

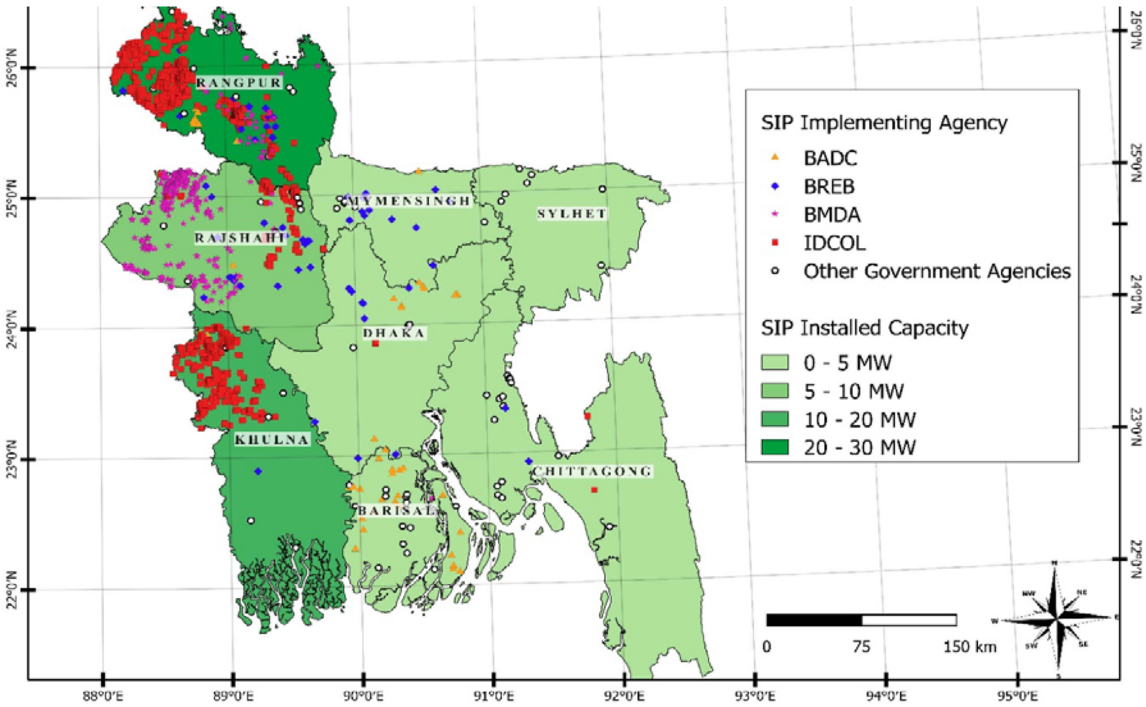
Figure 16: Cumulative installed capacity for solar pumps in Bangladesh

4. Key Stakeholders

Sustainable and Renewable Energy Development Authority (SREDA) was established by the government in 2012 through an act of parliament with the objective of reducing global warming and to ensure energy security by reducing dependence on fossil fuel through the expansion of renewable energy.

The Ministry of Power, Energy and Mineral Resources (MoPEMR) is responsible for all policies and matters relating to power generation, transmission and distribution, from conventional as well as non-conventional energy sources. MoPEMR is also responsible for the import, distribution, exploration, extraction and pricing of primary fuels. With MoPEMR, the Power Division is responsible for renewable energy policies and implementation.

The Infrastructure Development Company Limited (IDCOL), a government-owned financial institution, takes the lead in advancing solar pumps in Bangladesh.



Source: Mitra et al. (2024)

Figure 17: SIP deployment in Bangladesh by different agencies

Much of the development partner support and government funding for solar pumps is channelised through IDCOL, which employs a blend of concessional credit and grants to finance solar pump deployment. Majority of the solar irrigation pump installed in Bangladesh are supported through IDCOL. So far, IDCOL has successfully deployed 1,523 solar irrigation pumps (42.1 MWp capacity) and it aspires to establish 10,000 SIPs by 2030 (Mitra *et al*. 2024). The Barind Multipurpose Development Authority (BMDA) has been playing a significant role in the development of the drought-prone Barind region in N-W Bangladesh. One of its key achievements has been the expansion of groundwater irrigation through an innovative pre-paid metering system, coupled with related interventions in water resource augmentation and sustainable groundwater management. In recent years, BMDA has also deployed 453 community-managed SIPs in the region targeting delivering irrigation as a service to small and marginal farmers. The Bangladesh Agricultural Development Corporation (BADC) has also installed 272 community-managed solar pumps, for irrigation as well as for meeting domestic water needs, and has a target of installing 1,000 solar pumps.

With support from ADB, the Bangladesh Rural Electrification Board (BREB) has a project to deploy 2000 individual SIPs as demonstration projects all over the country. By September 2022, BREB has installed 150 SIPs in Bangladesh (ADB 2023). Other key players that have installed solar pumps at pilot scale include the Bangladesh Agricultural Research Institute (BARI), the Department of Agriculture Extension (DAE) and the Rural Development Academy (RDA). RDA executed two solar irrigation programs funded by the government and currently operates 35 SIPs (Figure 17).

In addition to government agencies, development partners such as GIZ have also invested in deployment of solar pumps, primarily for meeting domestic needs and targeted at populations without access to clean and reliable drinking water supply (ADB 2023).

5. Business Models

Solar pumps deployed for irrigation by IDCOL, BMDA, BADC and BERB account for 97% of the number of solar pumps in Bangladesh and 99% of the SIP installed capacity (Mitra *et al*. 2024). These systems have been deployed with different combinations of technical, financial and institutional arrangements. We discuss three dominant business models that can have been deployed in the country.

a. Solar Irrigation as a Service

Through a combination of grant and concessional credit, IDCOL has catalysed an innovative public-private partnership model that enables sponsors to invest in village-scale solar pumping systems. Typically, 10-30 kWp solar arrays are deployed with an irrigation pump and a network of buried pipes that can deliver 'solar irrigation as a service' to farmers in the 'command area' of the system. The financial model includes a 50% grant, 35% concessional loan and 15% sponsor equity – sponsors may be private companies or NGOs. The loan, offered at 6% interest, is to be repaid over 10 years and irrigation is to be offered to farmers at a (regulated) fee, just below the cost of diesel irrigation. Almost all of IDCOL's 1500-odd systems have been deployed in Rangpur, Khulna and Rajshahi.

This unique model has several advantages. It relieves farmers from the burden of investing scarce capital in the solar assets. It also does not require small farmers to undertake maintenance of a relatively new and complex technology. Both capital investment and asset operation and maintenance become the responsibility of the 'sponsor'. It also allows tenant farmers – who normally would have little incentive to invest in solar pumps – to benefit from solar irrigation. Recent IWMI studies in Bangladesh (Mitra *et al*. 2021; Buisson *et al*. 2022; Mitra and Mukherji 2022; Mitra *et al*. 2024) suggest that these systems can offer more reliable and convenient irrigation compared to diesel-powered pumps, and at a price that is marginally lower than that for diesel pumps. Mitra *et al*. (2024) also estimate that on average, bringing an acre of irrigated land within the command area of an IDCOL SIP can reduce annual diesel consumption by 58 l, avoiding 2.8 metric tonnes of CO_2 emission.

On the flip side, the model is likely to induce interest from 'sponsors' only in regions with high irrigation demand and the ability of farmers to pay a high price for irrigation – and therefore might score low on


IDCOL website (https://idcol.org/home/solar_ir)

expanding irrigation access equitably. The high unit cost of the asset and the pressure of loan repayment also requires high asset utilization. In many locations, IWMI studies found that sponsors were encouraging farmers to expand boro paddy cultivation to encourage higher irrigation demand and maximize revenues. The pressure also discourages sponsors from reducing irrigation costs to make it more affordable.

The high capital subsidy involved (50%) also puts the financial viability of the model in question. IWMI studies have estimated that replacing all of Bangladesh's 1.24 million diesel pumps would require 400,000 IDCOL-type SIPs! This is likely to require huge capital outlay and implementation capacity. Another key concern is the seasonality of irrigation demand. SIPs need to be sized to meet peak irrigation demand – in Bangladesh, this often means the high irrigation demand for boro paddy. However, this means the SIPs will have surplus generation capacity and little utilization during the remainder of the year. Bangladesh is field testing grid connecting IDCOL SIPs so that they can evacuate surplus solar power during off-peak season and add a supplemental revenue stream.

b. Community Managed Solar Pumps

In the community ownership framework, farmers or users participate in committees to own and operate solar pumps. Such community-managed solar systems have been deployed with support from BREB, BMDA, BADC and RDA and are targeted at small and marginal farmers who lack the resources for direct investment and need extended repayment periods for loans. Consequently, most are relatively smaller capacity systems (3-5 kWp) deployed through a 100% grant-based approach. Usually, the farmer on whose land the system is deployed also becomes the operator. The user group determines the user fee that is charged to cover operating costs.

The key challenge of scaling this model is the need for high capital subsidies. Another key requirement for this model to work well is training and capacity building of farmers – to ably maintain the system hardware as well as the institutional aspects involving member conflicts and avoiding dominance by local elites.

In the case of BADC systems, the farmers' groups are charged an initial participation fee (USD 240 for 7.5 HP, USD 370 for 10+ HP) followed by a fixed annual payment of USD 50-100, depending on pump size. In BMDA's solar low-lift pumps, farmers use a pre-paid metering system to pay for pump use, roughly USD 1.20-1.90 per hour.

Compared to diesel-powered irrigation, community-managed solar pumps have minimal operating costs. The grant they receive for initial deployment significantly reduces expenses and is anticipated to augment income and enhance production. SREDA data reveals that BMDA has successfully implemented 327 units with a combined capacity of 1758.2 kW using this model.

c. Individually owned Solar Pumps

With support from ADB, BREB invites individual farmers to receive 55-65% capital subsidy and a 30-35% loan repayable over a 10-year period, to own and operate SIP systems. The owner may also share irrigation services with their neighbours, a common practice in parts of South Asia.

The primary beneficiaries of this model are predominantly small-scale farmers, resulting in system capacities ranging from 2 to 5.5 kWp. An innovative feature of the SIP system in BREB's individual ownership model is the plan to link the SIPs to the grid with a specified tariff. The associated grid connection costs are covered by BREB. While the tariff structure remains under development, BREB sees grid connection as crucial to enhancing the competitiveness of SIPs compared to electric pumps. This setup not only offers farmers the opportunity for additional income without climate-related risks but also increases the likelihood of SIP adoption.

A key challenge of this model is targeting the right farmers with the right-sized pumps. Large-scale deployment of individual solar pumps would also require the development of ancillary services – which are currently missing. One good way to facilitate this is through promotion in clusters and through a saturation approach, however, this is difficult to implement politically. Finally, a longer-term concern with the proliferation of individual, off-grid solar pumps is the potential impact on groundwater. This is particularly critical in regions where groundwater aquifers have water quality (salinity, arsenic) concerns or where the resource is already over-developed and further development will lead to long-term decline. ADB (2023) identifies 145 upazilas where SIP rollout for groundwater is not recommended (Figure 8).

6. Way Forward

IRENA data suggests that Bangladesh doubled its off-grid solar capacity deployed for use in agriculture between 2018 and 2022. This is driven by a strong government impetus on replacing diesel. Bangladesh's focus on promoting solar pumps targets two key objectives: [a] cut GHG emissions to meet NDCs; and simultaneously [b] reduce reliance on imported diesel that costs the exchequer USD 2.6 billion a year. Recent estimates suggest that solarizing the country's 1.24 million diesel irrigation pumps will require an investment in roughly 400,000 IDCOL-style SIPs and will cut CO_2 emissions by 1.2 million metric tonnes (Mitra *et al*. 2022). Besides savings in labor and time, using solar pumps for irrigating water-intensive crops like *boro* paddy can reduce cost by 20-30% and can offer significant adaptation co-benefits (Buisson *et al*. 2022).

Despite the potential, the expansion of solar pumps faces competition from the government's resolve to extend grid electricity access across the country. While grid irrigation's emissions are likely to be lower than diesel, it will not be emission-free. The cost gap between electric and diesel-based irrigation is narrowing, and coordinated energy planning is essential to ensure the competitiveness of solar pumps. Connecting solar pumps to the grid for surplus energy sales can help reduce diesel and coal dependency while contributing to renewable energy targets. Overall, solar pumps have significant potential to transform Bangladesh's water-energy-food sectors while also reducing import and subsidy bills and improving climate resilience.

IDCOL's innovative PPP-model of delivering solar irrigation as a service has multiple advantages over conventional deployment of off-grid, individual solar pumps. By eliminating the need for small and marginal farmers to invest in and maintain solar systems, the model can extend the benefits of solar irrigation faster, and at lower cost. However, the model will need to be tweaked to fit local contexts, ensure equity in access, and improve financial viability through innovative experiments such as grid-connectivity and the ability to sell surplus power and earn FiT. Where groups of users can be organized into well-performing cooperatives or informal user groups, community-managed SIPs can deliver reliable and affordable irrigation. In this context, BMDA's past experience with pre-paid metering system can be leveraged to expand viable community-led solar irrigation systems.

Finally, as noted in multiple studies (ADB 2023; Mitra *et al*. 2024), long-term viability of solar pumps in Bangladesh can be ensured by reducing unit costs, bringing them at par with the rest of south Asia. To do this, government must invest in enhancing local manufacturing and fabrication – learning from the positive experience of countries like India and China.

Shashwat Cleantech Pvt. Ltd.

Abbie Trayler-Smith/Panos Pictures

Bhutan

Baby Steps

C. Bhutan: Baby Steps

The Himalayan kingdom of Bhutan was the first country in modern times to become '*carbon-negative*'. Landlocked between China in the north, and India in the east, west and South, Bhutan occupies a land area of 38,394 km^2, spanning roughly 300 km east to west and 170 km north to south. The country is almost entirely mountainous with altitudes ranging from 100 m in the foothills to more than 7,500 m above mean sea level in the north. This mountainous landscape makes communication and transport highly expensive and fragile and leaves the country's ecology highly vulnerable to extreme weather events. Before economic activity got hit by the CoViD-19 pandemic, Bhutan's economy had been growing steadily with GDP crossing USD 2.1 billion in 2020 (RGoB 2022).

Bhutan's small population (0.78 million), dense forest cover (~70% of land area), largely subsistence agriculture, and high reliance on hydropower have driven the country's carbon negative status. The country already has almost all its energy consumption drawn from renewable sources, primarily hydropower. However, this high reliance on hydropower has exposed the country to seasonal variations in energy generation resulting from climate-induced uncertainties. As the economy grows and energy demand grows with it, Bhutan is keen to develop its own sources and reduce reliance on seasonal hydropower and imported electricity from India.

1. Agriculture and Water Resources

Mean annual precipitation (long-term average) for Bhutan is estimated at 2,200 mm – almost twice that in neighbouring India. This varies widely from a low of 477 mm in Gidakhom of Thimpu district to as high as 20,761 mm in Dechenling in Samdrup Jhongkhar district (FAO 2011). The kingdom's major rivers flow from north to south, with tributaries flowing from east to west. Most of the river systems (Figure 18) originate in the glaciers and are fed by rainfall. It is estimated that about 2-12% of the river discharge comes from glacial-melt and another 2% from snow-melt. The combined outflow of rivers is estimated at a little over 70.5 billion cubic meters, roughly corresponding to 100,000 m^3 per capita, the highest in the region.

Agriculture – mostly subsistence-oriented and labor-intensive – is the largest user of freshwater resources in Bhutan, accounting for more than 90% of annual withdrawals (FAO 2011; RGoB 2016a). Official estimates vary slightly but FAO AQUASTAT estimates that 27,685 ha is equipped for irrigation in the country, mostly through small-scale, surface water schemes. The National Irrigation Master Plan (RGoB 2016*a*) estimated that the potential irrigable area in the country is around 200,000 acres or 80,000 ha. Diversion from rivers is the dominant mode of irrigation with lift irrigation being the exception in a few places. Where irrigation is available in agricultural fields below 2,600 m elevation, farmers traditionally grow paddy; other irrigated crops include wheat, barley, oilseeds, and vegetables. With such abundant surface water resources, little is known about the country's groundwater resources. In fact, except in the valleys adjoining the plains in India, there is little groundwater use and it may be tapped in the future.

Arable land is a scarce commodity in Bhutan, amounting to less than 3% of the country's geographical area. Like most countries in the region, agriculture is the dominant source of livelihood, employing more than 60% of the rural population. The other important sectors contributing to the economy are hydropower and tourism.

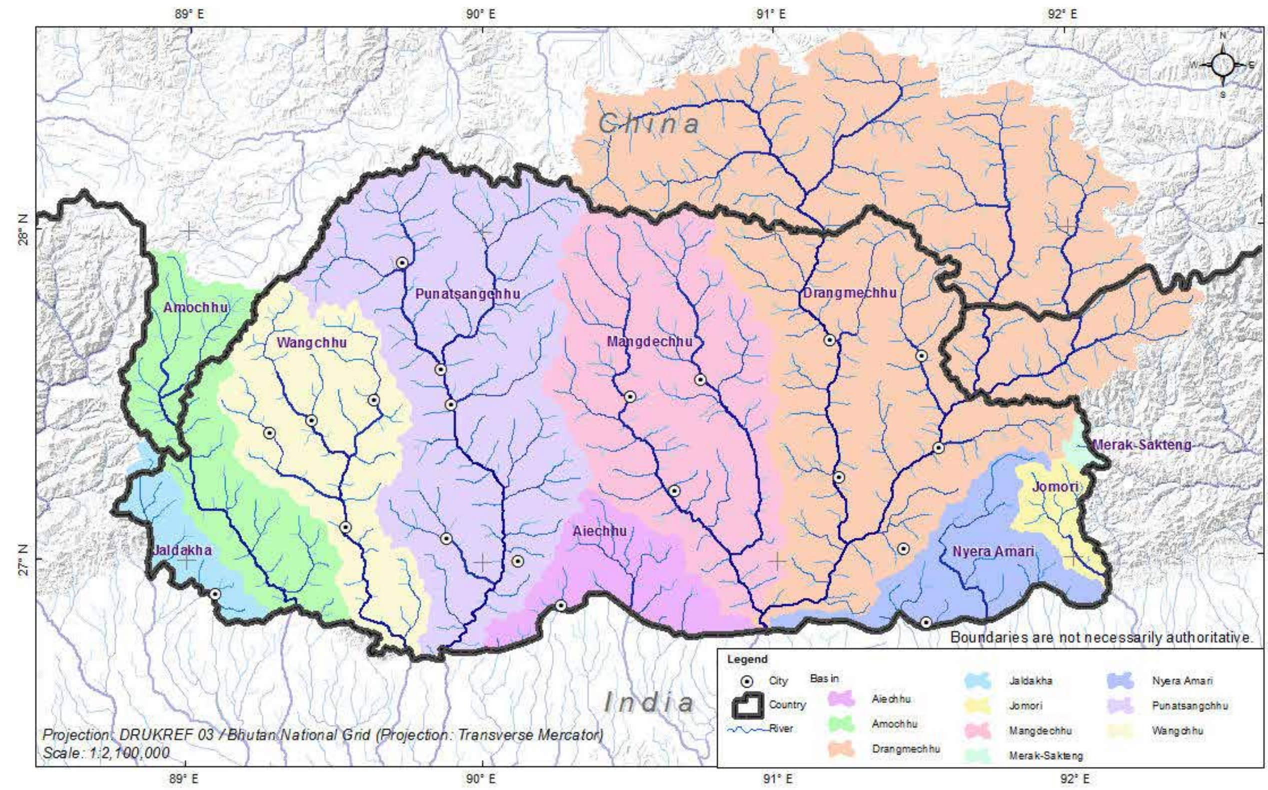
Despite the high annual and per capita resource endowment, Bhutan faces high seasonal and temporal variability in water availability. Most of the discharge is limited to the monsoon months between April and October, with the rest of the year experiencing little or no precipitation. The rugged terrain, steep gradients and narrow stream beds result in rapid run-off, which is not sufficiently managed or stored for use in the dry season (RGoB 2016). A study on the status of water availability in irrigation systems conducted by the Department of Agriculture noted that 86% of the existing irrigation systems could operate throughout the year as they drew water from perennial sources. It further found that most irrigation systems have abundant (30%) or adequate (41%) water supply while 20% experienced inadequate supply and 9% faced acute water shortage (RGoB 2013).

