2018
03

IWMI
International Water Management Institute

IWMI-TATA
Water Policy Program

DISCUSSION PAPER (SDC-IWMI Special Issue)

Solar Irrigation for Agriculture Resilience (SoLAR)

A New SDC-IWMI Regional Partnership

Shilp Verma, Divya Kashyap, Tushaar Shah, Marylaure Crettaz and Alok Sikka

TATA TRUSTS

ICAR

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Agency for Development and Cooperation SDC

CGIAR
RESEARCH PROGRAM ON Water, Land and Ecosystems

CGIAR
RESEARCH PROGRAM ON Climate Change, Agriculture and Food Security
CCAFS

Solar Irrigation for Agriculture Resilience (SoLAR)*

Shilp Verma, Divya Kashyap, Tushaar Shah, Marylaure Crettaz and Alok Sikka

1. The Water-Energy-Climate Context

There is a growing recognition that the energy system is intertwined with other global systems like water, climate change and food production systems. By 2050, global demand for energy will nearly double, while water and food demand is set to increase by over 50 per cent. Meeting this surge of demand presents a tremendous challenge, given competing needs for limited resources amid heightened climate-induced uncertainty.

Water is required for extracting and processing fossil fuels as well as for generating electricity from various sources. Energy supply presently accounts for nearly 15 per cent of global freshwater withdrawals annually. As a consequence, the availability and accessibility of water resources for fuel extraction, processing and power generation represent a key determinant for energy security. Conversely, disruptions in the provision of energy services, which are essential for water treatment, production and distribution, also have direct implications for water security. Today, the amount of energy used in the water sector is almost equivalent to the entire energy demand of Australia (IEA, 2016). Energy consumption of the water sector worldwide was 120 Mtoe (Million tonnes of oil equivalent) in 2014; a majority of this is used to pump groundwater for agricultural purposes. In fact, the agri-food supply chain alone accounts for 30 per cent of the world's energy consumption and approximately 70 per cent of all freshwater use.

The issue of energy-water nexus is especially acute in the populous South Asian region where groundwater irrigation is the mainstay of irrigated agriculture in much of India, the Punjab and Sindh provinces of Pakistan, the *Terai* region of Nepal, and Bangladesh. Farmers in this region deploy more than 25 million pumps to irrigate their fields. In Bangladesh, peak electricity demand during the irrigation season increases by almost a quarter, and over 25 per cent of annual diesel use is linked to agriculture (BPC, 2014). In India, agriculture consumes about 18 percent of the total electricity and about 15 per cent of the total diesel (IEA, 2015)[1]. It is estimated that South Asia uses energy worth US$3.78 billion per year to pump approximately 220-250 km^3 of groundwater, mostly for irrigation. Recent studies on greenhouse gas emissions from the water sector highlight that in countries like India, lifting water for irrigation can contribute up to 6 per cent of total national greenhouse gas emissions. Also with the land area under irrigation expanding, water tables have dropped and deeper aquifers and more distant freshwater sources are being tapped. Continued expansion in groundwater use, its impact on declining water tables, demand for energy, dependence on oil imports and the cost to the power sector are highly relevant for the Asian region where neither energy nor water prices reflect the true cost of supply.

Provision of energy to ensure access to affordable irrigation in a sustainable and resource efficient manner has become a global challenge, particularly in the context of climate change. Heat waves and persistent periods of drought increase local demand on water and (supplementary) irrigation. Under the "business as usual" projections, energy requirements for agriculture are set to increase by at least 84 per cent by 2050 because of impacts of climate change. At the same time, wide spread water scarcity has led to shutting down of thermal power plants in Maharashtra (Parli, Chanderpur) and Karnataka (Raichur), West Bengal, a situation which is likely to worsen due to climate induced variability in the region's rainfall patterns. Rapid decline in groundwater tables in the 'rice and wheat' belt of Indo-Gangetic Plains could have implications for groundwater availability in neighbouring countries such as Bangladesh, Nepal, Pakistan and Myanmar that India shares trans-boundary aquifers with. Energy-Water nexus, is fast emerging as a key security-of-supply risk for both the energy and water sectors in entire South Asia.

2. South Asia's Energy-Groundwater Juggernaut

In South Asia, the practice of well irrigation is more than two thousand years old. The earliest mention of it can be found in the *Arthshastra* (third century B.C.) where a distinction is made for lands irrigated with wells, and a higher land revenue assessment is recommended for such land parcels. Abu-al-Fazl wrote that "*most of the province of Lahore is cultivated with well-irrigation*". Shah (2009) estimates that around the year 1800, two million hectare of farmland was irrigated by wells run on muscle-power – both human and bovine. Even in those days, the energy needed to lift well water defined the extent and scope of well irrigation expansion. For centuries, well irrigation was limited by the laborious and limited technologies of lifting water: the leather bucket

* The opinions, analysis, interpretations and recommendations expressed herein do not necessarily reflect the views of the Swiss Agency for Development and Cooperation (SDC) or the International Water Management Institute (IWMI).

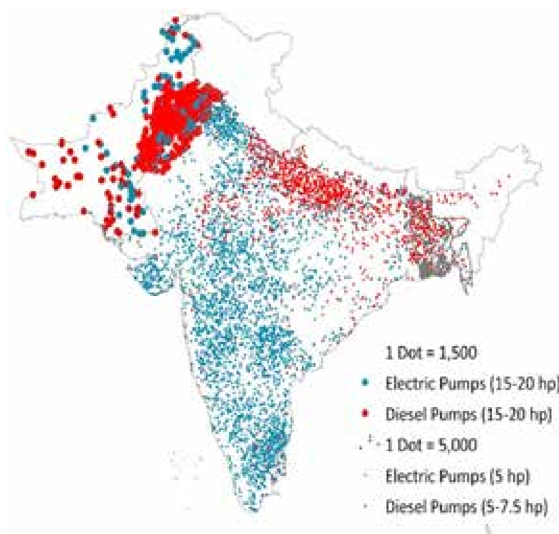
[1] In 2013-14, agriculture sector used 166,712 million kWh of electricity and government provided USD 10.98 billion in subsidies (IAI *et al*. 2016).

(*charasa*), the swing basket and the bamboo basket (*dhenkuli*). Well irrigation got a major boost with the invention of the *Persian Wheel*; a significant improvement over the traditional *Charasa* (Hardiman 1998). Over time, the wooden frames of the early Persian wheels were replaced by iron; the heavy earthen buckets gave way for lighter aluminium; metal roller bearings helped reduce friction; and towards the end of the nineteenth century, muscle power was mostly replaced by diesel-engines and electric-motors.

Meanwhile, the arrival of the British in undivided India saw a shift in emphasis and significant public investments in gravity-based surface irrigation systems. During what is known as the 'Cotton-Cautley Era'[2], the East India Company, and later the British Crown, saw an opportunity in irrigation to combine the "*interests of charity and the interests of commerce*" (Whitcombe 2005). As a result, independent India and Pakistan inherited irrigation establishments dominated by the civil engineering profession and focused almost exclusively on public canal irrigation. It wasn't until the mid-1960s that well irrigation regained prominence in South Asia owing to a multitude of techno-economic drivers.

In the 40 years between 1973 and 2013, South Asia's irrigated area almost doubled from 49.6 mha to 98.0 mha. Given that groundwater irrigation was limited till 1970 and that it reached 55.5 mha in 2013, we can surmise that much of the irrigation expansion in the region over this period was attributable to the spread of groundwater irrigation. Rapid rise in the numbers of wells and tubewells; and mechanized irrigation pumps are, by far, the best indicators of this 'silent revolution' in South Asia. In India, mechanised pumps were just around 5,000 in 1951 (Dhawan 1982); but their numbers soared to 19 million by the turn of the millennium. In Bangladesh, the total number of shallow tubewells increased from 45,000 in the early 1980s to more than 800,000 by the end of 1990s (GoB, 2001); today the number exceeds 1.2 million. While tubewell irrigation accounted for just 15 per cent of irrigated area in Bangladesh in 1980, by 2000, this had increased to 71 per cent; low-lift pumps on surface water bodies accounted for another 15 per cent (GoB, 2003). In Pakistan, tubewell numbers increased from less than 200,000 in 1980 to 1.1 million in 2015 (see Figure 1).

Figure 1: The spread of groundwater irrigation in South Asia



A lot of factors led to the phenomenal rise of the 'colossus' of groundwater irrigation in South Asia. Improvements in drilling and pumping technologies and a steady decline in their cost; government support and aggressive promotion; investments in rural electrification; introduction of green revolution technologies; the provision of institutional credit to farmers; the growth of a cottage industry for drilling and maintaining groundwater irrigation assets; poor performance of public irrigation systems; growing demographic pressure on land for intensification; politics of farm power subsidies; growth of irrigation service markets; decline of traditional community-led irrigation systems; and even changing rainfall and climate – all contributed. Today, no region in the world uses as much groundwater as South Asia.

On the positive side, South Asia's groundwater juggernaut has all but freed the region from famines and large-scale starvation. It has also helped lift millions of poor, smallholder farmers out of poverty. In fact, some scholars have attributed the success of 'Green Revolution' largely to the advent of tubewell irrigation. On the other hand, the unsavoury aspects of this boom include numerous pockets of severe groundwater depletion and the rising carbon footprint of irrigated agriculture. Above all else, unplanned and unregulated expansion of groundwater irrigation threatens the viability and sustainability of smallholder agriculture in the region.

The next section describes eight unique energy-groundwater interaction scenarios / settings (EGIS) that have taken shape in South Asia over the past few decades. The eight settings represent a diversity of agro-climatic and hydrogeological contexts, stages of groundwater development, farm power supply and tariff regimes and governance challenges across the sub-continent.

3. Energy-Groundwater Interaction Scenarios (EGIS) in South Asia

Figure 2 illustrates eight broad energy-groundwater interaction settings (EGIS) that define different patterns of interplay between energy and groundwater within South Asia. The built-in legend provides key summary statistics about the 8 EGIS. The effective cost of energy for groundwater irrigation in the sub-continent ranges from US$ 0/ megawatt hour (mWh) to US$ 600/mWh[3].

[2] 1830 – 1947; Sir Arthur Cotton and Major Proby Cautley were British engineers who did pioneering construction and rehabilitation work in irrigation in south and north India respectively.

[3] A litre of diesel delivers 34,400 BTU of heat energy equivalent to around 10.2 kWh at 100% efficiency. Diesel pumps in South Asia operate at 25-30% efficiency and a litre of diesel does work equivalent about to 3 kWh. At May 2018 prices, the effective cost of 1 mWh in diesel pump irrigation is US$ 390 in India, US$ 283 in Pakistan, US$ 234 in Bangladesh and US$ 240 in Nepal. Studies on South Asian water markets suggest that hourly irrigation price is generally 1.5-1.8 times the cost of diesel use per hour, which means that water buyers bear much higher energy cost. This led us to estimate energy prices in EGIS 2 and EGIS 4 as US$ 350/mWh and US$ 250/mWh respectively. Farm power tariffs in West Bengal and Bangladesh are US$ 55-100/mWh and US$ 48/mWh respectively; this led to our estimate of US$ 65/mWh in EGIS 3. For Indian states falling under EGIS 5 and EGIS 6, farm power tariffs have been sourced from the documents of different state electricity utilities; amounting to less than US$ 5/mWh. For Balochistan and KPK provinces of Pakistan, EGIS 5, farm power tariff set by government varies from US$ 45-85/mWh. However, reports indicate less than 5% realisation from farmers (The Express Tribune, 2017), which makes farm power estimates close to US$ 2-5/mWh.

EGIS 1: Groundwater use in agriculture is insignificant

The region covers the Himalayan mountain ranges in India (Jammu & Kashmir, Himachal Pradesh, Uttarakhand, Sikkim, Arunachal Pradesh, Nagaland, Manipur, Mizoram, Tripura and Meghalaya) and Nepal. In eastern and western Himalayas, there are significant water implications projected under different climate change scenarios. The flow regimes in snow-melt rivers will be affected as temperatures rise, glaciers melt and precipitation events become more extreme and uncertain. However, in terms of water use, especially groundwater use in agriculture, this region differs from the rest of South Asia. Most agriculture in the region is high value despite being rainfed, or only mildly irrigated – horticulture, orchards, plantations etc. At the same time, the region also has high potential for hydropower generation.

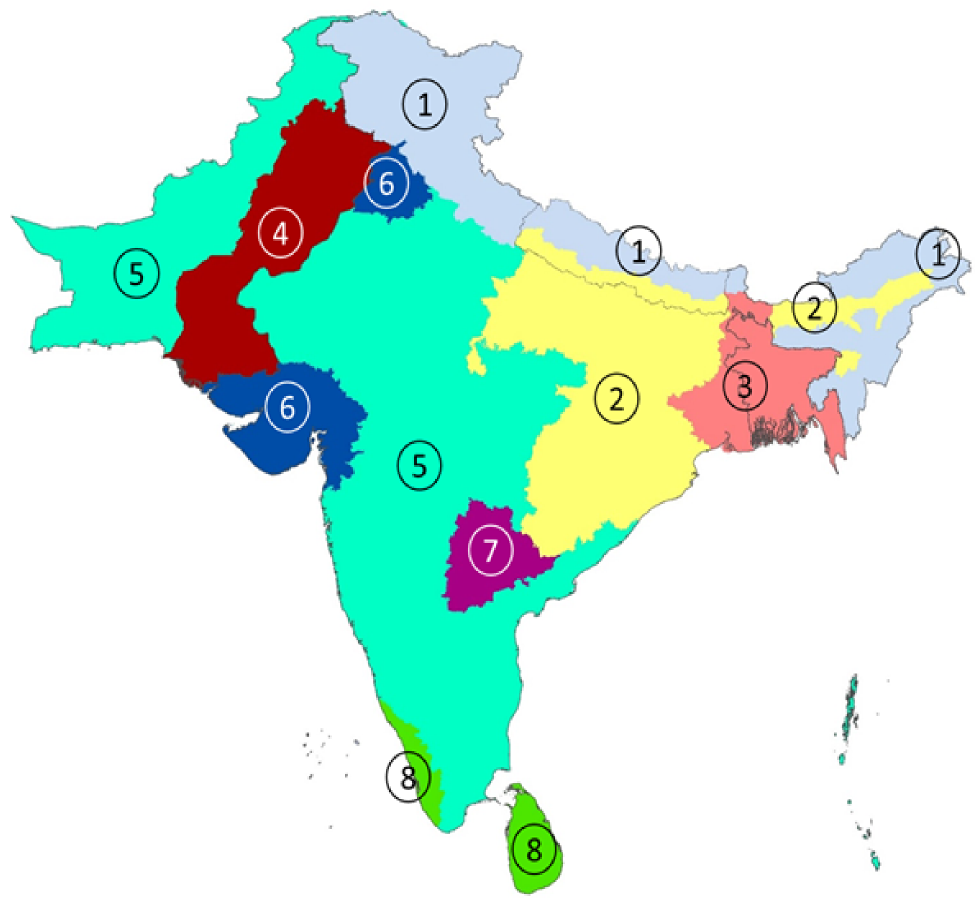
EGIS 2: High energy cost limits the livelihood potential of abundant groundwater