2. Energy Scenario & Solar Landscape

The availability of hydropower has been a major advantage for Bhutan as it generates significant revenues and helps balance trade deficits. Bhutan has achieved near universal grid connectivity for households (99.71%) with a healthy per capita annual energy consumption estimated at 4,633 kWh (ESCAP 2021). Hydropower accounts for 99% of the installed capacity of 2,343 MW and has an estimated theoretical potential of 36,900 MW (NSB 2023). The large energy exports to India offset the fossil fuel imports required to meet domestic and transport demand. There is now a strong emphasis on reducing reliance on imported fossil fuel by promoting electric cooking and vehicles in the country. There is also a strong support for deployment of biogas plants in villages to reduce reliance on imported LPG, in collaboration with the Department of Livestock (Gyelmo 2020). All these efforts would not only reduce the country's import bill but also help remain carbon positive and prevent potential deterioration in air quality and environment.

Bhutan's RE sector is guided and governed by the Electricity Act (2001), Alternative Renewable Energy Policy (AREP 2013), the Economic Development Policy (EDP 2016), Renewable Energy Master Plan (2017-2032) and the Energy Efficiency Roadmap (2019).

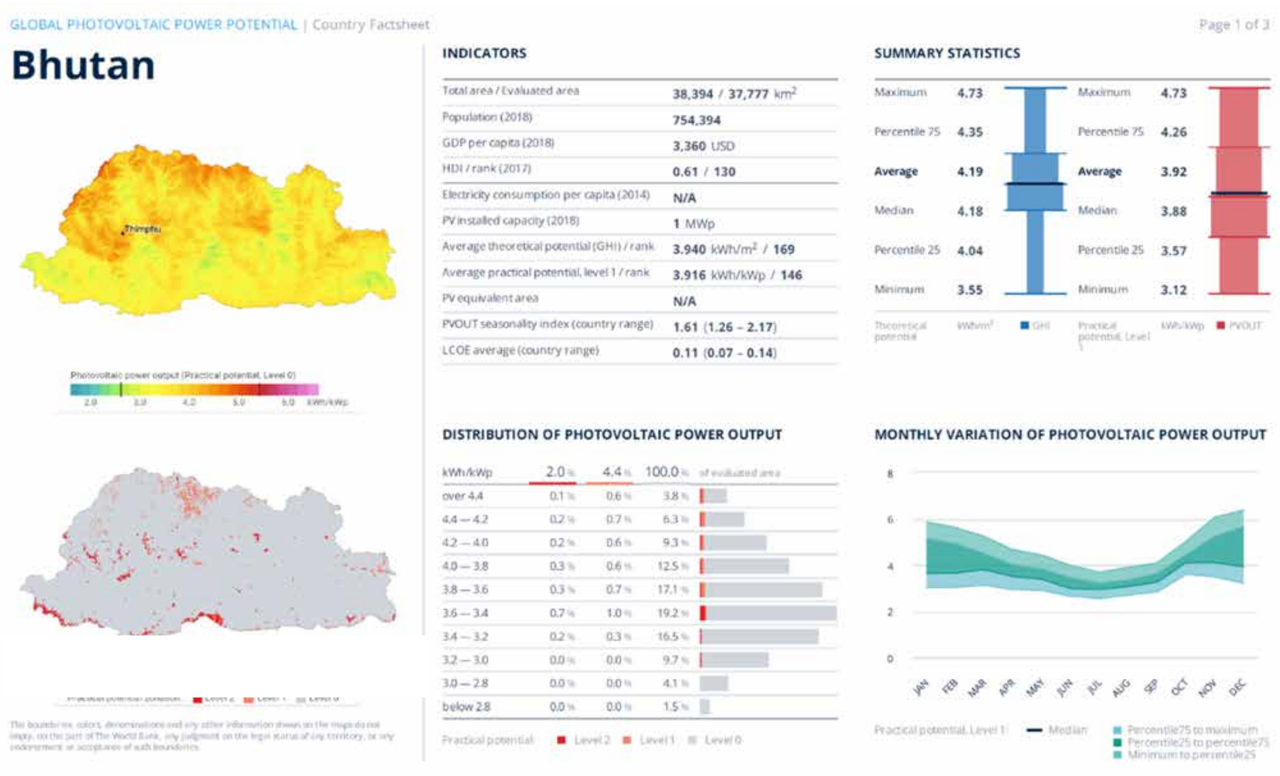
Much like the upper reaches of Himalayas in Nepal, Bhutan can also harness solar energy to meet its pumping requirements by designing solar-powered water lifting and multiple use systems that can service both domestic and productive needs. Bhutan has piloted some solar micro lift irrigation systems as part of an UNDP-GCF project[2] and has also requested technical assistance from ICIMOD to set up some additional pilots as part of climate resilient agricultural practices. Solar pumps are also deployed in conjunction with spring rejuvenation programs so that communities in the spring shed can benefit from improved water availability. The alternative renewable energy strategy elucidated by DRE (2022) highlights improved climate resilience and energy security, as well as the ability to reach the 'unreached' users as key benefits of diversifying Bhutan's energy mix.



Source: RGoB (2016)

Figure 18: Hydrological basins in Bhutan.

[2] In Khawajara village in Punakha https://www.bbs.bt/news/?p=164821



Source: Global Solar Atlas 2.0

Figure 19: Photovoltaic Power Potential and related indicators for Bhutan.

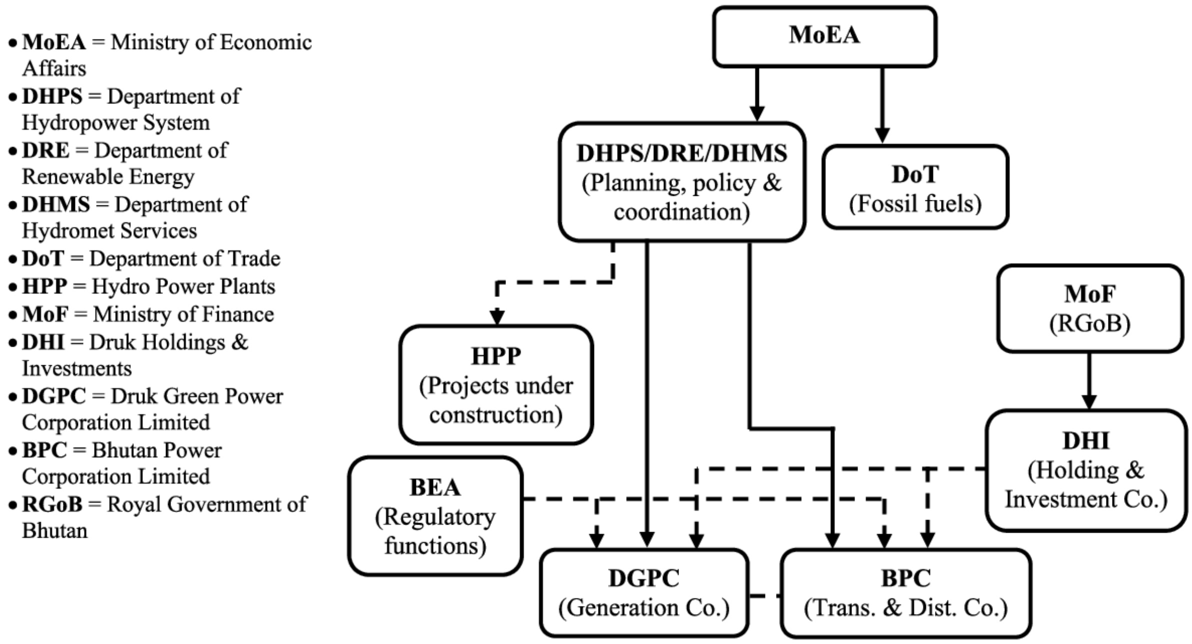
Despite the mountainous terrain and associated challenges with satellite-based solar energy potential estimation, DRE (2016) estimated the theoretical solar potential of Bhutan at close 5,978 MW and restricted development potential at 12,018 MW. Global Solar Atlas 2.0 pegs the PV power potential of Bhutan at 3.916 kWh/kWp, not very different from the same in Nepal and Bangladesh (Figure 19). The Royal Government of Bhutan has a plan to deploy 500 MW of solar PV capacity by 2025 and 1 GW by 2030.

3. Key Stakeholders

Bhutan's water sector is governed primarily in line with the Bhutan Water Policy, 2007[3] published by the National Environment Commission (NEC) which reflects the vision of the country vis-à-vis the conservation, development, and management of water resources in the country. The policy mandates the NEC with the responsibility of effective coordination of water resources management at the national level, including planning, legislation, international cooperation, licensing and regulation, and reporting to the national assembly. The Ministry of Agriculture and Forests (MoAF) for irrigation, wetlands and watershed management in the country. The department of hydropower is part of the Ministry of Economic Affairs (MoEA). The other key stakeholders in water governance are the River Basin Committees, the District Development Councils (Dzongkhag Tshogdu) and civil society organizations such as the Bhutan Water Partnership and the Royal Society for the Protection of Nature (Tariq et al. 2021).

The key stakeholders in Bhutan's energy sector are the Department of Hydropower Systems (DHPS), Department of Renewable Energy (DRE), Department of Hydromet Services (DHMS), Bhutan Electricity Authority (BEA), Bhutan Power Corporation Ltd. (BPC) and the Druk Green Power Corporation (DGPC) (Figure 20).

[3] Available: https://bt.chm-cbd.net/sites/bt/files/inline-files/Bhutan%20Water%20Policy%202007.pdf



Source: Dukpa (2023)

Figure 20: Key stakeholders in Bhutan's energy sector.

4. Way Forward

There seems to be growing interest and political will in Bhutan to replace fossil fuel use with decentralized renewable energy. This is the opportunity that solar pumps can tap by offering reliable and affordable solutions for lifting water for irrigation and other productive uses. To what extent will solarization reduce diesel consumption in agriculture remains to be seen. Evidence from north Bihar suggests that solar pumps can almost entirely crowd-out diesel pumps; with diesel consumption becoming a fraction of what it was. Elsewhere, while solar pumps help expand irrigation access and irrigated area, they may not necessarily reduce diesel use. While some farmers will shift to solar pumps, others may continue to rely on diesel-powered pumps.

The solar pump sector in Bhutan is nascent, but its potential is immense. Inter-governmental organizations such as the International Centre for Integrated Mountain Development (ICIMOD) are already working closely with the Royal Government of Bhutan to explore the opportunities of solar pumps in irrigation. ISA and ADB should consider building-on the ongoing work through a detailed study on the ultimate potential for solar pumps in Bhutan and the immediate steps that ISA-ADB can collaboratively undertake to support the country on its solar roadmap.

Prashanth Vishwanathan/IWMI

Prashanth Vishwanathan/IWMI

India

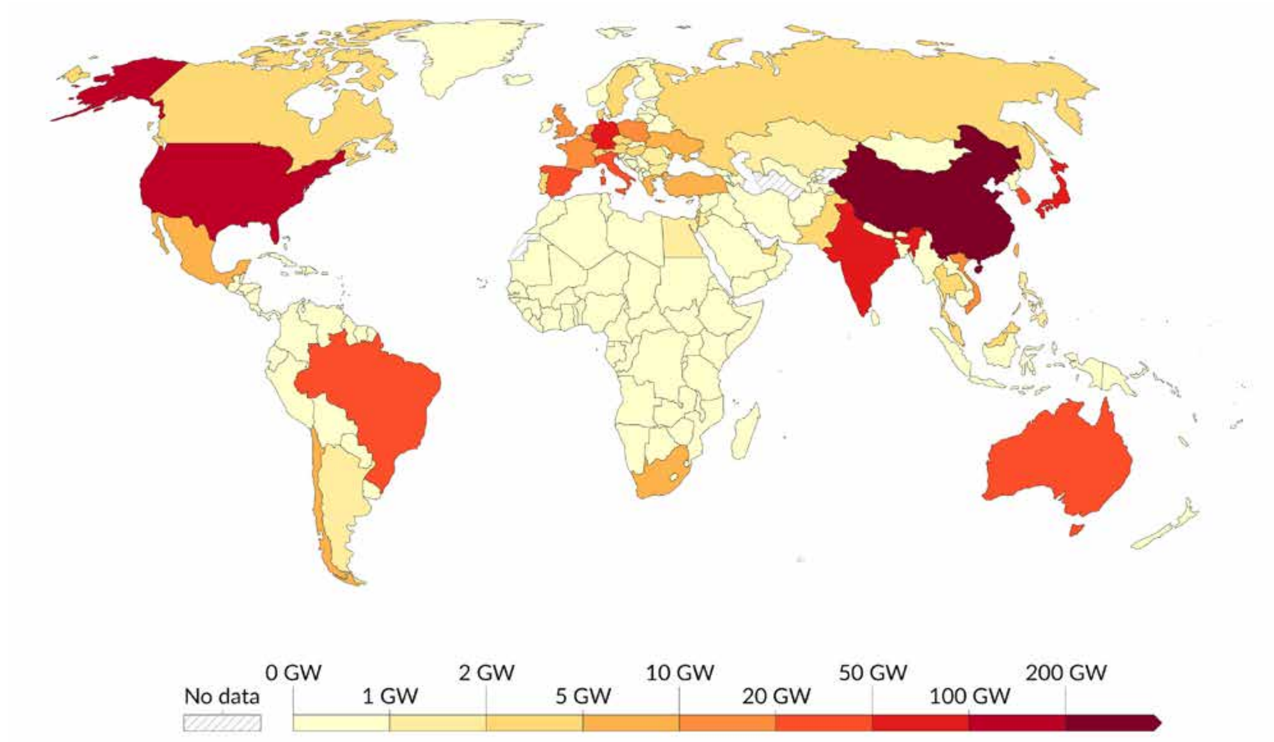
A Mosaic of Innovations

D. India: A Mosaic of Innovations

With a little over 63 GW, India ranks fifth in terms of cumulative solar energy generation capacity installed by 2022, behind China (393 GW), United States (113 GW), Japan (83 GW) and Germany (67 GW), with no other country exceeding 30 GW (IRENA 2023; Ember n.d; Figure 21). However, in terms of solar pumps, India is a world leader, accounting for more than 90 percent of the solar pump capacity deployed for use in agriculture (IRENA 2021). This is not surprising given the prominent role played by groundwater in India's large agrarian economy.

Estimates suggest that Indian farmers pump anywhere between 250 and 300 billion cubic meters of groundwater annually through 21-22 million wells and tubewells, 15.5 million of which run on free or highly subsidized grid power and almost all the remaining on diesel. Since 2010, government programs – at the state as well as federal level – have been aggressively promoting solar pumps for irrigation. Besides the intension of reducing the carbon footprint of India's massive groundwater economy, another important driver is the need to check ever-increasing farm power subsidies – last estimated at around USD 18-20 billion annually.

This aggressive promotion has helped solar pumps reach a scale where unit costs have reduced significantly as the number of pumps have grown from a handful in 2010 to about 400,000 by 2022. Yet, the cumulative capacity of these off-grid pumps is likely to be less than 2 GW, a footnote compared to utility-scale ground-mounted systems (55.71 GW) and even rooftop solar (11.08 GW). A study by IWMI-Tata Program, GERMI and GreenPeace India estimated that the capacity required to solarize all of India's irrigation pumps would exceed 150 GW[4] – a significant dent in India's 2030 solar target of 450 GW.