This region, comprising of Nepal Terai, plains of eastern India and Bangladesh, sits on one of the world's largest aquifer systems and is also home to arguably the largest concentration of rural poverty outside Sub-Saharan Africa. Rural electricity grid in this region is either completely missing or does not service the agriculture sector. Agricultural productivity is low as farmers, forced to use expensive diesel for irrigation, tend to under-irrigate their crops.

EGIS 3: Full-cost pricing of farm power works against the poor

For two decades, agricultural growth in West Bengal was stifled by a perverse and restrictive permit system that made it difficult, costly and time-consuming for farmers to get electricity connection for a tubewell. In 2011, through a radical move, liberalization of permits made it easier, cheaper and quicker for farmers to install electric tubewells. Increased tubewell density increased irrigation access to well owners as well as water buyers. However, a parallel policy of metering electric tubewells and charging farmers commercial tariff all but nullified gains to water buyers who now have to surrender the bulk of the irrigation surplus as water price. Even as farmers in western and peninsular India; and in Balochistan and NWFP in Pakistan receive highly subsidized or free farm power, West Bengal farmers face a peak-time tariff of ₹7.48/kWh, more than anywhere else in South Asia.

Figure 2: Eight Energy-Groundwater Interaction Scenarios (EGIS) in South Asia



Legend	Region	Hydro-Geology	Defining Feature	Energy Cost (US$/MWh)	Objective of GW Governance
	EGIS 1: Mountain South Asia	Humid / Alluvial	Insignificant GW Use in Agriculture	N.A.	*Calibrated, Planned Development*
	EGIS 2: Nepal *Terai*, Eastern India (excl. WB)	Humid / Alluvial	GW Irrigation dominated by Diesel pumps	US$ 350	*Accelerate GW Irrigation for Poverty Reduction & Flood Control*
	EGIS 3: West Bengal and Bangladesh	Humid / Alluvial	Full Cost, Metered Farm Power Supply	US$ 65	
	EGIS 4: Punjab and Sindh Provinces, Pakistan	Arid / Alluvial	GW Irrigation through Diesel pumps with Conjunctive Use	US$ 250	*Planned Conjunctive use of canal and GW for salinity and depletion control*
	EGIS 5: Western and Peninsular India, Balochistan, Khyber Pakhtunwa	Arid to Semi-Arid / Alluvial to Hard Rock	Subsidized, Rationed, Poor Farm Power Supply	US$ 0-5	*Reduce GW withdrawals to match long-term renewable resource*
	EGIS 6: Gujarat, Indian Punjab	Arid to Semi-Arid / Alluvial to Hard Rock	Intelligent Rationing of Farm Power	US$ 10	
	EGIS 7: Telangana, India	Semi-Arid / Hard Rock	24*7 Free Farm Power	US$ 0	
	EGIS 8: Kerala and Dry Zone of Sri Lanka	Humid / Hard Rock	Over-Priced Power	US$ 250	*Sustainable GW use for small farmer irrigation development*

EGIS 4: Co-management of energy and groundwater can promote conjunctive management

In Pakistan Punjab and Sindh, home to the world's largest contiguous irrigation system, farmers use canal water in conjunction with groundwater. Unlike its Indian counterpart, groundwater irrigation is not subsidized in Pakistan Punjab. More than 80% of the tubewells run on diesel and irrigating with diesel costs as much as 63-times more (US$ 190/ha/season) than with subsidized surface irrigation (US$ 3/ha/season) (Bell *et al*. 2014).

EGIS 5: Perverse energy subsidies deepen groundwater crisis

In Balochistan and NWFP (North West Frontier Province) in Pakistan; and in several states in western and peninsular India (Haryana, Rajasthan, Western UP, Madhya Pradesh, central Chhattisgarh, Andhra Pradesh, Maharashtra, Karnataka and Tamil Nadu), more than 80 per cent of the groundwater structures are electrified where farmers have access to highly subsidized or free electricity to pump groundwater. This has led to large-scale groundwater depletion in many parts and the electricity utilities suffer huge losses every year owing to limited or no returns from the agriculture consumers. In India, farm power consumption accounts for nearly 20 per cent of the total electricity consumption and this proportion is much higher in the western and peninsular states. The total farm power subsidy burden of the region would be in excess of US$ 15 billion per year and this region alone would account for more than 150 km^3 (Billion Cubic Meters, BCM) of groundwater withdrawals. Unless this invidious nexus is managed well, climate-induced uncertainties are likely to make the groundwater situation worse, especially for smallholder farmers.

EGIS 6: Intelligent rationing moderates perverse impact of farm power subsidies

Among all the states that offer free or highly subsidies farm power, Gujarat and Punjab manage to ration farm power intelligently in a manner that minimizes losses for the electricity utilities without affecting agricultural output and without any opposition from farmers. Gujarat took the lead in intelligent rationing in 2005-06 when it invested in rewiring the rural electricity distribution network to separate agricultural feeders from the rest under *Jyotirgram Yojana*. Doing so enabled Gujarat to supply 24*7 power to non-agriculture users while rationing power supply to farmers. Farmers in Gujarat get 8 hours of high quality, uninterrupted power according to a pre-announced fortnightly schedule. Over time, several states followed Gujarat's model of feeder separation but Punjab implemented it even better. Electricity utilities in Punjab realized that farmers' demand for electricity is driven by their crop water requirement – which is not constant throughout the year. During times of critical moisture stress, farmers need lots of electricity but on most other days, they can manage with only a few hours of power supply. Punjab's rationing of farm power supply accounts for this variability in irrigation water demand. In fact, Punjab even managed to enforce delayed sowing of paddy by intelligently rationing power supply in the pre-monsoon season. This seems to have had a significant and positive impact on the state's overall groundwater draft.

EGIS 7: Competitive populism threatens to deepen the perverse nexus

Even when farm power is free or subsidized, most states and regions limit the total amount of electricity available to farmers by tightly rationing farm power supply. Farmers in most Indian states, for example, get no more than 6-8 hours of farm power supply per day. Telangana, India's newest state, recently announced unlimited power supply to agriculture. Initially announced as a pre-poll promise by the Indian National Congress party in undivided Andhra Pradesh, the K. Chandrasekhra Rao-led new government in Telangana fulfilled the promise of 24*7, free power to all its 2.3 million farm power connections on 01-Jan-2018. The move is expected to increase total power demand to 11,000 MW at the peak of the *Rabi* season in March 2018 and the state electricity utility has already invested more than ₹126 billion to boost the distribution network to handle the peak demand (Reddy 2018). What this will mean for groundwater depletion is not difficult to imagine. Over the past four years, Telangana has been implementing *Mission Kakatiya* – an ambitious state-wide program to desilt and rehabilitate the state's 48,000+ irrigation tanks. Besides positive impacts on water storage and agricultural output, early assessments of the program indicate significant benefits in terms of enhanced groundwater recharge. All of this is now under threat of being undone by 24*7 free power to agriculture.

EGIS 8: Energy use in agriculture subject to penalty price

While most parts of sub-Himalayan South Asia struggle to manage farmers' almost insatiable demand for farm power, in Kerala and to an even greater extent in Sri Lanka, we find that the farming system has moved away from low value, high water intensive crops like paddy to less water intensive and high value horticulture and plantations. In Sri Lanka, farmers don't mind paying near-commercial tariff because despite high tariffs, electricity bill constitutes a small proportion of the farmers' gross value of output.

4. The Unique Governance Challenge in South Asia

The populous South Asian region's 25-30 million pumps lift approximately 330 – 350 km^3 of groundwater each year to support agriculture-based livelihoods of nearly 700 million smallholder farmers, besides ensuring drinking water security for nearly a billion people and contributing to more than half the industrial output. Roughly, 70-80 per cent of the pumped groundwater is used for irrigation and this pumping accounts for more than a fifth of the total electricity consumption in the region; responsible for 6-8 per cent of the CO_2 emissions. Not surprising then that the fates of the energy, groundwater and agriculture economies of the region are intertwined, especially in the context of impending climate-induced uncertainties. While many countries make intensive use of groundwater but the governance challenge we discuss here refers to a class of issues unique to South Asia, and perhaps north China. Unique because nowhere else does this economy sustain such a large proportion of the population; nowhere else are the stakeholder in this economy so poor; and nowhere else is resolution of these issues so politically sensitive and therefore complex. Elsewhere in the world, hydro-geology, cropping systems, and surface water availability explain the extent and spread of groundwater irrigation. In South Asia, however, energy pricing and supply regimes are the key drivers (Dossani and Ranganathan, 2004; Shah *et al*., 2006).

Meeting the growing water, energy and food demand of South Asia requires serious efforts to address the challenge of maintaining food security at the expense of depleting groundwater, along with high energy consumption. South Asian governments have launched various schemes offering subsidies/ financial support to promote water efficient and renewable energy technologies. Despite recognized benefits, the penetration of these technologies is abysmally low. The reason for this is not only perverse incentives like free electricity and water but also challenges faced by farmers in the financing, adoption and smooth operation of some of these technologies. Also in the absence of changes in agricultural and irrigation practices (requiring, in turn, a strong consultative and educational effort with farmers), adoption of a particular water/ energy efficient technology can potentially have negative impacts on the other resource. For instance, the introduction of efficiency-enhancing technologies like energy-efficient pumps and micro-irrigation can invariably lead to overall increase in resource use (groundwater and energy) (Impact Energy and TERI, 2017). It is therefore becoming increasingly apparent that the siloed approach of managing energy and water is no longer an option. Considering the complex and dynamic interactions between energy and water, a nexus approach enhances resource use efficiency, facilitates effective climate adaptation and encourages policy coherence.

Several governments have deployed different strategies in their attempt to manage the water-energy-climate nexus in South Asia. One relatively successful attempt at reforming and reorganizing the energy sector to better respond to the needs of the agriculture sector was made in Gujarat in 2005-06. Gradual reduction in power supply to farmers had severely deteriorated the rural power supply environment in the state. Attempts by the Gujarat Electricity Board to ration farm supply to farmers were repeatedly defeated by farmer ingenuity. The Board supplied 8-hours of three-phase power and 16-hours of single-phase power to rural areas. This was to ensure that the farmers' irrigation pumps – which require three-phase power – were unable to run for more than 8 hours a day. In response, farmers invented "phase splitters" with which they could convert single-phase supply to two-phase and run their pumps anytime of the day. Though inventive, such fixes were also troublesome. Running the motors on two-phase supply often led to pump and transformer burnout. It also meant that the utility had little control over farm power demand and voltage at feeder tail-end was often insufficient. There were frequent disruptions and breakdowns took longer and longer to repair. At the end, neither the farmers were happy, nor the utilities. What's more, the farmers were holding the rest of the village including rural commercial users to ransom.

In 2005-06, the Government of Gujarat under its *Jyotigram Yojana* invested ~US$ 250 million to completely re-wire the state's countryside. Agricultural feeders were separated from non-agricultural feeders and this allowed more effective rationing of farm power supply while allowing the utility to offer 24*7 power supply to rural non-farm consumers. Agriculture feeders were promised (and delivered) high quality power supply according to a strict but pre-announced 8-hour roaster. These changes were coupled with institutional and organizational reforms in the electricity sector – the electricity board was unbundled and corporatized. Several studies reported significant positive impacts on agriculture as well as the quality of rural life (Shah and Verma 2008; Shah *et al*. 2012) and several states attempted to replicate Gujarat's model, *albeit* with variable results. Punjab is one of the most agriculturally prosperous states in India and has been at the heart of India's agrarian growth through the Green Revolution. Like many other states, farmers get free farm power but Punjab is able to synchronise its farm power supply with agricultural demand much better than any other state. While groundwater depletion continues to be a major threat in the state, some recent policy measures – such as enforcing delayed sowing of *Kharif* paddy – seem to have been extremely effective in checking groundwater extraction.

5. The Advent of Solar Irrigation

It is against this wider backdrop in South Asia that upcoming solar revolution in irrigation needs to be considered. Growing popularity of Solar Irrigation Pumps (SIPs) in South Asia is destined to change the energy-groundwater interaction in all 8 EGIS. The arrival of every new technology opens up a new institutional pathway in its wake (Chlebna and Simmie, 2018); and solar pump technology can create a whole new energy-groundwater nexus, potentially more virtuous and benign, than the one in which South Asia is stuck today. Studies show that SIPs meet the needs of small holders admirably well in the eastern (Kishore *et al* 2014; Durga *et al* 2016) as well as the western (Gupta 2017; Anchal and Thakur 2016) parts of South Asia. In India, from just around 18,000 in 2014-15, SIP numbers have soared to nearly 200,000 in recent years, an annual growth rate of 68 per cent. At this rate, India will have many more solar pumps in 2025 than electric and diesel pumps it has today!

The worry is that SIPs are today promoted with the sole objective of reducing power subsidies whereas they can do much more. Over 90 per cent of SIPs are installed where power utilities are broke offering free grid power to farmers. SIPs have many advantages compared to electric and diesel pumps. They provide affordable and reliable daytime power in South Asia which, at 5-6.5 kWh/m^2/day (Shukla *et al* 2017), has amongst the highest solar irradiation levels in the world. By replacing electric and diesel pumps, they can reduce the carbon-footprint of irrigation and promote green growth. However, SIPs have two downsides, one economic and one ecological. SIPs enjoy near–zero operating cost but require 10-15 times the capital investment compared to diesel or electric pumps. Without 70-95 percent capital subsidy, SIPs would have few takers in India. Such capital-intensive asset becomes viable only with a high utilization rate whereas Indian farmers find diesel pumps viable even at annual operation for just 450 hours (Rajan and Verma 2017).