Source: IRENA (2023) | https://ourworldindata.org/grapher/installed-solar-pv-capacity

Figure 21: Cumulative installed solar energy generation capacity | GW, 2022

[4] See Choudhury (2018)

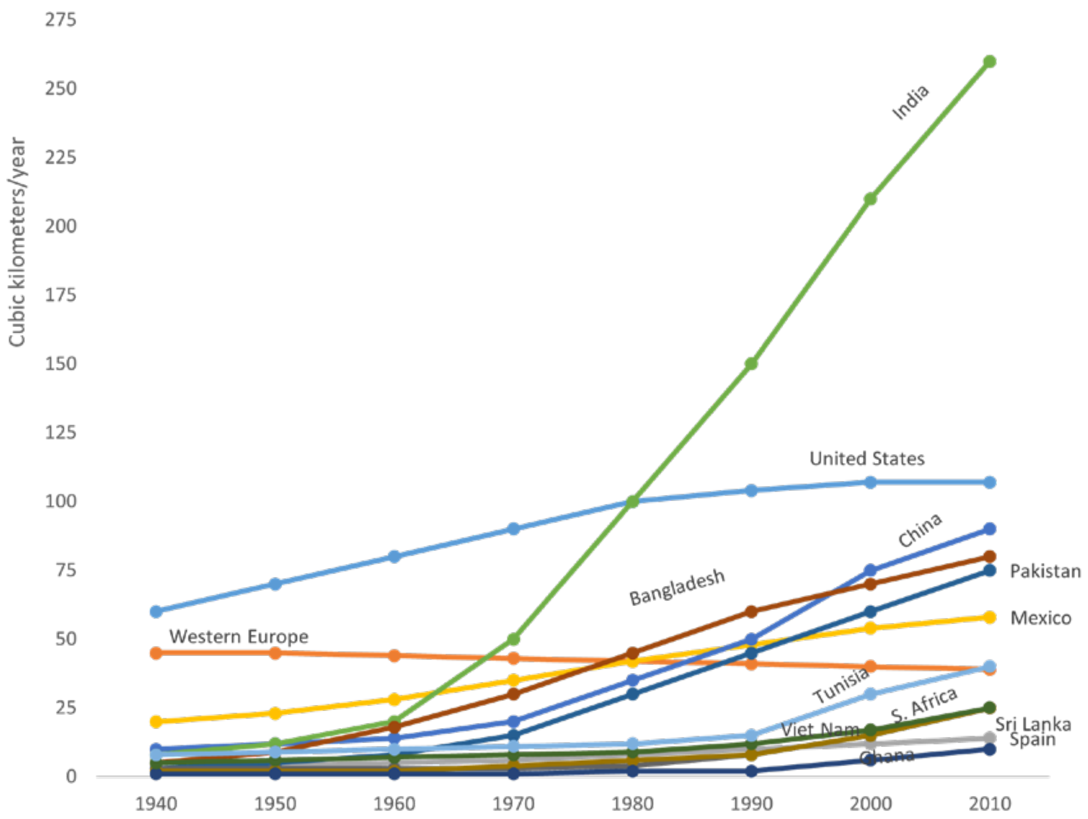
1. Water-Energy-Food Nexus

With a growing economy, rapid urbanization and greater connectivity with the world, India's socio-economic aspirations are rising and so is demand for secure food, water, and energy systems. Not surprising then, maintaining self-sufficiency in food production and delivering basic services including water and sanitation, year-round food security, livelihood social security net and basic health facilities remain central to India's development policy. A key component of this lies in the agriculture sector – which continues to employ, fully or partially, more than half of the workforce.

A newly independent India inherited surface irrigation systems built under British Raj and early governments doubled down on investments in dams and canals to augment gravity flow irrigation and boost food production. However, this turned out to be a costly proposition with little returns as large surface irrigation systems delivered unreliable irrigation to a handful of farmers within canal command areas and despite significant public investments, India's irrigated area from gravity flow systems has been shrinking.

In the 1970s, a new World Bank program introduced dedicated power lines and a network of buried pipes to distribute groundwater to small commands of public tubewells.

On most counts, the public tubewells program was a failure as these were found to be poorly managed, highly politicized and offered unreliable irrigation (Palmer-Jones 1995, Kolavalli *et al.* 1989, Pant 1991). However, these public investments unleashed a tsunami of private investments in groundwater irrigation over the next 30 years, resulting in India adding more irrigated area between 1970 and 2000, than through intensive dam and canal building activity over the previous 170 years (Shah 2009). India's mechanised pumps grew from 200,000 in 1960 to 14 million by 1994 (GoI 2001) while groundwater irrigated area increased from 6 mHa in 1950-51 to 11.9 mHa in 1970-71 and 33.3 mHa by 2000 (GoI 2005). Thus, within a short time period, India became the world's biggest groundwater user – pumping more groundwater each year than the next two big users combined, the United States and China (see Figure 22).



Source: Shah (2005)

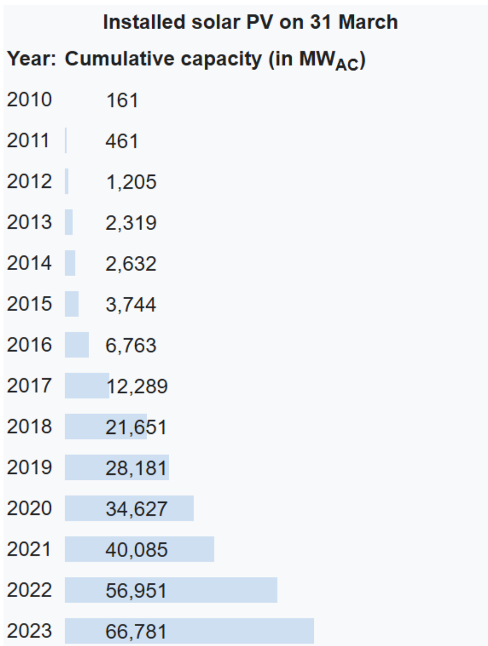
Figure 22: Trends in country-wise annual groundwater withdrawals.

This transformation in Indian irrigation was supported initially by rural electrification, and later by rural electricity tariffs. As the number of agricultural connections rose, power utilities began to feel the burden of serving a large, scattered group of remote consumers. The cost of metering, their maintenance and controlling pilferage, tampering, under-billing and corruption was significant. Utilities found it prohibitively costly to maintain a large cadre of 'meter readers' who were notoriously corrupt and were often accused of either over-charging farmers or colluding with them for a bribe (Shah 1993). This paved the way for 'flat rate tariffs'. Well owners were charged on the basis of the size of their pump and, in turn, they started offering irrigation service to non-well owners through a variety of formal and informal exchange mechanisms. This was a major turning point for India's agriculture, groundwater, and electricity economies.

The interactions between farmers, electricity utilities, groundwater authorities and policy makers have defined the contours of India's insidious Water-Energy-Food nexus. The issue became vexed politically and till around 2005, it seemed that no government would be able to fix the perverse nature of farm power subsidies. Farmers' demand for farm power motivated politicians to offer it for free during elections. This bankrupted electricity utilities and they were forced to cut back on supply to limit their losses. As farm power supply became rationed and unreliable, farmers resorted to auto-switches to run their pumps. This led to more wasteful use of groundwater, falling water tables and higher demand for farm power. By the mid-1990s, farmers in most states were receiving less than 8 hours of power supply per day. The situation was worse in eastern India where vast swathes of rural areas practically became de-electrified.

Through a series of innovative farm power reforms in 2006-07, states like Gujarat – it appeared – had managed to contain the WEF Nexus. However, by 2010, the growing popularity of solar-powered irrigation pumps threatened to undo these reforms by mimicking free power regime. India's aggressive agri. solarization campaign and ambitious targets underline the country's commitment to renewable energy. But in the context of the WEF Nexus and the general agrarian scenario in the country, they also highlight the desire of electricity utilities to get farmers off their backs and control the ever-increasing farm power subsidy bill. By encouraging, enticing and supporting farmers to adopt solar pumps, utilities and state governments can save billions of dollars in current and future farm power subsidies.

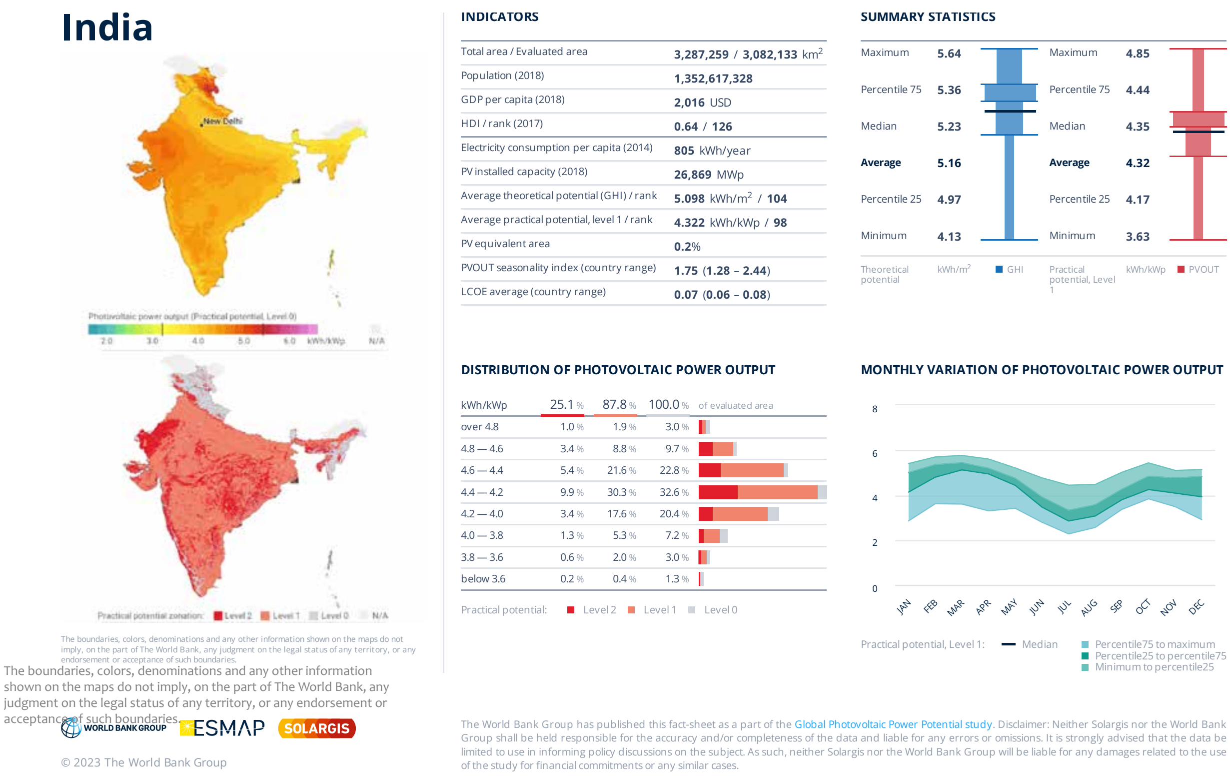
Recognizing growing discontent among rural communities across the country, the current government made 'doubling farmers' income' as one of the central pillars of its policies. Towards this, the federal government has launched several flagship initiatives including *Pradhan Mantri Krishi Sinchai Yojana* (PMKSY – which promised to deliver water for irrigation to every farm), Jal Jeevan Mission (which promises to deliver safe and adequate drinking water to every household), *Swachh Bharat Abhiyan* (Clean India Mission – to eliminate open defecation and improve rural sanitation and waste management) National Mission for Sustainable Agriculture (NMSA), *Paramparagat Krishi Vikas Yojana* (an initiative to develop and promote organic agriculture), *Pradhan Mantri Fasal Bima Yojana* (PMFBY – Prime Minister's Plan for Crop Insurance), *Atal Bhujal Yojana* (ABhY - flagship scheme for improved Groundwater Management and Governance), and *Pradhan Mantri Kisan Urja Suraksha evam Utthan Mahabhiyan* (PM-KUSUM – Prime Minister's Plan for Farmers' Energy Security and Welfare). Of these, at least four – PM-KUSUM, PMKSY, ABhY and JJM – are of direct consequence for sustainable expansion of solar pumps in India.



Source: https://en.wikipedia.org/wiki/Solar_power_in_India
Figure 23: India's installed solar capacity, 2010-2023

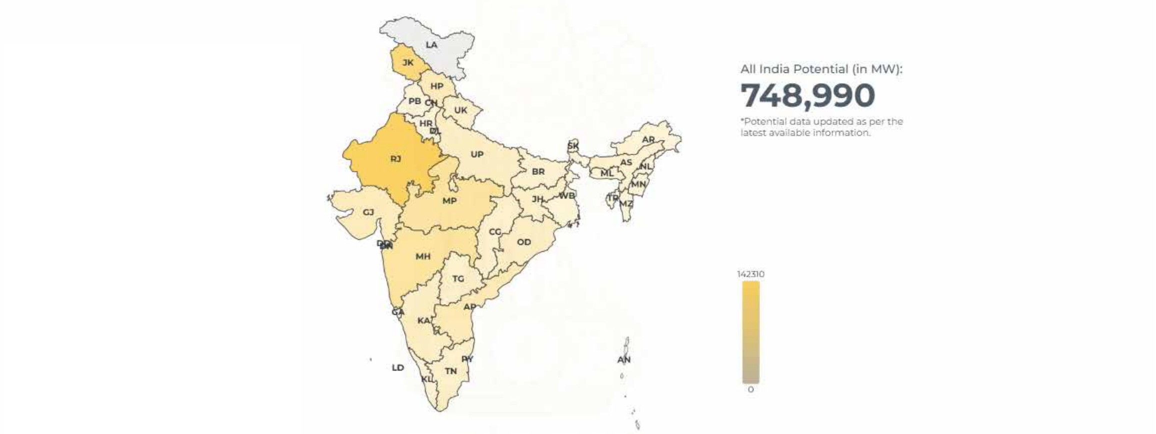
2. Solar Landscape

Set into motion in 2010, as part of the National Action Plan on Climate Change, India's solar mission set itself an initial target of 20 GW capacity deployment by 2022. This was an ambitious target at that time, when India's installed solar capacity was a mere 161 MW. However, the solar economy received a major boost when in 2015, the government raised target to 100 GW. The initial target was achieved in 2018, but the revised target was missed by around 40 GW (Figure 23). Despite that, India's solar economy has been growing admirably and now looks on-target to help India achieve 500 GW RE capacity by 2030. According to ICED, India's overall solar potential is currently estimated to be around 750 GW (Figure 25).



Source: Global Solar Atlas 2.0

Figure 24: Photovoltaic Power Potential and related indicators for India.



Source: https://iced.niti.gov.in/energy/fuel-sources/solar/potential

Figure 25: India's state-wise solar potential, as per latest estimates.

Table 4: State-wise cumulative deployment of solar capacity

State / UT	Ground-Mounted	Rooftop	Hybrid	Off-Grid	Total Solar
Andhra Pradesh	4,277	169	0	88	4,534
Arunachal Pradesh	1	4	0	6	12
Assam	105	33	0	9	148
Bihar	141	31	0	21	193
Chhattisgarh	507	55	0	387	949
Goa	1	25	0	0	26
Gujarat	6,580	2,492	128	54	9,255
Haryana	266	429	0	334	1,029
Himachal Pradesh	38	19	0	30	87
Jammu & Kashmir	2	23	0	24	49
Jharkhand	19	38	0	48	106
Karnataka	7,617	594	0	30	8,241
Kerala	300	441	0	21	761
Ladakh	6	2	0	0	8
Madhya Pradesh	2,459	257	0	86	2,802
Maharashtra	3,009	1,489	0	225	4,723
Manipur	0	6	0	6	12
Meghalaya	0	0	0	4	4
Mizoram	20	2	0	6	28
Nagaland	0	1	0	2	3
Odisha	404	22	0	28	453
Punjab	832	255	0	81	1,167
Rajasthan	14,026	887	1,579	564	17,056
Sikkim	0	3	0	2	5
Tamil Nadu	6,286	386	0	65	6,736
Telangana	4,360	297	0	9	4,666
Tripura	5	5	0	8	18
Uttar Pradesh	2,075	265	0	176	2,515
Uttarakhand	298	263	0	14	576
West Bengal	114	53	0	13	180
Andaman & Nicobar	25	5	0	0	30
Chandigarh	6	52	0	1	59
Dadar & Nagar Haveli	2	3	0	0	5
Daman & Diu	10	31	0	0	41
Delhi	9	208	0	1	218
Lakshadweep	1	0	0	3	3
Pondicherry	1	35	0	0	36
Others	0	0	0	45	45
TOTAL	53,802	8,878	1,707	2,393	66,780

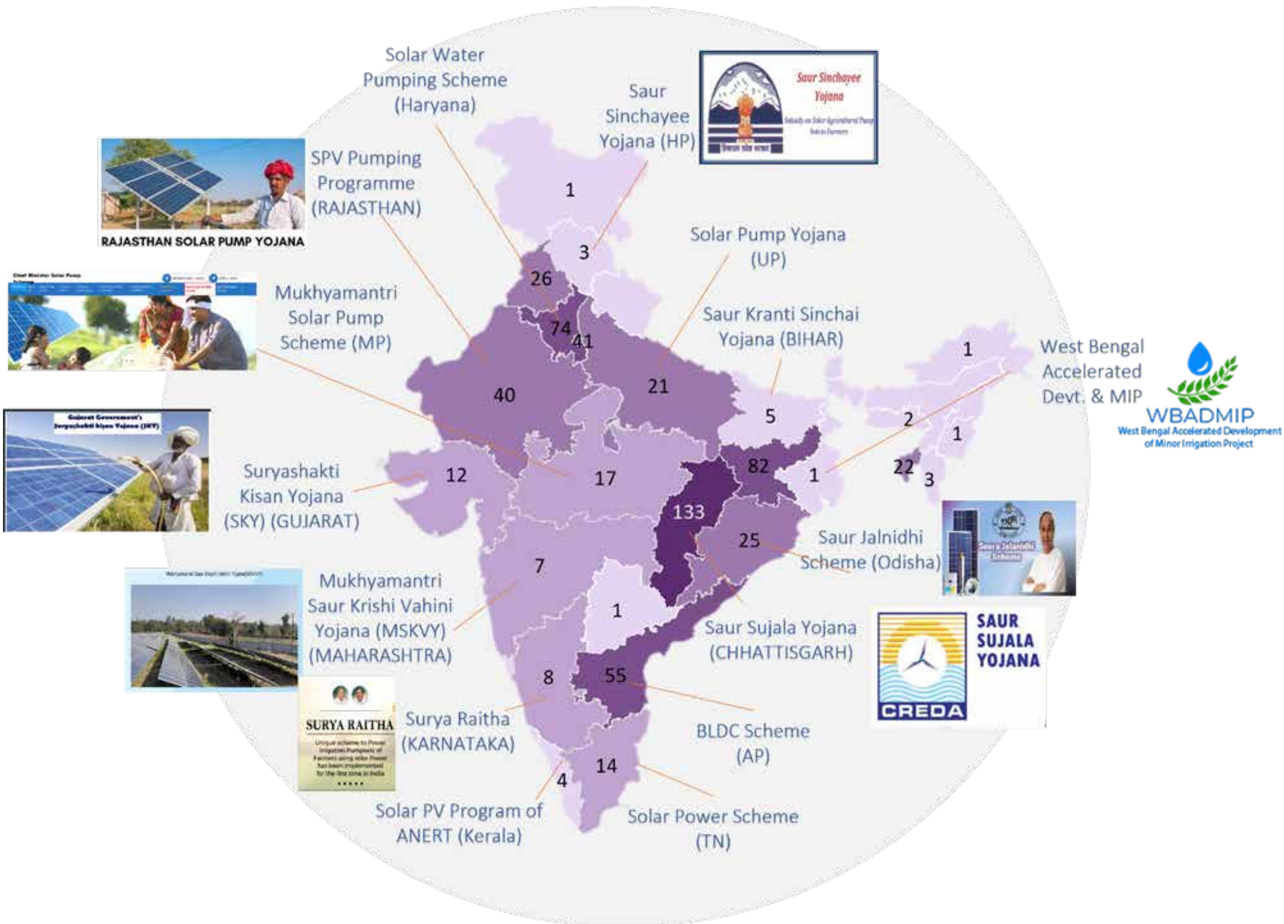
Source: MNRE, Government of India

Within the larger solar discussion, solar pumps have so far played a minor role – contributing less than 4% to the country's installed solar capacity (Table 4). However, given the size of India's minor irrigation economy and the centrality of groundwater and surface water lifting – for agricultural, domestic, as well as industrial uses – this sub-sector holds tremendous potential.

India's first program to install solar pumps was started in 1993 by MNRE (Rathore *et al*. 2018). However, their numbers remained limited till after 2011 when several states launched dedicated schemes to promote solar pumps for drinking water and irrigation (Figure 26).

Rajasthan was among the early movers and by smartly combining resources from existing central and state schemes, it managed to offer 86% capital subsidy for farmers to deploy small-capacity solar pumps. Tewari (2012) estimated that most farmers could recover their investment within 2 years through saving in diesel cost and were uniformly happy with the government's offer. A follow-up study (Kishore *et al*. 2014) confirmed these findings and also noted that bulk of the early adopters were medium and large farmers. Thereafter, Gupta (2017, 2019) estimated a 50-106% reduction in diesel use, 1-17% reduction in electricity use and a 16-39% increase in groundwater use.

Despite starting late, **Chhattisgarh** has done well to deploy nearly 100,000 solar irrigation pumps – the highest in India – through its *Saur Sujala Yojana*. Field studies in Chhattisgarh show that solar pumps benefited farmers across the board, but especially those who were first time irrigators. In an interview with IWMI, the Chief Engineer of Chhattisgarh Renewable Energy Development Agency (CREDA) attributed the success of the scheme to active involvement of the Department of Agriculture – which played a pivotal role in taking the scheme to farmers. In neighbouring **Gujarat**, solar pumps were initially offered to farmers in lieu of farm power connections. Government of Gujarat announced that farmers waiting in queue to get farm power connections could opt out and deploy solar pumps



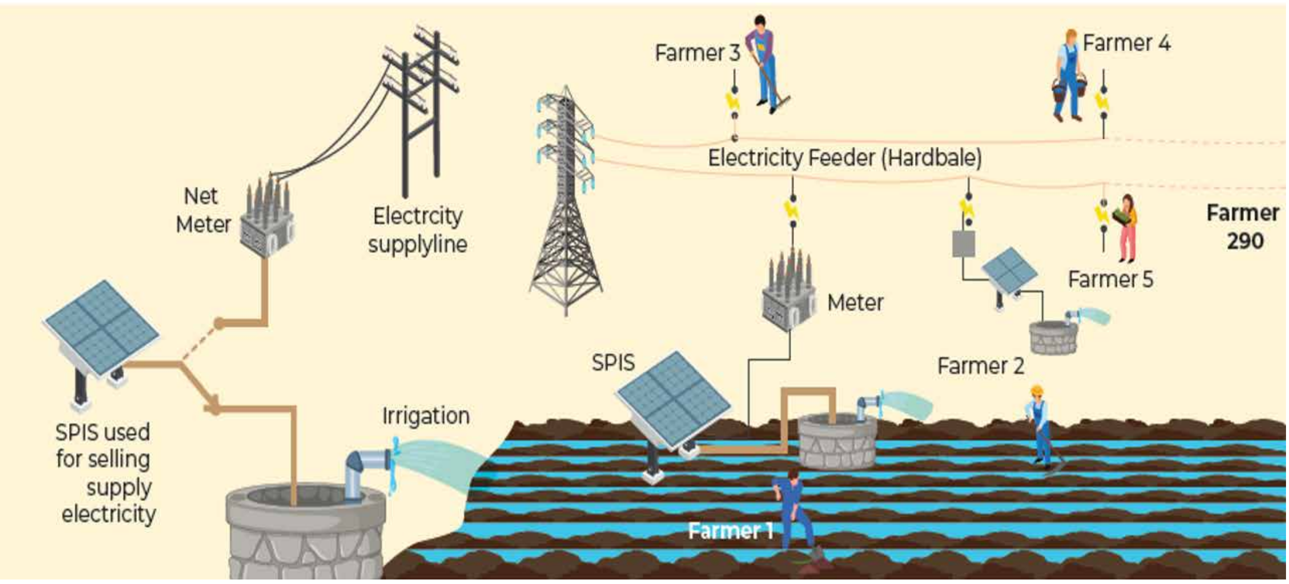
Source: Author's compilation

Figure 26: Solar Irrigation policy landscape in India.

instead and receive 95% capital subsidy. However, most farmers opted to wait for grid connections and there was limited demand. The Gujarat Water Supply and Sewerage Board (GWSSB) also deployed around 500 community solar water supply systems across 12 districts with the goal of delivering safe drinking water to remote tribal habitations. An IWMI-IRMA study found that while the systems did offer relief from fetching water from far-off sources, maintenance of these systems was a challenge (Shankar and Dave 2014). The study also found that in some locations, the systems were also used for irrigating small plots of vegetables – but were handicapped due to their small capacity. Later, in 2017-18, inspired by IWMI's SPaRC (Solar Power as Remunerative Crop) experiment (DSUUSM 2018; Verma 2022), Gujarat launched Suryashakti Kisan Yojana (SKY) which offered grid-connected solar pumps and the option to get paid for net energy evacuation. To date, SKY is the largest scale implementation of grid-connected solar pumps, covering more than 4,200 farmers across 96 agricultural feeders. Early analysis of SKY data shows that income from sale of solar power has emerged as a driver of efficient pumping behaviour (Shah and Rai 2021).Variants of grid-connected solar pumps have also been tried in Karnataka and Andhra Pradesh. When it was announced, **Karnataka's** *Surya Raitha* (solar farmer; Figure 27) policy was hailed as innovative and a model for demand-side management for electricity utilities (Shah *et al*. 2014; Sreedharan *et al*. 2020). However, the scheme remained limited to a single-feeder pilot of 300 farmers and an IWMI study (Durga *et al*. 2021) observed that the scheme was 'over-sold' to farmers and several of its promises breached. **Andhra Pradesh's** experiment with Brushless Direct Current (BLDC) motors (Figure 28) also did not receive an enthusiastic response from farmers. SPIPA (2022) reports that 38% of the participating farmers have reverted back to electric pumps.

In **Maharashtra**, the *Mukhyamantri Saur Krishi Vahini Yojana* (MSKVY) invited private developers to set-up and operate decentralized solar plants (2-10 MWp capacity) at the tail-end of agricultural feeders. The solar energy generated would be first supplied to farmers for pumping and the rest would be evacuated to the grid, the developer would be paid a fixed tariff for solar energy generated. Through this, it was argued that the state would be able to significantly reduce its USD 2.5 billion annual farm power subsidy burden. SPIPA (2022) surveyed 177 farmers in three districts and found significant improvement in farm power supply and an overall reduction in the utility's 'cost-to-serve'. Another study (Saha *et al*. 2022) found mixed evidence and only marginal improvements in farm power supply.

In March 2019, the Government of India announced PM-KUSUM, the flagship agri. solarization initiative with the target of deploying 30.8 GW of solar capacity through 2 million off-grid and 1.5 million grid-



Source: Durga et al. (2020b)

Figure 27: Schematic illustration of Karnataka's *Surya Raitha* pilot.

connected solar pumps by March 2026. With an outlay of roughly USD 5 billion, PM-KUSUM aims to increase the income and welfare of farmers by: [1] reducing dependence on diesel for irrigation; [2] reducing farmers' cost of irrigation; [3] delivering water and energy security in agriculture for farmers; and [4] reducing pollution. PM-KUSUM has been designed in three components:

Component A:	10,000 MW of solar capacity through installation of small, decentralized solar power plants, up to 2 MW each.
Component B:	2 million stand-alone, off-grid solar powered agricultural pumps
Component C:	Solarization of 1.5 million grid-connected agricultural pumps

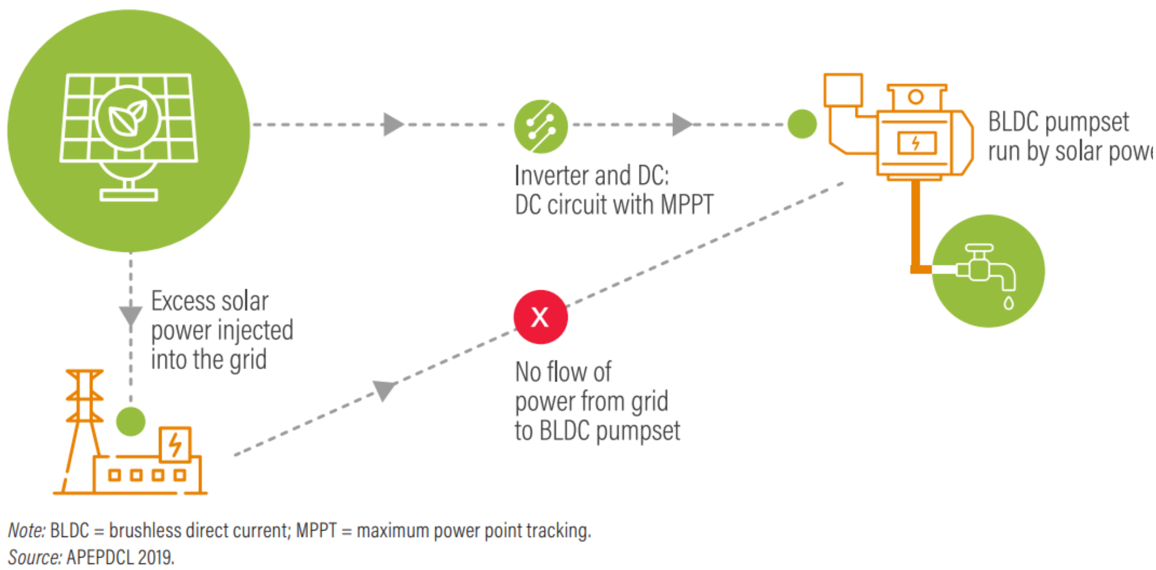
Through PM-KUSUM, Government of India offers 30% capital subsidy, which is usually matched by a similar (or higher) capital subsidy from the state government. The three components are designed to fit solar business models to diverse contexts and farmer requirements. So far, 165 MW has been installed under Component A, 295,823 stand-along pumps have been installed under Component B, and 2117 individual grid-connected solar pumps and 5267 feeder-level grid-connected solar have been installed. MNRE estimates that progress thus far accounts for a reduction in carbon footprint of 190,584 tons.

3. Key Stakeholders

With the launch of PM-KUSUM, the Ministry of New and Renewable Energy (MNRE), Government of India is responsible for solarization of agriculture. MNRE works through State Nodal Agencies (SNAs) and these are defined for each of the three components (Table 5).

In addition to government agencies, several bilateral and multilateral donors, foundations, corporate social responsibility projects and NGOs have also been actively promoting solar pumps. The Indo-German bilateral cooperation and World Bank also provide technical assistance to MNRE for implementation of PM-KUSUM. Thanks to the scale India has already achieved, a vibrant private sector ecosystem has also developed with a diverse list of empaneled vendors and agencies in each state.

India is also the founding member of the International Solar Alliance (ISA), an action-oriented, member-driven, collaborative platform conceived on the sidelines of COP21 as a joint effort to mobilize efforts against climate change through deployment of solar energy solutions. As of date, 118 countries have signed the ISA Framework Agreement and 97 have ratified the same. Scaling solar applications for agricultural use is one of the nine key programs of ISA.



Source: APEPDCL (2019), Pasupalati et al. (2022)

Figure 28: Schematic illustration of Andhra Pradesh's BLDC pilot.

Table 5: Component-wise State Nodal Agencies for PM-KUSUM

	COMPONENT A	COMPONENT B	COMPONENT C
Andhra Pradesh		New & Renewable Energy Development Corporation of Andhra Pradesh Ltd	
Arunachal Pradesh		Arunachal Pradesh Energy Development Agency	
Assam	Assam Power Distribution Company Ltd.	Assam Energy Development Agency	Assam Energy Development Agency
Chhattisgarh	Chhattisgarh State Power Distribution Company Limited	Chhattisgarh Renewable Energy Development Agency (CREDA)	
Delhi	Concerned DISCOM		BSES Rajdhani Power Ltd
Goa	Goa Energy Development Agency	Goa Energy Development Agency	
Gujarat	Gujarat Energy Development Agency (GEDA)	Gujarat Urja Vikas Nigam Limited (GUVNL)	Gujarat Urja Vikas Nigam Limited (GUVNL)
Haryana	Concerned DISCOM	Department of New & Renewable Energy	
Himachal Pradesh	HIMURJA	Agriculture Department	
Jammu & Kashmir	Jammu And Kashmir Energy Development Agency (JAKEDA)	Jammu And Kashmir Energy Development Agency (JAKEDA)	
Jharkhand	Jharkhand Bijli Vitran Nigam Limited (JBVNL)	Jharkhand Renewable Energy Development Agency (JREDA)	Jharkhand Renewable Energy Development Agency (JREDA)
Karnataka		Karnataka Renewable Energy Development Limited (KREDA)	
Kerala	Kerala State Electricity Board (KSEB)	Agency for Non-conventional Energy and Rural Technology (ANERT)	KSEB and ANERT
Ladakh	-	Ladakh Renewable Energy Development Agency	
Madhya Pradesh	Madhya Pradesh Urja Vikas Nigam Limited (MPUVNL)	Madhya Pradesh Urja Vikas Nigam Limited (MPUVNL)	
Maharashtra	Maharashtra State Electricity Distribution Company Limited	Maharashtra Energy Development Agency	
Manipur		Manipur Renewable Energy Development Agency	
Meghalaya	Meghalaya Energy Corporation Limited (MeECL)	Meghalaya Non-Conventional & Rural Energy Development Agency	
Nagaland		Department of New & Renewable Energy, Nagaland	
Odisha	Orissa Renewable Energy Development Agency (OREDA)	Orissa Renewable Energy Development Agency	Orissa Renewable Energy Development Agency
Puducherry	Puducherry Electricity Department		
Punjab	Punjab Energy Development Agency (PEDA)	Punjab Energy Development Agency	Punjab Energy Development Agency
Rajasthan	Rajasthan Renewable Energy Corporation Limited (RRECL)	RHDS (Department of Horticulture) Rajasthan	Concerned Electricity Distribution Company
Tamil Nadu	Tamil Nadu Generation & Distribution Corporation Ltd. (TANGEDCO)	Agricultural Engineering Department	Tamil Nadu Energy Development Agency
Telangana	Telangana State Renewable Energy Development Corporation Ltd. (TSREDCO)	Telangana State Renewable Energy Development Corporation Ltd. (TSREDCO)	
Tripura	Tripura State Electricity Corporation Ltd. (TSECL)	Tripura Renewable Energy Development Agency	Tripura Renewable Energy Development Agency
Uttar Pradesh	Uttar Pradesh New and Renewable Energy Development Agency (UPNEDA), Uttar Pradesh Power Corporation Ltd.	Agriculture Department	
Uttarakhand		Minor Irrigation Department	Uttarakhand Power Corporation Ltd
West Bengal			West Bengal State Electricity Distribution Company (WBSEDCL)

4. Business Models

Adoption of solar pumps can catalyse positive and transformative impacts on food, water and energy systems through four key trajectories. By delivering affordable and reliable clean energy for pumping, it can support sustainable expansion of irrigation. By replacing costly and polluting diesel pumps, solar pumps can improve profitability and reduce carbon footprint of pump irrigation. In certain contexts, grid-connected solar pumps can also become a key component of sustainable groundwater management and governance strategy. Finally, given the seasonality and intermittence of water demand – for irrigation and domestic use – the surplus energy in solar pumps can be used to power productive rural applications.

India's large and ambitious solarization plan has been helped by government initiative, private sector enthusiasm as well as a mosaic of innovative experiments that have seeded new business models through combinations and configurations of technical, financial and institutional designs. We present four models that are already at a significant scale, and also discuss a few emerging business models.

a. Stand-alone off-grid individual solar pumps

This represents the most common deployment strategy for solar pumps. With aggressive government support in the form of capital subsidies – and additional support often available from civil society organizations, this is the simplest and easiest model to deploy. For farmers that use diesel pumps for intensively irrigating crops, a switch to solar is almost a no-brainer as the investment can be easily recovered through savings in fuel cost. The ease of operation, day-time availability, reduced drudgery and elimination of pollution that accompany solar pumps are a bonus. However, there remain challenges.