A 5 kWp[4] SIP costing ₹500,000 (in mid-2017) and operated for just 500 hours/year in irrigation against its potential of 2500 hours—is a poor investment for the farmer and the society. An SIP owner will always be tempted to 'encash' free solar energy by irrigating water intensive crops, increasing cropping intensity and selling more water to neighbours at a low price—all of which will increase groundwater draft, deepening the crisis in parched aquifers. Free or highly subsidized farm power regime is blamed for groundwater over-exploitation in several parts of South Asia, but its destructive impact is limited by restricted hours and unreliable, often nightly supply. With reliable daytime free solar power, SIPs can be way more lethal for sustainable groundwater irrigation than free grid power (Shah 2018; Gupta 2017).

SIPs are being promoted with different financing and subsidy models without understanding the availability of water resources and the potential negative impacts on the environment caused by groundwater over-abstraction. There is a need to develop institutional models to address the limitations of this technology and potential negative impacts within the Water-Energy-Climate nexus. A comprehensive approach is required for nexus thinking in planning and policy-making for water and energy resources, integrating interactions (synergies and trade-offs) between the systems to help adaptation measures (e.g. irrigation, crop inputs) to be less energy intensive and more efficient in resource use; and for climate mitigation measures (e.g. renewable energy, energy efficient agricultural technologies) to be 'water smart'.

6. Current Efforts at Promoting Solar Irrigation in South Asia

We have discussed earlier that most government as well as donor-led programs to promote solar irrigation in South Asia have so far been focussing on delivering high capital subsidies. Table 1 summarizes some of these programs across India, Pakistan, Bangladesh and Nepal. It also cites the rough number of solar pumps already on the ground in different regions and some innovative field experiments and new solar promotion policies. Box 1 and Box 2 summarize some innovative field experiments for promoting solar irrigation.

Table 1: Examples of key solar irrigation pump promotion policies and schemes in South Asia

Region (No. of SIPs)	Solar Irrigation Promotion Program(s)	Scheme Features
INDIA (~150,000)	**National Solar Mission: 100 GW solar capacity by 2022**	**70-90% capital subsidy**
	KUSUM: Announced in 2018; 1.75 million SIPs; 28 GWp	**30-60% subsidy; 30-60% loan**
Rajasthan, India (~25,000)	2-10 kWp individual solar pumps	70-87% capital subsidy
Chhattisgarh, India (~15,000)	Saur Sujala Yojana: 2-5 kWp individual solar pumps	70-90% capital subsidy
Gujarat, India (~10,000)	3-10 kWp SIPs for farmers waiting for grid connections	95% capital subsidy
	SPICE: Solar Pump Irrigators' Cooperative Enterprises (Box 1)	60-90% capital subsidy
	SKY: Feeder-level solar cooperatives	30% subsidy; 60% loan ~₹7/kWh FiT + EBI
	Farm-top solar parks; no capital subsidy	Developer-led model
Bihar, India (~5,000)	Solarization of NABARD Public Tubewells	100% capital subsidy
	Small 0.2-1.8 kWp Mobile Solar Solutions; Pay-per-use model	70-100% capital subsidy
	Solar Irrigation Entrepreneurs: Pay-per-Use model (see Box 2)	50-60% capital subsidy
	Bihar Saur Kranti Sinchai Yojana (BSKSY): Off-grid 2-3 kWp SIPs	90% capital subsidy
Maharashtra, India (<500)	Saur Krishivahini Yojana: Off-grid 3-5 kWp individual SIPs	80% capital subsidy
	Feeder-end 1-3 MWp solar plants; No farmer involvement	No capital subsidy
Karnataka, India (<500)	Surya Raitha: Grid-connected SIPs; ₹7-9/kWh	Subsidy + Loan model
Punjab, India (<500)	2-10 kWp individual solar pumps	75% capital subsidy
Haryana, India (<500)	2-10 kWp individual solar pumps	90% capital subsidy
Pakistan (<500)	**SIPs available commercially with bank loans**	
	Plan to install 300,000 SIPs with government subsidy	**PKR 12 billion budget allocation requested**
Bangladesh (~2,000)	**Pay per Use Solar Irrigation Pumps**	**50% subsidy; 30% loan**
	Proposal to install 50,000 SIPs by 2025; multi-donor project	**50% subsidy; 30% loan**
Nepal (<500)	**< 1 kWp SIPs for kitchen gardens under donor programs**	**75-100% subsidy**
	1-5 kWp SIPs	**75-100% subsidy**

[4] Kilo watt potential

7. Relevance of Solar Irrigation in South Asia

Table 2 charts out the key characteristics and primary WEC Nexus concerns of five different hydro-socio-ecologies in South Asia, as well as the likely impacts of, or the role that solar technologies can play in shaping the region's W-E-C landscape.

Table 2: Contours of South Asia's W-E-C Nexus

Region	Key Characteristics and W-E-C Nexus Concerns	Potential Role for / Impact of Solar
1. N-W and Peninsular India; Balochistan, FATA and NWFP provinces in Pakistan	*- Physical water scarcity* *- Free or highly subsidized farm power* *- Groundwater depletion major concern* *- Sustainable Groundwater Management*	*SIPs can reduce the carbon footprint of irrigation but can also lead to over-pumping of groundwater*
1A. Gujarat and Punjab, India	*- Separation of agri and non-agri feeders* *- Intelligent rationing of farm power supply*	*SIPs can reverse the gains from intelligent farm power rationing*
1B. Telangana	*- Heavy investment in tank desilting* *- Announced free, 24*7 power to farmers*	*Free power and SIPs can reverse the gains from recharge*
2. Gangetic plains in Nepal *Terai*, eastern India and Bangladesh	*- Abundant groundwater; energy scarcity* *- Deficit irrigation, low productivity, poverty* *- Ensuring affordable irrigation for all*	*SIPs can deliver reliable and affordable irrigation, especially for smallholder farmers*
2A. West Bengal	*- Abundant GW; abolished SWID* *- ToD meters[1] and near-commercial farm tariffs* *- Water buyers at mercy of well owners*	*SIPs can catalyse competitive irrigation service markets*
3. Himalayan Mountain Ranges in Pakistan, India and Nepal	*- Rain-fed / low-irrigation agriculture* *- Springs for domestic and productive uses* *- Spring revival and maintenance*	*Solar can provide reliable access to energy in remote areas and reduce carbon footprint*
4. Punjab and Sindh provinces, Pakistan	*- Subsidized canal; costly diesel as supplement* *- Primary and Secondary Soil Salinity* *- Conjunctive Management to reduce Salinity*	*Solar pumps can replace dirty diesel and reduce carbon footprint of irrigation; W-E-C Nexus consequences likely minimal but unclear*
5. Sri Lanka; Kerala, India	*- From low-value, water-intensive paddy* *- To high-value plantations and spices* *- Irrigation small proportion of value of produce* *- Maintaining Groundwater Ecosystem Services*	*SIPs can reduce carbon footprint of irrigation but unlikely to have significant W-E-C Nexus implications*