Field studies suggest: [a] subsidies for off-grid solar pumps are poorly targeted, and often do not reach the poorest; [b] pumps installed have low asset utilization factor – also highlighted in a survey of 959 solar pumps commissioned by GIZ (2021); [c] farmers find it difficult to get good after-sales service; and [d] over-time, farmers demand larger capacity PV arrays and pumps (Kishore *et al.* 2014; Durga *et al*. 2016; Rahman and Jain 2021). Another key challenge with off-grid solar pumps is that they mimic the 'free power regime'. In areas where groundwater is critical or over-exploited, there's a danger that indiscriminate promotion of stand-alone solar pumps can worsen the groundwater situation. Financing is another area of concern as formal sources of finance are under-developed and there is need to develop appropriate and accessible financial products, especially for small and marginal farmers, women and other disadvantaged groups.

b. SPaRC: Grid-connected SIPs

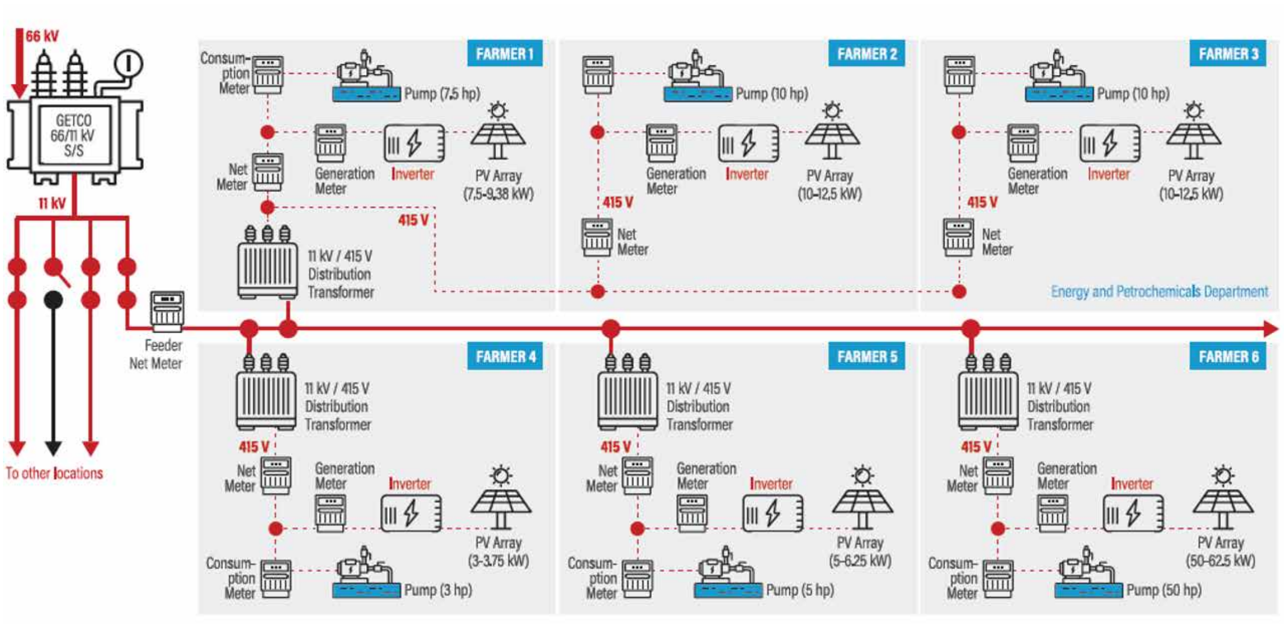
We have discussed earlier how India's groundwater-based minor irrigation economy is the backbone of its agriculture. The possibility of generating near-zero marginal cost energy, reliably for about 300 days, during day hours, and without the possibility of 'rationing' makes it important that solar pumps expansion in groundwater-scarce regions is accompanied by business models that also create incentives for efficient energy and groundwater use. One way of doing this is by creating a non-trivial opportunity cost for the solar energy being generated. In 2015-16, with support from partners, IWMI managed to demonstrate this by implementing the SpaRC pilot in Dhundi village of Gujarat.

The pilot aimed to field test a novel business model, SPaRC (Solar Power as Remunerative Crop) with the basic premise that a reasonably attractive feed-in-tariff can create incentives for efficient use of energy – and therefore groundwater (Shah *et al.* 2017; Shah *et al.* 2018). The SPaRC experiment offered solar pumps to nine small farmers and organized them into the world's first 'Solar Pump Irrigators' Cooperative Enterprise'. The members of this cooperative pooled their surplus solar energy (via a local micro-grid) and entered into a 25-year power purchase agreement with the local electricity utility to sell their surplus power to the grid. To encourage efficient energy generation and use, IWMI topped-up the feed-in-tariff with nominal 'green energy' and 'water conservation' bonus, available to members only for an initial period of 18 months.

The experiment has been fully functional since May 2016 and the nine farmers 'sell' roughly 2/3rd of the energy that their panels generate to the grid – without compromising their own farming operations or that of their neighbors. The additional money from solar matches their earnings from agriculture – in effect, doubling their income. The experiment inspired Gujarat's Suryashakti Kisan Yojana (SKY) (Figure 29) and component C of PM-KUSUM. IWMI has argued that grid-connecting solar pumps can have several benefits: [1] it creates incentives for efficient energy and water use; [2] by offering additional, climate-resilient income to farmers, it will encourage more farmers to adopt solar; [3] by converting farmers from consumers of free or highly subsidized power to net producers of clean energy, it will improve the financial viability of power utilities; [4] it will reduce the carbon footprint of irrigation; and [5] it ensures full utilization of installed solar capacity.

c. *Solar irrigation entrepreneurs and enterprises*

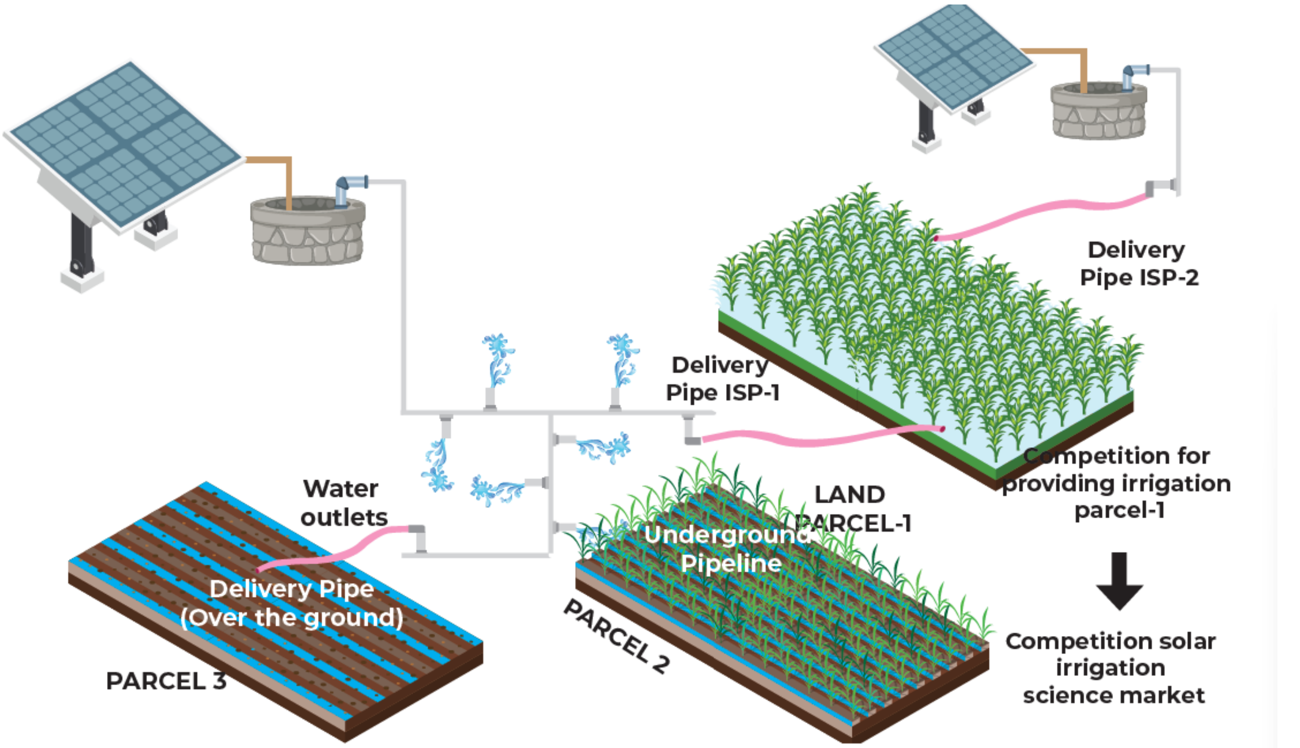
Not all off-grid solar pumps are deployed for individual use. Especially when land holdings are small and fragmented, as is the case in eastern India, investing in a solar pump only for personal use becomes unattractive. Several early civil society led experiments deployed small-capacity community-owned solar pumps. One of the early pilots in Bihar solarized several public tubewells in Nalanda and handed them over to operators to sell solar irrigation as a service to farmers (Tiwary 2012). These faced challenges similar to public tubewells, but some enterprising operators operated them as efficient enterprises. In 2016, IWMI partnered with AKRSP-I to set up a field pilot in Chakhaji village in north Bihar. The objective was to attempt catalysing competitive irrigation service markets by setting up solar irrigation entrepreneurs. Each 5 kWp solar pumps was coupled with 1000-1500 feet buried pipes for water distribution, to facilitate 'water selling' and several such entrepreneurs were promoted to encourage competition. Shah *et al.* (2018), Durga and Rai (2018) report that: [a] each entrepreneur delivers high quality irrigation service to 60-80 small farmers; [b] the effective cost of irrigation reduced by more than 50%; [c] diesel pumps got crowded out; and [d] there has been a significant increase in irrigation and cropping intensity (also see Figure 30; Shirsath *et al.* 2020). Staring off with five entrepreneurs, AKRSP-I has scaled this model to more than 130 systems across Samastipur, Muzaffarpur and Vaishali districts. Efforts are underway to establish 'solar irrigation' as an enterprise for women members of Self-Help Groups established all over Bihar by Jeevika – the state rural livelihood mission.



Note: GETCO = Gujarat Energy Transmission Corporation Limited; hp = horsepower; kV = kilovolt; kW = kilowatt.

Source: Jani (2018) c.f. Pasupalati et al. (2022)

Figure 29: Schematic illustration of Gujarat's SKY scheme.



Source: Durga et al. (2020a)

Figure 30: Schematic illustration of Solar Entrepreneurs in Bihar.

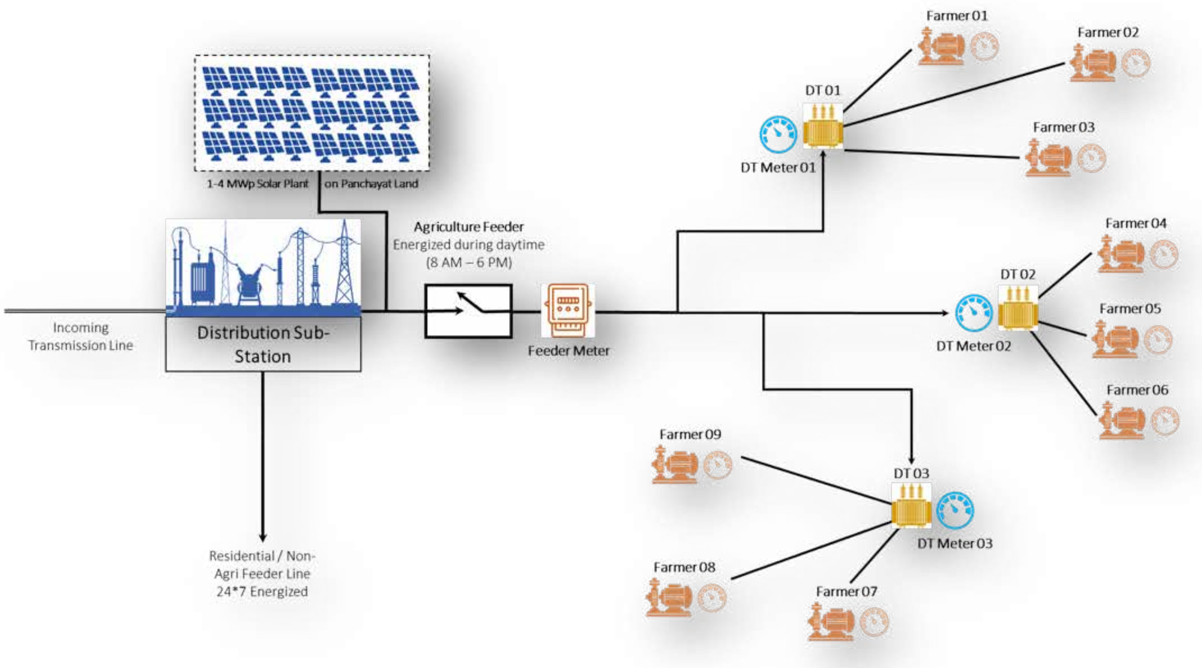
In Bahraich district of eastern UP, a private entrepreneur, Oorja Development Solutions Ltd. has invested in 100-odd solar pumps that offer irrigation service to farmers. These systems are deployed after initial interaction with farmers who agree to purchase water for irrigation on volumetric basis (p. 49 /USD 0.05 m^3). The effective cost is comparable to diesel, but this comes with greater reliability and less hassle. After paying the operator a fixed salary plus revenue-linked incentive, Oorja expects to recover their initial investment over 4-5 years.

Three key challenges emerge from these experiments. One, as the rural power grids and rural power supply situation improves, the solar systems will increasingly face competition from subsidized farm power connections, offered by electricity utilities. Two, not all entrepreneurs / user groups / enterprises are able to operate the systems efficiently and profitably – and a litmus test would be any significant and urgent O&M requirement. Finally, like other off-grid systems, these too have surplus capacity and experiments are underway to utilize the surplus capacity for other productive energy uses in the village.

d. Feeder Tail-end Solar Plants

Maharashtra's innovative MSKVY program offers another business model for inviting the private sector to invest in decentralized solar plants at the tail-end of agricultural feeders. Generating energy at the tail-end of feeders can improve rural power supply environment as well as significantly cut transmission and distribution losses and reduce cost-to-serve. Gambhir *et al.* (2021) also argue that this model will save the government any capital subsidies – as the capital investment will be made by private developers – and will not require any changes to be made at the farmer end (Figure 31).

Despite initial enthusiasm, MSKVY found it difficult to attract private developers to deploy such decentralized plants. Public sector companies were more easily able to invest in such plants, although much of the operations were outsourced.



Source: Verma (2018)

Figure 31: Schematic illustration of feeder tail-end solar plants.

e. Some Emerging Business Models

Each of the business models described so far has been implemented at scale across multiple geographies. In addition, there are some models that are still evolving, or it is too early for us to know how well they will perform when implemented on scale. We present some such cases.

A rapidly evolving model of solar deployment entails installation of solar panels over water bodies. Gujarat experimented with the world's first canal-top solar on the Sardar Sarovar canal system that boasted of zero land footprint, decentralized energy generation, as well as reduction in evaporation losses from the canal. Water body underneath the panel, scientists have argued, will lead to an improvement in performance of panels by reducing ambient temperature. However, results from Gujarat's experiment reported 1.5% lower performance ratio and vis-à-vis ground mounted systems in the same vicinity (Kumar and Kumar 2019). The reduction in evaporation losses is difficult to know from this experiment as the panels only covered a small portion of a large canal system. With significantly higher mounting costs, the viability and scaling potential for this business model will likely rely heavily on the relative price and availability of land. A complimentary and possibly more promising business model that is gathering pace in India is 'floto-voltaics'.

Another emerging model is that of Agrivoltaics, which entails co-generation of energy and agricultural output. The model is well established in countries like Germany, France and Japan. However, its viability in the Indian context remains untested. A report by NSEFI (2023)[5] provides details on 20-odd pilots that have been commissioned and a few that are upcoming. The impact of different designs of agrivoltaics on agricultural and energy yields is well studied in Europe but similar data for India is still being generated. The Fraunhofer Institute for Solar Energy argues that nearly all crops can be grown underneath panels, in fact in dry season, the crop yield underneath solar panels might get enhanced (Trommsdorff *et al.* 2020). However, given the high capital investment required, how to gainfully involve India's small and marginal farmers remains an unanswered question. The Ministry of New and Renewable Energy (MNRE)

[5] https://www.energyforum.in/fileadmin/user_upload/india/media_elements/Photos_And_Gallery/20201210_SmarterE_AgroPV/20201212_NSEFI_on_AgriPV_in_India__1_.pdf

has constituted a committee to evaluate prospects of mainstreaming agrivoltaics in India through a conducive policy and regulatory environment.

Another nascent but promising business model involved low-capacity (typically sub-HP), portable solar pumps. These are ideal for lifting surface water or shallow groundwater over short distances and for irrigating small parcels of land. NGOs in eastern and central India are also experimenting with shared ownership and financing these assets through micro credit. As panel efficiency improves and lighter solar panels become easily available and affordable, this model is likely to pick up pace, especially for small and marginal farmers.

5. Way Forward

The Indian solar pump market is rapidly expanding – in breadth as well as depth. As each model scales, it also generates more data and information on its relative viability in different contexts. India is also fortunate that civil society has been actively experimenting with new models and that government programs have been fairly responsive to adapt policies to allow / include new and emerging business models. The government of India's aggressive promotion and continued support is also catalyzing the creation of an ecosystem of products and services that will enable this market to expand faster in the coming years.

Domestic manufacturing of solar modules; blended and flexible financing options; continuous public and private investments in capacity building and ecosystem development; and a vibrant civil society are all contributing to fulfilling India's solar pump promise. As the global leader in solar capacity deployed for use in agriculture, India can offer several ideas and lessons for deploying solar pumps at scale.

Shashwat Cleantech Pvt. Ltd.

Prashanth Vishwanathan/IWMI

Metro Media/IWMI

Nepal

Growing Interest in Solar

E. Nepal: Growing Interest in Solar

Nepal, a landlocked nation between India and China, with land area of 147,181 km² and population of around 30 million (World Bank nd). The nation has seven provinces which are organized into a three-tiered government system adapted into the country's constitution in 2015. Topographically, Nepal can be categorized into three distinct regions, namely the mountains (with altitudes ranging from 4877m to 8848m above sea level), the Hills (with altitudes ranging from 610m to 4876m above sea level), and the Terai (with altitudes below 610m above sea level) (MoH *et al*. 2002). These three zones cover 15%, 68%, and 17% of the total land area, respectively, each exhibiting diverse climatic conditions (NPC 2013). The Terai region, characterized by flat terrain, serves as Nepal's primary food basket. Owing to the varying geographical, climatic, and hydrological characteristics, Nepal experiences a wide range of agricultural land use and cultivation patterns (IBN 2019).

Nepal's GDP increased from USD 5.49 billion in 2000 to USD 30.64 billion in 2019. However, in the aftermath of the CoViD-19 pandemic, GDP growth dropped to 0.02% in 2020, with an average inflation rate of 6.2%[6]. Agriculture accounts for one-third of the country's GDP, and another significant portion comes from remittances. Another major contributor is the service sector (Gaudel, 2015). The country is categorized as a low-income nation and ranks 94 out of 180 for ease of doing business.

Even though Nepal produces only 0.027% of the world's CO_2 emissions, it is among the most vulnerable to the effects of climate change (GoN, 2020). As a result, Nepal is dedicated to global projects and goals including Sustainable Energy for All (SE4ALL), the Sustainable Development Goals (SDGs), and the Paris Climate Change Agreement. Nepal submitted its first NDC in 2016 and a revised one in 2020, as part of the Paris Climate Change Agreement, with a goal to reduce CO_2 emissions by 28% by 2030 (GoN, 2021).

Source: https://www.un.org/geospatial/file/2132/download?token=Aj4_d-eA

Figure 32: UN Geospatial map of Nepal

[6] https://data.worldbank.org/country/nepal

1. Agriculture and Water Resources

About 2/3rd of the population of Nepal is either directly or indirectly employed in agriculture. Average landholding is less than 0.8 hectare and productivity is heavily dependent on rainfall and impacted by the lack of water throughout the summer – November to March. As a result, many farmers leave their land uncultivated during this season. Better-off farmers can grow high value vegetables using either diesel or grid-powered electric pumps for irrigation. Surface irrigation covers about 80% of the total irrigated area; the other 20% is irrigated through groundwater or mixed systems (Nepal *et al.*, 2021). The irrigation command area varies from 90% of the system in the wet season to 25% in the dry season (Nepal *et al* 2021).

Nepal has 3.5 mha of cultivated land out of which 1.1 mha (31%) receives year-round irrigation and about 1.3 mha is potentially irrigated (GoN, 2019). *Terai* consists of 1.59 mha of cultivated land of which 60% receives some irrigation from surface, ground water and conjunctive uses (Nepal *et al.*, 2019; Khadka *et al.*, 2021) but another 600,000 ha has potential for irrigation expansion through groundwater development. Nepal is well suited for growing high-value off-season crops, along with edible oils and medicinal herbs. Oilseed, potato, tobacco, sugarcane, jute, cotton, and rubber are the main economic crops in Nepal. Additionally, the principal crops include paddy, maize, millet, wheat, barley, and buckwheat. The overall cereal yield in Nepal is 2.8 MT/ha, far below the regional and global average (FAO 2022). Access to year-round irrigation is vital to improve crop yields and quality. The government of Nepal intends to extend year-round irrigation to 50% by 2024 and 80% by 2030 in accordance with the 15th periodic plan (NPC, 2020). To support commercial agriculture, groundwater and lift irrigation systems will be deployed in cooperation with the provinces.

Smallholder farmers who are primarily involved in subsistence farming dominate the agricultural sector (Thapa *et al.*, 2019). Although a sizable portion of Nepal's population works in agriculture, this industry has a negative trade balance, which adds to the country's overall trade deficit. Low agricultural output due to conventional farming methods and land fragmentation is one of the key causes. It is crucial to convert subsistence farming into commercial farming with the provision of irrigation facilities because agriculture is the foundation of Nepal's economy. Compared to rain-fed land, the productivity of irrigated land is roughly three times higher.

The estimated annual renewable groundwater resource available in the Terai region of Nepal is 8.8 BCM. The region normally faces flooding in the monsoon and seasonal droughts in the springs. Therefore, pre-monsoon pumping of groundwater for irrigation not only provide irrigation in the dry season but also create more room to absorb excess water in the monsoon and can play important function in moderating floods (Verma *et al.*, 2018; Rasul *et al*, 2021). Like the eastern Indo-Gangetic plains in India, Terai may be classified as groundwater abundant region with low agricultural productivity and has tremendous potential for sustainably expanding irrigation (Verma *et al.*, 2018). Estimates indicate that there is potential to double irrigated area through investments in irrigation and energy infrastructure.

2. Energy and Renewable Energy

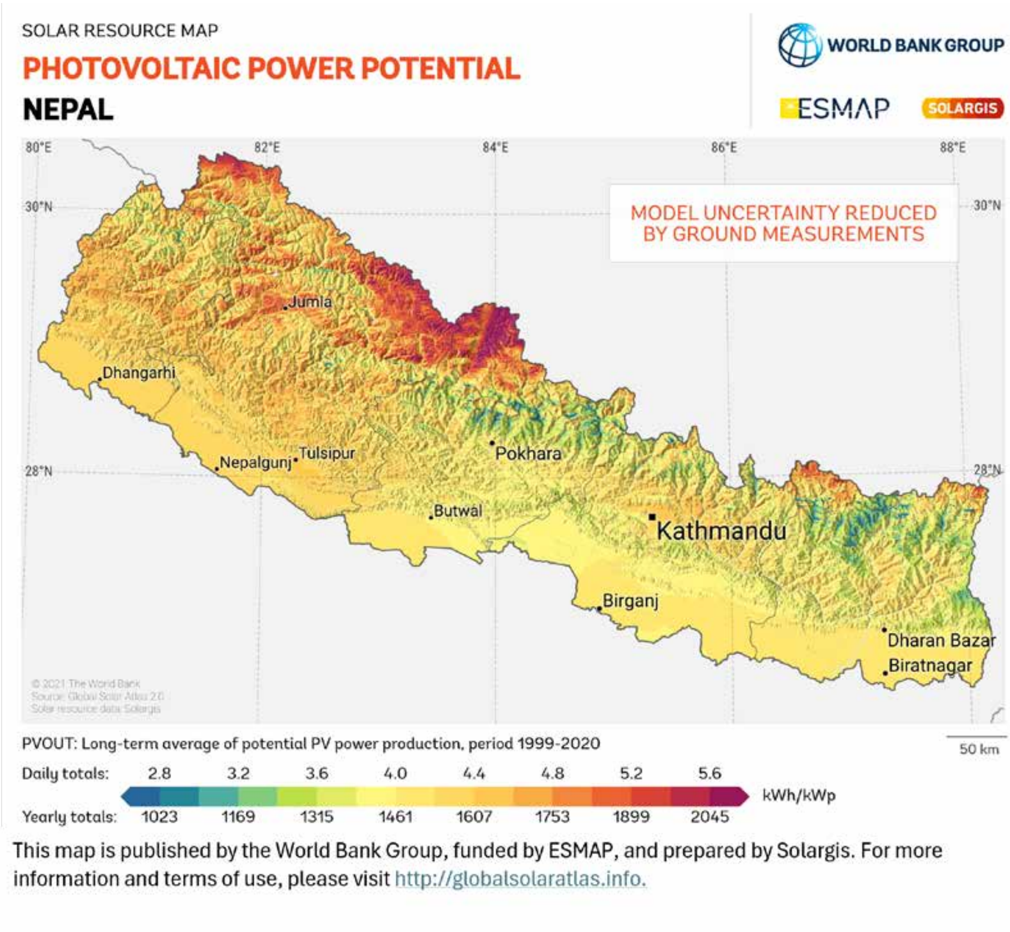
Nepal's energy sector has undergone tremendous change after nearly a decade of power shortages leading up to 2018. According to MoEWRI (2018), Government of Nepal (GoN) intends to enhance electricity generation by 5,000 MW in five years and 15,000 MW over the next fifteen years. With a number of significant hydroelectric projects under construction, Nepal is on course to achieve energy independence within the next few years.

As of 2018, Renewable Energy (RE) accounted for only 3.5% of the total energy generation in Nepal. According to the Alternative Energy Promotion Center (AEPC 2019), Nepal has set ambitious targets to expand the proportion of renewable energy in its energy mix to 12% by 2024. The 15th periodic plan of the National Planning Commission (NPC) also plans to generate about 4000 MW of energy from renewable sources by the year 2030. Further, the government intends to increase the production of solar energy through the private sector, with an aim of producing more than 550 MW by 2024 (*ibid*). Additionally, as part of its Nationally Determined Contribution (NDC) commitment, Nepal wants to add 2100 MW of solar energy to the national grid by 2030, in order to meet 15% of the overall energy demand from clean energy sources (GoN, 2020). The GoN's emphasis on RE is also clear from its 2019-20 budget, which specifies goals to build at least two sizable solar and hydroelectric projects in each province. Emphasis will be placed on the implementation of solar energy technology in Province #2, which lacks hydroelectricity supplies. Additionally, lift irrigation and groundwater irrigation projects managed by province and local governments will greatly benefit from solar energy.

On average, Nepal has 6.8 sunshine hours per day (see Table 6), i.e. 2,482 sunshine hours per year with the potential of solar power generation ranging from 3.9 to 5.1 kWh/m²/day (Ranabhat and Khadka, 2019). Studies suggest that up to 47,628 MW solar energy can be harnessed in Nepal. Karnali and Gandaki provinces of Nepal have the highest solar energy potential (Figure 33). However, a recent survey by IWMI shows the demand for solar pumps in western Nepal is quite muted, possibly due to poor awareness levels.

Table 6: Average daily sunshine hours in select districts of Nepal

District	2008	2009	2010	2011	2012	2013	2014	2015
Banke	6.9	7.7	7.3	7.4	7.5	6.9	6.9	6.9
Bara	7.6	7.3	7.3	NA	7.3	7.2	5.5	6.8
Kathmandu	6.0	6.4	6.4	5.9	6.7	6.2	6.4	5.7
Morang	6.5	6.5	6.1	6.0	7.1	6.7	6.1	5.2
Okhaldhunga	6.2	6.6	6	6.1	6.5	6.2	6.1	5.8
Taplejung	6.0	6.8	6.3	5.9	6.5	6.2	6.4	6.2



Source: Global Solar Atlas 2.0

Figure 33: Photovoltaic Power Potential in Nepal

3. Solar Landscape

For a long time, Nepal seemed reluctant to aggressively invest in solar energy owing to its historical and substantial investments in hydroelectric projects. However, in a recent stakeholder consultation co-organized by ISA and ADB in Kathmandu, a senior government official as well as industry representatives argued how investments in solar energy would complement hydroelectric power, especially as water availability becomes more erratic owing to climate change.

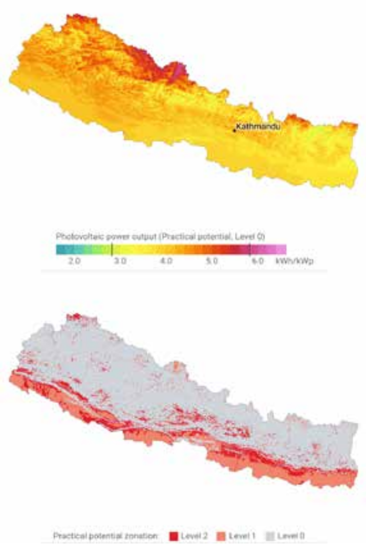
Nepal's first 4 kW solar system was deployed in Sundari-ghat in 1993 (Renewable World 2018), followed in 1998 by larger systems in Bode (40 kW), Bhulke Siraha (60 kW), and Phulberiya, Siraha. The Government of Nepal (GoN) announced subsidies to support renewable energy around the turn of the century, including incentives for rural communities to utilize solar energy through solar-powered water pumps. This opened the door for Nepal to use solar pumping technology more widely.

By 2015, solar-powered pumps had emerged as a promising solution for providing drinking water and supporting irrigation in rural areas. These decentralized technologies proved to be particularly beneficial for reaching farmers who lacked access to the electricity grid. However, uptake remained lukewarm – largely because of limited awareness and high costs.

In 2015, Winrock International implemented a three-year project called the USAID Accelerated Commercialization Solar Photovoltaic Water Pumping (AC-PVWP) project. The project aimed to expand the commercialization and adoption of solar photovoltaic water pumping systems. In the first phase, 69 solar pumping systems with a combined capacity of 53.15kWp were piloted in 16 districts, benefiting 392 farmer groups. The second phase, implemented in 2017, saw the installation of an additional 120 systems.

ICIMOD (International Centre for Integrated Mountain Development) piloted 1.2-2.4 kWp solar irrigation pumps (SIPs) in 2016 in the Saptari, Bara, Sarlahi, and Ruatahat districts in the Terai region. Meanwhile, Winrock International and International Development Enterprises (iDE) focused on promoting small-scale solar water pumps ranging from 80–300 Wp, targeting smallholder and marginalized farmers (Bastakoti *et al.*,

Nepal



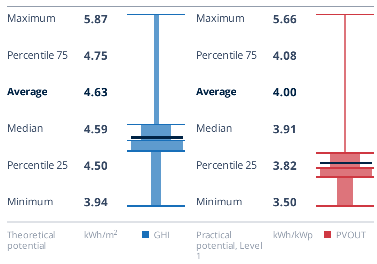
The boundaries, colors, denominations and any other information shown on the maps do not imply, on the part of The World Bank, any judgment on the legal status of any territory, or any endorsement or acceptance of such boundaries.

WORLD BANK GROUP ESMAP SOLARGIS

INDICATORS

Total area / Evaluated area	**147,180** / **147,180** km^2
Population (2018)	**28,087,871**
GDP per capita (2018)	**1,026** USD
HDI / rank (2017)	**0.57** / **145**
Electricity consumption per capita (2014)	**146** kWh/year
PV installed capacity (2018)	**53** MWp
Average theoretical potential (GHI) / rank	**4.534** kWh/m^2 / **144**
Average practical potential, level 1 / rank	**3.996** kWh/kWp / **139**
PV equivalent area	**0.019**%
PVOUT seasonality index (country range)	**1.59** (**1.30** – **2.10**)
LCOE average (country range)	**0.11** (**0.05** – **0.12**)

SUMMARY STATISTICS

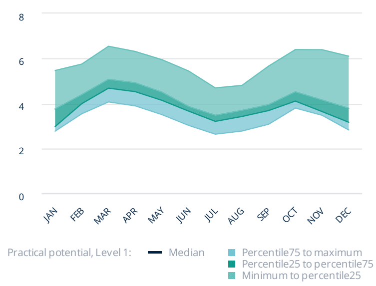


DISTRIBUTION OF PHOTOVOLTAIC POWER OUTPUT

kWh/kWp	11.4 %	27.9 %	100.0 % of evaluated area
over 5.0	0.3 %	0.8 %	4.9 %
5.0 — 4.8	0.1 %	0.2 %	2.8 %
4.8 — 4.6	0.2 %	0.3 %	4.6 %
4.6 — 4.4	0.4 %	0.6 %	8.2 %
4.4 — 4.2	1.3 %	2.0 %	13.8 %
4.2 — 4.0	3.9 %	8.1 %	21.3 %
4.0 — 3.8	3.0 %	10.0 %	21.4 %
3.8 — 3.6	1.9 %	5.6 %	14.1 %
3.6 — 3.4	0.2 %	0.3 %	5.0 %
below 3.4	0.0 %	0.1 %	3.9 %

Practical potential: Level 2 Level 1 Level 0

MONTHLY VARIATION OF PHOTOVOLTAIC POWER OUTPUT



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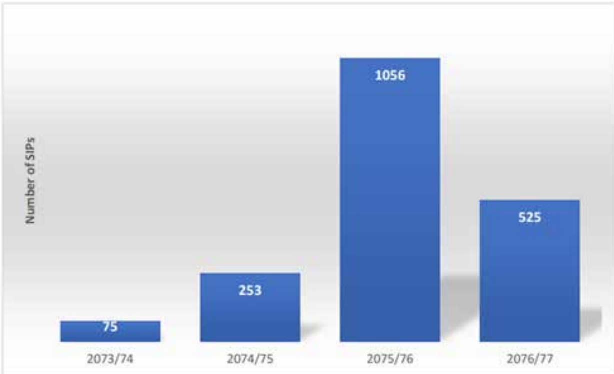
Source: Global Solar Atlas 2.0

Figure 34: Photovoltaic Power Potential and related indicators for Nepal

2020). In collaboration with implementation partners, IWMI also contributed to the effort by installing 80 Wp solar irrigation pumps in the Saptari district of Nepal.

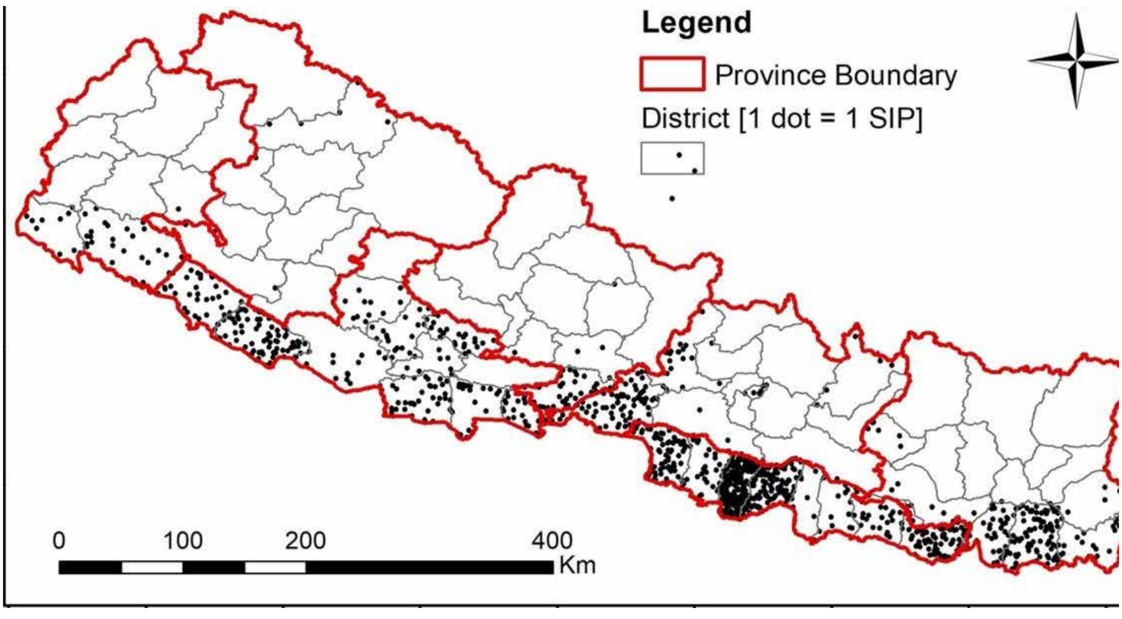
Due to its significant groundwater potential and extensive agricultural activity, the Terai region of Nepal has seen the majority of SIP installations. There is a strong link between solar generation and water demand, so SIPs can irrigate at full capacity during the dry seasons when crop water needs are highest (Foster *et al*., 2009). Off-grid SIPs are especially well suited for supplying energy to irrigation systems in places with sparse grid infrastructure. Despite the lower long-term operating costs of these systems, small and marginal farmers find it difficult to finance them because of the high upfront costs. The continual increase in the funding allotted for supporting SIPs is certainly evidence of Nepal's strong support for SIP technology. However, despite government support, on average, only 31% of the total demand for SIPs was found to have been met through subsidies in 2019, and this number has decreased even more in 2020 owing to growing demand and reduced budgetary allocations (Pandey *et al*., 2020).