Notes: SIP = Solar Irrigation Pump; SWID = State Water Investigation Directorate; ToD = Time of Day

Region 1: Subsidized Farm Power and Groundwater Over-Exploitation

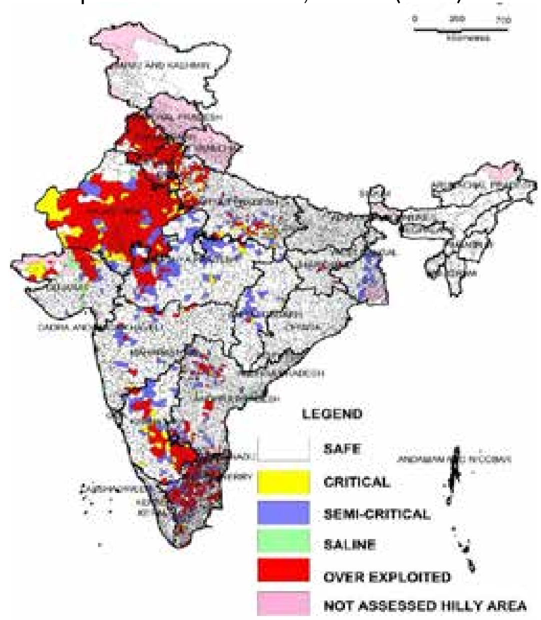
Agriculture is well established as the prime culprit behind the poor financial health of India's power utilities. Farm sector consumes, on average 20-22% of the total energy but in some areas, its share is as high as 40%. Against this, its contribution to the utilities' revenues is often less than 5%. Despite significant cross subsidization by commercial consumers, the Government of India's annual farm power subsidy continues to rise rapidly and has already crossed US$ 12 billion. Further, free or highly subsidized farm power supply creates perverse incentives for farmers, especially in water scarce western and peninsular India. Despite physical water scarcity, farmers face no economic scarcity and the impact of their resultant pumping behaviour is evident in large swathes of the region experiencing secular decline in groundwater tables (see Figure 3).

The vicious and perverse cycle of negative feedback loops is rapidly spiralling out of control. As groundwater depletion becomes more severe, farmers need more power to pump the same amount of groundwater and as a result, the finances of the utilities keep worsening. To maintain viability, utilities respond by curtailing power supply to agriculture and neglecting farm consumers leading to poor power supply environment. As farm power supply becomes unreliable, farmers resort to measures such as hooking and deploy auto-switches – which in turn lead to more wastage of electricity and water. Given the centrality of groundwater to the region's agrarian economy, despite its obvious downside, politicians dare not attempt rationalization of farm power tariffs; in fact, they continue to announce more populist schemes. Any attempt to discipline farm power use is viciously opposed by farmers and elected leaders are forced to apply political pressure on utilities to ignore rampant power theft and other malpractices.

This situation is common to almost all the states in western and peninsular India (Punjab, Haryana, Rajasthan, Madhya Pradesh, Gujarat, Maharashtra, Karnataka, Andhra Pradesh, Telangana and Tamil Nadu) as well as in Balochistan, Federally Administered

Tribal Areas (FATA) and Khyber Pakhtunwa provinces of Pakistan. Bulk of the agricultural pumps in these regions are electric and farm power is either free or highly subsidized. The only limit on farmers' pumping is imposed by the rationing of farm power – most farmers in the region receive power supply for only 6-8 hours a day; sometimes also during the night. The Indian states of Punjab and Gujarat represent a special case as the only parts of South Asia that have effectively implemented intelligent rationing of farm power. In both states, agriculture and non-agriculture feeders have been separated and farmers receive power supply according to a strict roaster. Another special case is the Indian state of Telangana which has, in recent years, invested heavily in restoring and desilting more than 45,000 irrigation tanks under '*Mission Kakatiya*' to improve groundwater recharge. However, since early 2018, the government of Telangana announced free 24*7 power supply to farmers. This might reverse any groundwater gains the state might have achieved through Mission Kakatiya (see Shah *et al*. 2017).

Figure 3: Categorization of groundwater development blocks in India, CGWB (2011)



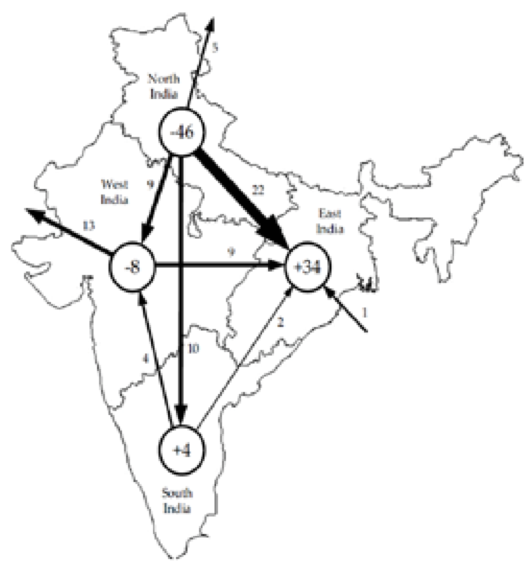
As discussed earlier, unless promoted smartly, solar irrigation pumps in this region can worsen the already precarious groundwater situation by giving farmers zero marginal cost, day-time power, effectively nullifying the effect of farm power rationing. Thus, solar irrigation promotion in this region has to be mindful of the invidious energy-irrigation nexus and the strong political economy associated with it. If so done, SIP introduction can actually offer decision makers a tool to get rid of the perverse farm power subsidies while earning political capital, as we shall discuss later.

Region 2: Groundwater Abundant, Electricity Scarce and Low Productivity

In sharp contrast to western and peninsular India, eastern India has relative abundance of groundwater but the rural electricity supply infrastructure is either non-existent or poorly equipped and managed. As a result, a very small proportion of the farmers in the region have access to electricity and more than 80% of the agricultural wells and tubewells rely on diesel or kerosene to operate. Since diesel is expensive and exerts a significant marginal cost of pumping, farmers tend to under-irrigate their crops despite better natural water endowment. As a result, agricultural productivity is generally low and rural poverty is quite severe.

In the early 1950s, the region's agriculture was as vibrant as the rest of South Asia. However, while the provision of subsidized farm power and the resultant rapid expansion of groundwater irrigation catalysed the 'Green Revolution' in the west, this region lagged behind on several parameters. While several factors have contributed to the agrarian stagnation in the region, lack of access to affordable energy for pumping the abundantly available groundwater is one of the key factors responsible for low value agriculture. This skewed provision of subsidized farm power has also resulted in "perverse direction of virtual water trade" in India where naturally water-scarce regions end up producing and exporting water intensive agricultural commodities to naturally water abundant but energy scarce regions (see Figure 4; Verma *et al*. 2009).