In Nepal, particularly in the Terai, there is a sizable demand for SIPs, and if the government allocates greater subsidy, the adoption of SIPs is likely to be accelerated. However, thanks to their well-established supply chain and reduced initial costs, diesel pumps continue to dominate. About 10.5% of Nepal's diesel consumption is in the agricultural sector. Grid-connected electric pumps are typically used for lift irrigation from surface water sources or lifting groundwater in locations with stable grid connectivity. The SIP program has seen an increase in demand for the technology since it was launched in 2016-17 with financial support from AEPC, resulting in a progressive rise in the number of SIPs issued by 2018-19 (Pandey, *et al*., 2020). Although CoViD-19 lockdown presented challenges, 525 SIPs were successfully deployed with support from AEPC in 2019-20 (Figure 35). Further, AEPC released a list of 590 farmers for installation in 2020-21. The majority of these are located in the province 1, province 2, and Lumbini areas of the Terai region (Figure 36). More than 74% of the applications and more than 85% of the SIPs granted in 2019 came from these regions. This is explained by the Terai



Source: Shrestha and Uprety (2021), p.18

Figure 35: Number of SIPs supported by AEPC during 2016-17 to 2019-20



Source: Pandey, et al. (2020)

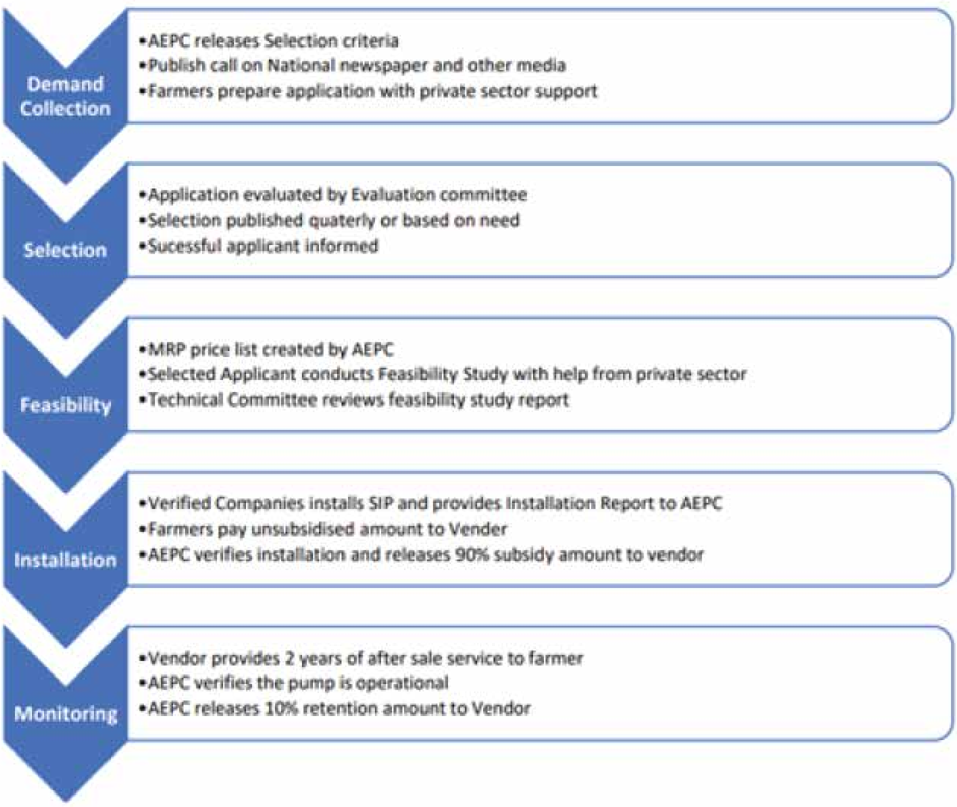
Figure 36: Geographical distribution of AEPC-supported SIPs in Nepal

region's profusion of sunlight, abundant groundwater supplies, and exceptionally productive soils.

Pandey *et al* (2020) reviewed the process followed by AEPC to select beneficiaries (Figure 37). The study notes that in general, AEPC chose applicants with considerably smaller land holdings; those who applied had an average land size of 3.4 ha, but those who received SIPs had an average land size of 1.7 ha. All provinces except Karnali followed this trend. Although the policy required applicants to possess land title or a lease agreement, 478 farmers who were unable to submit land titles were still granted SIPs. Notably, tenant farmers were not typical applicants. Among the beneficiaries, women accounted for up to 22% of the total applicants. However, this figure may not be a reliable indicator of the program's gender inclusivity. The authors note that it is possible that these female beneficiaries may not have the same level of ownership and management rights as men within their households.

Across all provinces, the average cost of SIPs was found to be high, especially when compared to those in India. This is not surprising given the scale of deployment is vastly larger in India. The calculated average cost of a SIP was NPR 659,482 (~USD 5,450). Considering that farmers were required to contribute 40% of the cost, this meant an average out-of-pocket expense of NPR 263,793 (~USD 2,180) for a single unit. As the pump size increased, the cost of the SIP also proportionally increased[7]. Even with 60% subsidy, most farmers found it challenging to afford the upfront costs. Pandey *et al*. (2020) also list delays in installation, discretionary power in pump allocation and weak program monitoring as some of the challenges faced by the program.

Improved financial access, integrated strategies, better technology, and greater awareness are required to increase the popularity of SIPs (Dhital *et al*., 2014; Renewable World, 2018). Work is also needed to increase SIPs' capacity utilization factor (CUF) and shorten their payback period. For land holdings up to four hectares, SIP deployment is more cost-effective vis-à-vis extending the grid network (Karki and Lohani, 2020). However, as land size increases, the cost difference between SIPs and grid-connected pumps diminishes.



Source: Pandey, et al. (2020), Shrestha and Uprety (2021)

Figure 37: AEPC's subsidy delivery process flow

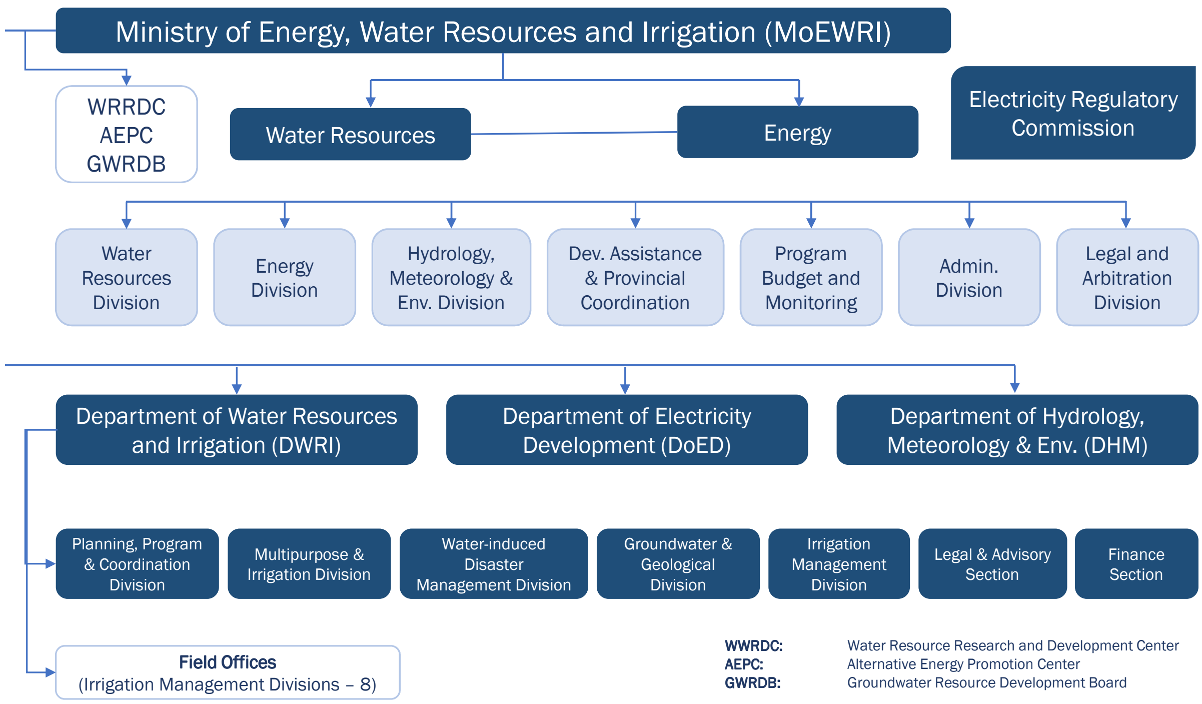
4. Key Stakeholders

The Ministry of Energy, Water Resources, and Irrigation (MoEWRI) is the key ministry responsible for solar pumps in Nepal, specifically, the Alternative Energy Promotion Center (AEPC) – a semi-autonomous national organization run by MoEWRI (see Figure 38). Further, the Ministry of Agriculture (MoA) and the Ministry of Physical Infrastructure Development (MoPID) are also involved at the federal level.

AEPC was established in 1996 with the main objective of advancing renewable energy technologies in Nepal. As the main institution in-charge of formulating and executing policies connected to RE, AEPC is crucial in developing short, medium, and long-term plans and policies for scaling solar pumps. Rural electrification is AEPC's principal area of focus, and it is accomplished through active coordination with numerous government agencies, development partners, non-governmental organizations (NGOs), international non-governmental organizations (iNGOs), and the business sector. Through the provision of subsidies, AEPC has played a vital role in promoting SIPs in Nepal since 2015.

MoEWRI also oversees DWRI (Department of Water Resources and Irrigation), a government agency with a clear mandate to design, construct, maintain, operate, manage, and monitor diverse irrigation projects that are both environmentally sustainable and socially acceptable. DWRI's mandate covers both groundwater and surface water resources and initiatives, with irrigation expansion receiving a lot of attention.

According to the provisions of the 2015 Constitution of Nepal, a three-tier government structure has been established that gives local governments more power and authority. With this decentralization, local governments are now able to take the initiative for designing and executing solar pump expansion programs. As a result, local governments are actively working with communities to facilitate several projects within their respective geographies. Local governments now have distinct local water and irrigation management agencies, allowing them to manage agriculture and irrigation issues as part of their sectoral line departments. The management and promotion of sustainable farming practices and irrigation projects have benefited from this devolution of responsibility and power, and this has reinforced the position of local governments.



Source: Authors' adaptation from Shrestha and Uprety (2021)

Figure 38: Governance structure for water in Nepal, at the federal level

Nepal's private sector plays a significant role in the solar energy domain, particularly in collaborating with iNGOs to initiate pilot projects for introducing SIPs in the country. Over the years, the private sector has been instrumental in developing and field-testing innovative business models through partnerships with development partners, financial institutions, iNGOs, and different levels of government.

AEPC collaborates with the private sector to promote SIPs and disburse SIP subsidies to farmers. Over 80% of SIP applications are received through private SIP service providers (Pandey *et al.*, 2020). Further, private sector entities assist farmers in preparing necessary documentation to apply for subsidies, conduct feasibility studies, and generate reports required to obtain subsidies from AEPC (*ibid*). However, one drawback of private sector involvement has been their focus on collecting applications primarily from better-off farmers, which may undermine some of the equity and inclusion policy goals.

AEPC annually compiles a roster of solar energy companies qualified to provide installation services. These pre-qualified solar companies are authorized to install AEPC-subsidized SIPs, and currently, there are over 50 such companies in Nepal. Gham Power, a prominent service provider, conducted a survey of 30 SIPs installed in Bara, Rautahat, and Sarlahi districts. According to this, after the installation of SIPs, agricultural production increased by 10.24%, and farmers' income rose by 16.32%. This positive impact led many farmers to shift from subsistence farming to commercial agriculture, with a majority transitioning to vegetable farming. Almost all surveyed farmers expressed satisfaction with their systems and reported a reduction of 7.6% in their agricultural expenses (Gham Power, 2019). Other prominent players active in the solar pump domain in Nepal include Sunbridge and SunFarmer.

Besides government agencies and private players, GIZ Nepal has a significant program on solar water pumps. ICIMOD, IWMI and Winrock International have undertaken several studies on solar water pumps in Nepal and have also seeded field experiments and action-research pilots. With support from SDC, IWMI has developed a bilingual training manual on solar irrigation pumps[7].

5. Business Models

a. Grant Model

This is the most popular mode of deploying solar pumps where the government or sponsoring organization offers a portion of the project cost as a subsidy, and the farmer or user group pays the balance up front. This model works particularly well for early adopters since it has a quick impact after deployment and incurs few transaction costs. However, because it requires significant capital subsidy as well as on-going support, its long-term viability is uncertain. AEPC offers a 60% grant to farmers under the renewable energy subsidy policy of 2016. One ongoing challenge with this model is the determination of unit costs. At the beginning of each fiscal year, AEPC determines and sets the MRP (maximum retail price) for each component that is offered to farmers on subsidy. This determination may or may not reflect the true cost of components in the open market. In the past, ICIMOD programs have offered 60% subsidy to male farmers and 70% to female farmers. The additional support encourages more applications from women farmers and aims to reduce land ownership disparities (Mukherji *et al.*, 2017; Foster *et al.*, 2017).

b. Rent-to-Own Model

With the Rent-to-Own (RTO) or Pay-as-You-Go (PAYGO) business model, farmers can rent SIPs without requiring a deposit by making recurring monthly or seasonal payments over a certain period. The farmer owns the system once s/he has fulfilled the terms of the rental agreement. The AC-PVWP and ICIMOD projects also used this model extensively, with 48% and 34% of implementations respectively. In the ICIMOD initiative, the SIP service provider received the first grant money, with the remaining funds being spent in the systems that were rented to farmers. Farmer gender made a difference in the leasing costs, which eventually led to ownership after three years. Local cooperatives and Nepal's private SIP service providers, like SunFarmer Nepal, collaborated to put this idea into practice by providing affordable finance and sustaining

[7] Available here: https://solar.iwmi.org/wp-content/uploads/sites/43/2023/05/Training-manual-on-solar-irrigation-pumps-2023.pdf

c. *Grant plus Loan Model*

In this model, a portion of the project cost is provided as a grant, with the farmer covering the balance through a loan and equity combination. This enables customisation depending on the financial situation of the farmer, encouraging them to continue using SIPs until the loan is repaid (IRENA 2016). However, long-term operation and ownership may be jeopardized if farmers receive SIPs without an upfront equity contribution, adding risk to the loan. This model was the most sought-after in ICIMOD SIP projects in Saptari, with 46% more demand than other models.

In contrast to female farmers, who paid 15% equity and took-on a 15% loan with a 70% grant, male farmers received a 60% grant, made a 20% equity contribution, and took out a 20% loan. Financial institutions need to be encouraged to provide accessible and affordable loans, especially for under-served groups like women farmers and minorities. Winrock International implemented 23% of the project under the AC-PVWP project using a similar approach. According to SunFarmer (2015), 60% of the cost of projects was covered by grants, 20% was financed by SunFarmer with a 5% interest loan, and the other 20% was covered by up-front payments from farmers. The SIP itself frequently serves as collateral in this strategy, which also encourages financial inclusion for vulnerable and landless farmers. After successful loan repayment, farmers receive full ownership of the asset.

6. Way Forward

Nepal's solar pump landscape can be seen in two distinct segments. In the Upper and Middle Himalayas, the remoteness of habitations, nature of hill agriculture, and the need to lift water over long distances make solar pumps attractive for multiple use systems, often involving multi=-stage pumping. In the *Terai* region, on the other hand, abundant shallow groundwater, the potential for intensive irrigation and cultivation, poor grid infrastructure and rural power supply environment, and rising cost of diesel make solar irrigation pumps attractive – provided they are promoted through smartly designed subsidies and equitable financial products.

Nascent supply chain, risk of elite capture, fragmented land holdings, and limited awareness are some of the key challenges in upscaling solar pumps. Despite these, solar pumps have tremendous potential in Nepal, especially with a growing recognition among policy makers that high dependence on hydropower will be difficult in the context of climate change. Particularly in the *Terai* belt, a smartly designed solar pump promotion program can be an instrument for sustainable intensification of agriculture. In the Himalayas, solar pumps designed for meeting multiple demands can help address growing scarcity of water for domestic use as well as for protective irrigation.


Hamish John Appleby/IWMI

Sri Lanka

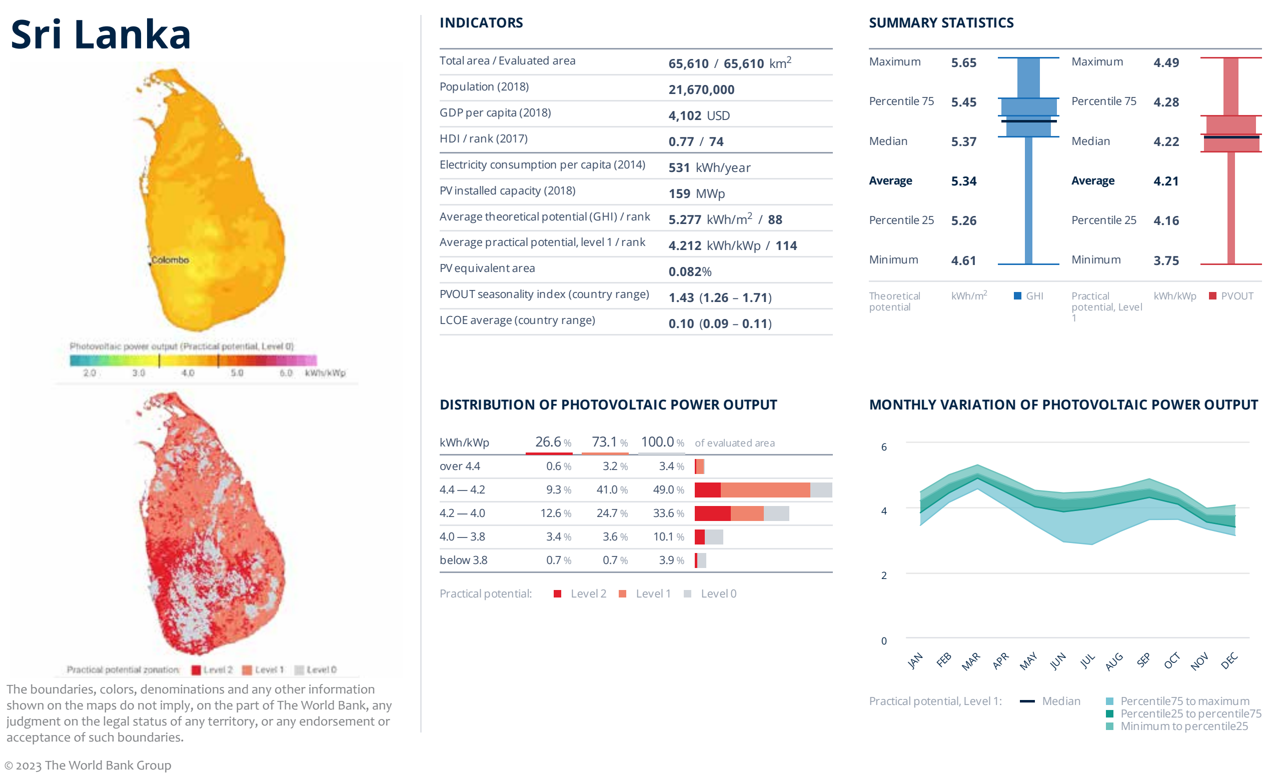
Emerging Solar Phoenix

F. Sri Lanka: Emerging Solar Phoenix

Owing to its proximity to the equator, Sri Lanka receives considerable amounts of solar radiation. The island country set ambitious plans to enhance the share of renewable energy in the energy mix – targeting 70% electricity generation from renewable sources by 2030 and carbon neutrality by 2050[8]. The Sri Lanka Sustainability Energy Authority (SLSEA) was established in 2007 as *"a key institution which would drive energy efficiency throughout the island by proactively identifying sustainable energy resources which could generate energy in an effective, efficient and eco-friendly manner"*[9].

The current energy generation capacity of approximately 6,048 MW (2024) comprises 55% from renewable energysources and the remaining from thermal oils (13%) and coal (32%) (MoPE 2024). Despite recent economic hardships, Sri Lanka has managed to expand installed solar capacity from 13 MWp in 2013 to 714 MWp by 2022, growing the share of solar in Sri Lanka's total renewable energy capacity from 10% to 25% (IRENA 2023*a*).

Most farmers in Sri Lanka use diesel pumps for irrigation as farms are often away from electricity grids. This entails very high cost for farmers and imposes a high forex burden on the economy. Grid connected farmers who use electric pumps were earlier offered concessional tariffs (lower than cost-to-serve) but after recent tariff reforms, they are now charged as per full cost recovery. For both these reasons, there's strong interest in solar pumps in the government as well as from farmers. Some better-off farmers have already invested private capital to instal solar pumps, but poor farmers are not able to invest, and in some cases, have resorted to giving up cultivation altogether, owing to high irrigation cost. Sri Lanka's solar pump program should therefore



Source: Global Solar Atlas 2.0

Figure 39: Photovoltaic Power Potential and related indicators for Sri Lanka

[8] https://climatepromise.undp.org/what-we-do/where-we-work/sri-lanka

[9] https://www.energy.gov.lk/index.php/en/about-us/inception

target these poor farmers and the objective should be to deliver the benefits of solar technologies to them through inclusive business models and financing mechanisms.

The country also has active solar rooftop (*Soorya Bala Sangramaya*) and solar parks program. Large, centralized solar plants have been implemented, with a combined capacity of around 15 MWp. Solar rooftop is implemented either with net metering (households are offered energy credits) or with net payment mode (FiT sometimes lower than electricity tariff charged to households). Unlike in countries like India, there is no capital cost subsidy offered for installation of solar rooftop systems.

The cost of solar installation in SL is roughly LKR 350,000 (~USD1400-1500) per kWp for small-scale deployment and roughly USD900-1000 per kWp for large-scale installations. A recent study estimated the investment required and benefit-cost ratios for installation of solar pumping system for sugarcane cultivation in different locations and using different irrigation methods (Wijayawardhana *et al*. 2023; Table 7).

With a tourism economy still recovering from the effects of CoViD-19 and the economic crisis that followed, Sri Lanka has been able to make little progress on solarization. With support from the Global Green Growth Institute (GGGI), the SLSEA has prepared a (draft) pre-feasibility report (submitted to ISA) for piloting solar pumps in the country. The report includes detailed mapping of solar and water resources and projects a demand for 2000 small-capacity solar pumps.

Table 7: Benefit-Cost ratio for solar pumps in Sri Lanka

Irrigation Method	Location	Total Initial Cost (LKR/ha)	Cost/ha/year (LKR)	Revenue (LKR/ha/year)	B/C Ratio
Furrow Irrigation (Tube Well)	Sevanaagala	729,990	65,699	100,000	1.52
	Pelwatta	729,990	65,699	80,000	1.22
	Hingurana	766,656	68,999	100,000	1.45
	Kantale	766,656	68,999	80,000	1.16
	Kilinochchi	638,325	57,449	200,000	3.48
Drip Irrigation (Tube Well)	Sevanaagala	546,660	49,199	100,000	2.03
	Pelwatta	546,660	49,199	80,000	1.63
	Hingurana	564,993	50,849	100,000	1.97
	Kantale	583,326	52,499	80,000	1.52
	Kilinochchi	491,661	44,249	200,000	4.52
Furrow Irrigation (Agro-Well)	Sevanaagala	344,997	31,049	100,000	3.22
	Pelwatta	344,997	31,049	80,000	2.58
	Hingurana	344,997	31,049	100,000	3.22
	Kantale	344,997	31,049	80,000	2.58
	Kilinochchi	344,997	31,049	200,000	6.45
Drip Irrigation (Agro-Well)	Sevanaagala	289,998	26,099	100,000	3.83
	Pelwatta	289,998	26,099	80,000	3.07
	Hingurana	289,998	26,099	100,000	3.83
	Kantale	289,998	26,099	80,000	3.07
	Kilinochchi	289,998	26,099	200,000	7.66

Source: Wijayawardhana et al. (2023)

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Shashwat Cleantech Pvt. Ltd.

Scaling Solar Pumps in South Asia

G. Scaling Solar Pumps in South Asia

By the end of 2022, global off-grid solar pump deployment breached 1.35 GWp of installed capacity; 86 per cent of this has been deployed for use in agriculture and more than 96 per cent is in Asia. At more than 1250 MWp, India is a distant front-runner, followed by Bangladesh (49.3 MWp), Ethiopia (17.6 MWp), Rwanda (6.7 MWp) and Nepal (3.2 MWp) (IRENA 2023).

In South Asia, solar pumps have caught the fancy of farmers, developers, civil society actors, and policy makers alike. Farmers view solar pumps as a means of accessing reliable, affordable, and clean energy for pumping water. The pumps can rid them from the uncertainties of rural grid power supply and the high cost imposed on them by diesel-powered pumps. Developers and the private sector realise the huge potential offered by the market for solar pumps. Our rough estimate (Table 8) suggests that the region has potential for more than 25 million solar pumps, amounting to a market size of roughly USD 120 billion – large and lucrative for any private developer. Civil society actors and development partners have advanced decentralized renewable energy deployment – particularly solar pumps – as a means for extending energy and water access and security for poor and marginalized groups and communities. Finally, policy makers too have realised that solarizing pumps can contribute significantly to national RE targets while delivering several co-benefits such as enhancing strategic energy security, reducing carbon footprint, advancing rural livelihoods, enhancing the economic viability of rural power utilities, and significantly reducing reliance on imported fossil fuel. The growing interest and government intent in the region suggests that large-scale deployment of solar pumps in South Asia is inevitable. The only variable is how quickly this will happen and to what extent will supportive policies and smart deployment strategies be able to maximize the net positive impact of such a solarization of the region's pump economy. In this report, we have reviewed in detail, the experience of India, Bangladesh, and Nepal – each of which have ambitious targets of deploying solar pumps. In this chapter, we also look at emerging demand for solar in the rest of South Asia before outlining a roadmap for ADB and ISA to invest in deploying solar pumps at scale in the region.

1. Opportunities in Rest of South Asia

While India, Bangladesh and Nepal have taken an early lead in deployment of solar pumps, the potential of solar pumps in South Asia also extends beyond these countries. Solar pump economies in Bhutan, Maldives, and Sri Lanka, though nascent so far, offer tremendous growth potential and deserve deeper exploration. Compared to countries like India, data, information, and studies available on the solar pump economies of these countries is sparse and this offers an opportunity for the International Solar Alliance (ISA) and Asian Development Bank (ADB) to step-in and make a useful contribution.

Table 8: Solar Pump Landscape in South Asia

PARTICULARS	BANGLADESH	BHUTAN	INDIA	NEPAL	SRI LANKA
RE share in electricity generation | 2022 % (IRENA 2023a)	3.1	99.6	33.7	97.8	58.9
Agricultural Land | '000 Km^2	99.0	5.1	1,790.5	41.2	28.1
PV Installed Capacity | 2022 GWp (IRENA 2023a)	0.45	0.00	73	0.09	0.71
Off-grid Solar Pump Capacity | 2022 MWp (IRENA 2023)	49.331	0.000	1251.704	3.247	0.001
Short-term Target for Solar Pump Deployment	~100,000	-	~2,500,000	~30,000	~2.000
Long-term Potential for Solar Pumps (*Authors' estimates*)	~1.5 million	NA	~23 million	~350,000	NA
Key Government Stakeholder	IDCOL	DRE	MNRE	AEPC	SLSEA

2. Roadmap for Scaling Solar Pumps

That solar pumps have tremendous potential for scaling in South Asia is well established. Our rough calculations show that the economy can outstrip USD 120 billion – driven largely by growing demand for solar-powered irrigation, and to a lesser extent, solar-powered drinking water and multiple use systems.

The last decade has seen a lot of innovation and experimentation in the region to field test business models and deployment strategies. Especially in India and Bangladesh – but also in Nepal, Sri Lanka, and Bhutan – both government and civil society have shown interest in investing in solar. Based on a decade of experimentation and experience in the region summarised here – and some lessons from around the world – we offer ten ingredients essential for deploying solar pumps at scale in South Asia. These can inform and inspire action by the International Solar Alliance (ISA) and the Asian Development Bank (ADB) to catalyse this crucial transformation.

1. **Enabling Policy Environment:** The rapid scaling of solar pumps in India and Bangladesh shows that a clear statement of ambitious policy goals at the highest level can provide the required momentum for deployment at scale. India's aggressive PM-KUSUM campaign and its ambitious targets provided confidence among state governments and the private sector about the potential of the 'solar pump' sub-sector. This also encouraged private sector to enthusiastically work with farmers and better understand their specific needs. Likewise, IDCOL's ambitions in Bangladesh have guided and inspired both public and private investments into solar pumps. In Nepal, AEPC is constantly collaborating with development partners and provincial governments to extend the reach of solar pumps. While solar pumps did not figure in either country's early RE plans, the potential of solar pumps to contribute to national ambitions has been (belatedly) recognised.

2. **Fitting Models to Contexts:** Programs designed to implement at scale always face a trade-off between the merits of standardisation and the need for customisation. Our deep dives into the experience of India, Bangladesh and Nepal shows that solar pumps will require different technical, financial, and institutional deployment models, depending on the local context. This need for customisation is accentuated with advancements in the technology itself – with new possibilities and models getting field tested routinely. The challenge acquires another layer of complexity when implemented through a federal government structure, in balancing the role of national, provincial and local stakeholders. India's PM-KUSUM campaign started with three broad components or models, but civil society led field programs continue to experiment with new models and deployment strategies. Likewise in Bangladesh and Nepal, while national programs have preferred the standardisation route, action on the ground highlights the diversity needed for successful deployment. Some attempts have been made for matching different business models and deployment strategies to the diverse physical, agroecological and socio-economic contexts presented in the region – but more is needed.

3. **Unit Costs:** The market for solar pumps is and will likely remain highly price sensitive. South Asian agriculture is replete with examples of technologies that struggled to achieve scale despite positive Benefit-Cost ratios simply because their pay-back period was high. Perpetually starved for cash and investible capital, small and marginal farmers are reluctant to invest in solutions that offer economic returns in 8-10 years. Even when adoption is supported and enabled by capital subsidies, the overall scale of deployment is determined by unit costs. Especially in India, but also elsewhere in the region, the sector has seen significant reduction in cost per watt-peak of installed capacity over the past decade. This has happened despite the disruptions to supply chains and volatility in the prices of raw materials. Just as the tariffs for MW-scale solar plants, the unit cost of solar pumps has been declining steadily. While some of this reduction can be attributed to improvements

in technology and the efficiency of solar panels, much of it has been catalysed by the scale of current and potential for future deployment. India has been aggressively trying to encourage domestic production (and fabrication) of solar panels in the hope that this would boost local employment generation while also bringing down costs – with mixed results.

4. **Financing:** A key bottleneck in scaling solar pumps is the lack of investible capital with end users and the paucity of appropriate financial products and financing mechanisms – both for end users as well as promoters. In South Asia, an overwhelming majority of solar pumps have been deployed with high capital subsidies – often offered through government programs, and in some cases, through donor-led initiatives. These subsidies have catalysed adoption by around half a million end-users but have also distorted the market. Solar pump market is a 'B2G' (Business to Government) market with end users often having minimal interaction with solar pump manufacturers as well as financiers. Retail bankers are often reluctant to offer loans for solar pumps due to various factors including lack of awareness, lack of clear financing mechanisms and policies, and limited development of a secondary market. This is an area which requires significant work if solar pumps are to be scaled meaningfully.

5. **Right Sizing:** When solar pumps are offered with high capital subsidies, there's a natural tendency to oversize PV-array installations. This tendency gets accentuated by the seasonal nature of pumping demand and the uncertainty surrounding future pumping needs. Indiscriminate over-sizing of solar pumps can lead to wasteful use of scarce public and private resources. Likewise, under-sizing of solar pumps can affect confidence in the technology and limit future market growth. In India, the Ministry of New and Renewable Energy (MNRE), Government of India requested GIZ, IWMI, BISA and ICAR to collaborate and develop a scientifically robust solar pump sizing tool. The Beta version of the tool – developed using the MS excel platform – has been adopted for use in PM-KUSUM. A similar tool for AEPC in Nepal is currently under development.

6. **Optimum Utilization:** Solar pumps are expensive assets where return on investment (ROI) is driven by how well the assets are used to service needs. However, the demand for pumping water – both for domestic use as well as for irrigation – is highly seasonal. Deployment with high capital subsidy and zero marginal cost of operating the pumps can encourage low utilization. The ultimate, long-term solution is to grid-connected all solar pumps such that any surplus energy available can be fed-back to the grid for an economic return. This will also incentivise efficient energy and water use (as piloted in SPaRC) and create a stable revenue stream for end users, making financing solar pumps more appealing to bankers. However, in contexts where grid-connecting solar pumps is not an option, work is required to utilize the surplus solar energy available for other productive uses. While several experiments have been done to find such solutions, we are still far from finding an elegant solution.

7. **Solar Sisterhood:** The South Asian experience over the last decade has demonstrated that scaling solar pumps requires context-specific models that will need to be tweaked to fit the local contexts. This also presents opportunities for cross-fertilization of ideas and learning across similar socio-ecologies. For technological advancements to cross political borders, smart trade policies will need to be designed. More importantly, robust documentation and synthesis of insights and learnings from field testing different financial and institutional models from across the region can help avoid duplication of mistakes and catalyse rapid uptake. A dynamic 'Solar Sisterhood' program that links provinces / districts with similar hydro-agro-ecological and socio-economic contexts can go a long way in supporting such

a knowledge exchange. As the early adoption hub of solar pumps, South Asia will also act as a 'lighthouse' for solar pump expansion globally. Especially for the International Solar Alliance (ISA), facilitative south-south learning and knowledge exchange offers a great opportunity.

8. **Awareness and Capacity:** Even with more than half-a-million deployments, solar pumps are few and far in-between. If the first decade of solar pump deployment has been about establishing the technology's credibility, the next decade must focus on establishing an entire value chain of trained users, policy makers, professionals, bankers, and investors. This involves providing training and capacity building to all stakeholders, especially farmers, who play a critical role in the adoption and success of solar irrigation systems. Fitting models to contexts is the most crucial aspect of agri-solarization.

9. **Sustainability and Equity:** The advent of any new technology has the potential to reshape incentives and power dynamics. Solar pumps are no exception and while they will offer affordable and reliable access to energy for pumping water, the zero-marginal-cost at which this energy will be made available can also create perverse incentives for over-pumping of water, especially groundwater in geographies where water tables are already declining, and aquifers are threatened. At current costs, solar pumps are beyond the reach of most small farmers in South Asia. Farmers therefore require subsidies and public resources to be able to deploy them. The design of subsidy programs also needs to pay special attention to issues of gender equity and social inclusion (GESI) to ensure that the benefits of solar pumps do not remain limited to the privileged few. In fact, smartly designed subsidy programs can help reduce existing inequities.

10. **Decision Support Systems:** Mapping contexts to models and strategies, designing innovative solutions, facilitating cross learning and training, tools for right sizing, financing and optimal utilization – each of these will require robust decision support tools. Making all such tools accessible and available to users and integrating them into decision support systems – for enabling public and private investments, supporting smart program design and informing effective policy making – is another key ingredient for successful deployment of solar pumps at scale in South Asia.

3. Some Immediate Actions

1. **Regional Learning Event:** The report has tried to capture a decade of experience in the rapidly evolving sub-sector of solar pumps. A regional / global learning event where this synthesis can be widely shared with key stakeholders and others can be invited to share their work can significantly enhance the utility of this exercise.

2. **Detailed Assessment in Bhutan, Sri Lanka, and Maldives:** Our current report relies largely on secondary data / literature and limited interactions with key stakeholders in the study region. The available literature on solar pumps in South Asia is dominated by the events in India and Bangladesh, and to a lesser extent, Nepal. Given how rapidly the sub-sector is evolving, there is a case for a detailed first-hand assessment of investment opportunities in solar pumps in each of Bhutan, Sri Lanka, and Maldives.

3. **Solar Pump Innovation Fund:** The potential for solar pumps is massive and the current scale of programs is limited by the available subsidy-kitty. Eventually, scaling would require business models that rely less on subsidies and more on capturing the private market for pumping equipment and pumping services. Despite significant private sector interest and investments, few government programs create room for field testing innovations. A regional / global solar pump innovation fund that combines grants and preferential financing can boost the sector and encourage product

innovations that are currently inert.

4. **Solar Pump Sizing:** A robust tool for 'right sizing' of solar irrigation pumps has already been designed for India – and adopted by the government of India for use in PM-KUSUM. A similar tool for use by AEPC in Nepal is currently being developed by IWMI and ICAR, with support from GIZ. Developing similar tools for other countries in South Asia – particularly Bangladesh, Bhutan, and Sri Lanka – can enhance confidence and encourage public and private investments.

5. **Regional Learning Platform:** Given the rapid strides being made in the sub-sector, support for a regional hub / platform would be most welcome. The hub maybe hosted in ISA or any other international organization with expertise and presence across the region. The platform can: [1] act as a repository of global knowledge around solar pumps; [2] act as a clearing house and help connect demand for solar pumps with suitable suppliers; [3] develop and deliver awareness campaigns, training programs and technical backstopping for solar pump users and stakeholders; and [4] help countries develop projects, design programs and formulate effective, inclusive and sustainable policies for deployment of solar pumps at scale.

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