Figure 4: Perverse direction of domestic virtual water trade in India, Verma et al. (2009)



The region faces seasonal flooding on an annual basis and according to some scientists, promoting pre-monsoon pumping of groundwater for irrigation will create more room in the otherwise saturated aquifers to absorb the excess runoff. Thus, groundwater development can not only help farmers cope with seasonal water shortages, it can also help reduce the negative impacts of floods. Importantly, there also exist pockets of poor groundwater quality which will have to be suitably negotiated while developing strategies for groundwater development interventions.

This situation is common to the Indo-Gangetic alluvial plains in Nepal *Terai* and eastern India (eastern Uttar Pradesh, Bihar, West Bengal, coastal Orissa and Assam); the undulating tribal districts in Chhattisgarh, Jharkhand and Orissa; and almost all of Bangladesh. Rural electricity infrastructure is weak and despite recent efforts to improve the rural power supply, it is unlikely that farmers will get reliable farm power supply in the near future. Solar irrigation pumps can play a crucial role in the region by replacing costly and dirty diesel pumps and offering access to affordable irrigation, especially for smallholder farmers. West Bengal represents a special case in the region for introducing and implementing '*time-of-day*' meters and near-commercial tariffs for farmers. The high cost of pumping means that water buyers are at the mercy of well owners for irrigation. Most well owners prefer to lease-in land at exploitative terms rather than selling irrigation. Solar pumps can catalyse competitive irrigation service markets that will offer better terms of trade for water buyers.

In this region, SIPs can be a god-send; they can help lower irrigation costs, improve agricultural productivity and boost rural livelihoods. The big constraint is the high capital cost and the need to ensure high operating factors. Investments in solar irrigation pumps – whether private or public (through subsidies) – will be viable only if the pumps so installed are utilized effectively and in a manner that promotes equitable and affordable irrigation access.

Regions 3, 4 and 5: Rest of South Asia

The rest of South Asia consists of three distinct socio-ecologies: [a] the mountain ranges with insignificant groundwater use; [b] the diesel-pump dominated Punjab and Sindh provinces in Pakistan with conjunctive use of surface and groundwater; and [c] Sri Lanka and the state of Kerala in India with significant shift to high value agriculture.

The mountain region in the north comprises of the Himalayas that cut across Pakistan, India, Tibet (China), Nepal and Bhutan. Owing to its unique geography and agriculture profile, intensive irrigation is not a prominent feature and groundwater use for irrigation is rare. The region is dominated by high value rain-fed cultivation and plantations that are often manually cultivated using springs or surface water sources. Revival and maintenance of mountain springs – for domestic as well as productive purposes – is one of the key groundwater concerns in the region as most springs are linked to the underground water flows. Solar pumps can play a role in offering affordable and reliable access to energy in the region but this is unlikely to have significant nexus implications.

The Pakistani provinces of Punjab and Sindh are home to the largest contiguous irrigation system in the world. While farmers in the region have access to subsidized canal irrigation, the provision of subsidized electricity for pumping groundwater is not common. As a result, farmers are forced to use diesel-pumps to supplement irrigation from canals – which costs about 60-times more than canal irrigation (Shah 2009). Salinity is a big concern in the region, caused in part due to excessive irrigation. Solar pumps can play a critical role in conjunctive irrigation in the region by replacing dirty diesel fuel and reducing the carbon footprint of the region's groundwater economy. However, the WEC nexus consequences of the introduction of zero marginal cost solar irrigation are yet to be fully understood.

While most of sub-Himalayan South Asia struggles to manage farmers' almost insatiable demand for irrigation (and therefore farm power), in Kerala and to an even greater extent in Sri Lanka, the farming system has moved away from low value, high water intensive crops like paddy to less water intensive and high value horticulture and plantations. In Sri Lanka, farmers don't mind paying near-commercial power tariffs because the electricity bill constitutes a small proportion of the farmers' gross value of output. Here too, solar pumps can replace existing diesel and electric pumps and reduce carbon footprint but with little or no water-energy-climate nexus consequences.

8. The SDC-IWMI Partnership

The project aims to support climate-compatible development of energy and water systems in rural South Asia for resilient livelihoods. The project will support mainstreaming of context specific financially and institutionally viable models for solar-powered irrigation systems in order to reduce the carbon footprint of irrigation sector while promoting efficient use of groundwater resources under climate-induced uncertainties in the South Asian region (covering India, Pakistan, Bangladesh and Nepal).

The specific objectives of the project are:

1. To continuously assess and evaluate various approaches to managing the Water-Energy-Climate nexus in South Asia on parameters of effectiveness, livelihood impacts, equity, sustainability, and scaling potential through political and market-led interventions;
2. To develop, propose and undertake field experiments, pilots and projects to test the underlying assumptions and demonstrate techno-economic and institutional viability, quantify impacts and understand potential for up-scaling and out-scaling; and
3. To undertake policy outreach and market uptake activities with the objective of mainstreaming successful solutions and approaches to managing the Water-Energy-Climate nexus in South Asia.

The outcomes envisaged include:

- Implementation of promising techno-institutional solar based irrigation models leading to reduction in CO_2 emissions while ensuring conservation of water resources;
- Access to reliable and affordable irrigation services and water efficient technologies sustainably enhances the agricultural productivity and farmers' standard of living;
- Knowledge exchange and learning leading to scaling up of approaches for the climate compatible management of energy and water resources in agriculture sector in South Asia and beyond; and
- Mainstreaming of effective management approaches implemented the project and country specific learnings into the public programmes in select South Asian countries.

The project would support mainstreaming of promising techno-institutional solar based irrigation approaches into country programs. This would require extensive mapping of South Asia's Water-Energy-Climate Nexus landscape in order to develop and implement integrated solutions to incentivize local farming communities to adopt water and energy efficient technologies that help enhance farmer's incomes while "greening" the agriculture production system. The project implementation is envisaged in three phases (Figure 5).

Figure 5: Overview of the proposed project implementation in three phases

Entry Phase [12 months]	Phase I [48 months]	Phase II [48 months]
Inception	**Scale Pilot Implementation**	**Dissemination & Outreach**
Stakeholder consultations; Conceptualizing 'Innovation Fund'; National Solar irrigation policy review; Identifying partners and locations; Detailed project design, incl. Scale Pilot DPRs.	*Operationalizing 'Innovation Fund'; Implementing scale pilots; Continuous monitoring and evaluation; Updated landscape mapping; Supporting technical, financial and institutional innovations.*	*Evaluating intended and unintended impacts of scale pilots; Supporting solar irrigation policy and business environment; Regional, national and sub-national dissemination workshops; Policy dialogues; Supporting global and regional cooperation on solar irrigation promotion.*

The proposed 'Scale Pilots' will demonstrate financial, economic and institutional models of promoting solar irrigation pumps in the diverse geography of India by following the 'nexus approach' for maximizing the benefits of SIP deployment while minimizing any negative resource governance outcomes. For instance, in South Asia's groundwater-scarce geography (Region 1 described above), the scale pilot will demonstrate grid-connected SIP deployment with surplus power buyback arrangement. This model, already tested on a small scale by IWMI in Gujarat (Box 1) incentivizes farmers to use energy and groundwater efficiently while offering them an additional source of counter-climatic income from sale of surplus solar power. In partnership with the Government of Gujarat, the scale pilot will extend the IWMI-experiment to the scale of an entire agricultural feeder. Likewise, in groundwater-abundant parts of South Asia, the scale pilot will implement a model of SIP promotion that ensures high asset utilization while catalyzing competitive irrigation service markets for affordable irrigation access for smallholder farmers. This model too has been tried on a small scale in Bihar by IWMI (Box 2) which now needs to be refined and scaled-up to cover a larger command area before it can be mainstreamed in government and donor policies.

Box 1: Growing 'Solar Power' as a Remunerative Crop

In Gujarat's Dhundi village, under a grant to implement "Climate Smart Agriculture", IWMI and CCAFS (CGIAR's research program on Climate Change, Agriculture and Food Security) have supported the creation of the world's first solar irrigation cooperative. Started in early 2016 with six small farmers, the experiment has received a lot of media and policy attention due to its unique model of promoting solar power as a 'remunerative crop'. Under the pilot, farmers have installed 5 – 10.8 kWp solar pumps that are connected to each other through a micro-grid. The solar pumps are installed at an elevation such that even land beneath the panels can be utilized for cultivation. The panels generate roughly 1500 kWh per kWp of capacity in a year and this energy can be used by the farmers to lift groundwater for irrigation. Also registered as a cooperative society, the farmers pool any surplus power they generate at a central point and, under a 25-year power purchase agreement, sell it to the local electricity utility to earn cash income. In order to incentivise generation of green energy and efficient groundwater use in agriculture, IWMI offers a top-up on the feed-in-tariff the cooperative gets from the utility. Over about 2 years of full-scale operations, the cooperative has avoided 136 tons of CO_2 emission and earned more than ₹850,000 (~US$ 12,500) from sale of surplus solar power; this in a context where the mean household income is just about US$ 2,000 per annum.

Beyond greening the groundwater irrigation economy and helping member farmers pool and sell their surplus solar power, as the cooperative matures, it can also undertake additional activities to help maximize member returns. It can provide technical services to ensure that the farmers' pumps operate smoothly; it can encourage adoption of water and energy efficient irrigation technologies; stimulate discussion on shifting cropping patterns to high value, less water and energy intensive crops etc. A mature and financially healthy cooperative can also help members make investments in new technologies and expanding solar capacity by acting as an intermediary with local financial institutions.

Dubbed as SPICE 1.0 (Solar Pump Irrigators' Cooperative Enterprise), IWMI argues that mainstreaming of such SPICE cooperatives constitutes 'smart solar promotion'. The central premise of the experiment is that when farmers have the option of selling their surplus solar power for non-trivial returns, this will incentivise them to use energy (and therefore groundwater) efficiently. With support the National Dairy Development Board (NDDB) – which has experience of promoting thousands of dairy cooperatives in India – IWMI is now working on SPICE 2.0 in another Gujarat village. While in Dhundi, farmers had shifted from diesel pumps to solar pumps, under SPICE 2.0 in Mujkuva, the pilot will solarize grid-connected farmers who will give up access to highly subsidized farm power. Another model of solar cooperatives that IWMI and SDC have explored is one where the solar cooperative can sell its surplus power to a commercial user – a local factory, for instance – rather than evacuating it to the electricity grid.

In groundwater-scarce western and peninsular India, every grid-connected farmer that shifts to solar under this model will relieve some grid capacity for the local utility; it will also reduce the government's farm power subsidy bill. But importantly, it will offer farmers an additional and reliable source of climate-proof income. While there are technical, financial as well as institutional challenges to taking this experiment to scale (see section 7.2), the idea is starting to appeal to farmers as well as policy makers. Inspired by the experiment, the Government of Gujarat has drafted a new solar irrigation scheme called SUKHY (Saur Urja Kisan Hit Yojana; Solar power farmers' benefit scheme) to promote feeder-level solar cooperatives across the state. At the national level too, under the Government of India's ambitious KUSUM scheme (Kisan Urja Suraksha evam Utthaan Mahaabhiyan; Farmers' Energy Security and Welfare Mission), the government is encouraging states to mainstream the model.

Box 2: Catalyzing 'Buyer-Friendly' Solar Irrigation Service Markets

In eastern India's fertile Gangetic plains, across India, Nepal Terai and Bangladesh, farmers have limited or no access to farm electricity. This is largely due to poor rural electricity infrastructure and as a result, farmers are forced to use expensive diesel to run their irrigation pumps. As a result, despite being situated on top of one of the world's best aquifer systems and having shallow groundwater table, farmers tend to economize on irrigation and practice deficit irrigation. This, to a large extent, explains the low productivity of agriculture in the region and the resultant rural poverty and massive scale of distress migration from the region. Here, if promoted smartly, solar irrigation can catalyse rapid agrarian growth and lift millions of smallholder farmers out of poverty by turning monopolistic diesel-pump based irrigation service markets into highly competitive and equitable, water buyer friendly solar irrigation service markets.

In Chakhaji village of Samastipur district in Bihar, IWMI, CCAFS and AKRSP-I (Aga Khan Rural Support Program, India) have supported seven solar irrigation entrepreneurs to install 5 kWp solar pumps along with a network of buried water distribution pipes. A financial model under which the entrepreneurs have to pay a fixed lease amount each year to take full ownership of the asset over a period of 5 years exerts pressure on the entrepreneurs to maximize returns from the asset by operating it throughout the year to sell irrigation service to farmers in the village. As it is, a shift from expensive diesel to solar pumps significantly reduces the cost of irrigation. Further, as the solar irrigation service market matures, the entrepreneurs compete with each other for a lion's share in the village irrigation economy by offering better irrigation service at the least possible cost. In Chakhaji's solar irrigation experiment, the average cost of irrigation has declined from ₹120 per bigha (1 bigha = 2,528 m^2 or roughly 0.25 ha) to ₹45 per bigha. After a little over an year of full-scale operation, the village is experiencing significant changes in crops and cropping patterns with area under summer cultivation – a rarity in the diesel regime – is expanding rapidly and the agricultural GDP has more than doubled.

IWMI has argued that such a model of promoting solar entrepreneurs is significantly more efficient in delivering reliable and affordable irrigation to the largest number of farmers as opposed to its current model of offering 90% capital subsidy on small 1-3 kWp stand-alone solar pumps. The Government of Bihar's BRLPS (Bihar Rural Livelihoods Promotion Society) is actively considering scaling up the experiment to 10, and eventually 100 villages over the next few years. This too will entail some technical, economic and institutional challenges in designing an accessible, transparent and supportive policy environment but the model lends itself to scale replication in much of the groundwater-abundant but energy-scarce Gangetic plains of eastern India, Nepal Terai and Bangladesh.

References

Anchal and Thakur, D.P. 2016. Study of the emerging solar irrigation economy. Anand: Institute of Rural Management, MTS Report, Anand, India

BPC 2014. Sector wise Sale of Petroleum Products During 2014-15. Bangladesh Petroleum Corporation (BPC). Available online: www.bpc.gov.bd/contactus.php?id=27

Bell, A.R., Shah, M.A.A. and Ward, P.S. 2014. Reimagining cost recovery in Pakistan's irrigation system through willingness-to-pay estimates for irrigation water from a discrete choice experiment. *Water Resources Research*, 50 (8): 6679–6695.

Central Ground Water Board (CGWB), 2011. Dynamic Ground Water Resources of India. Ministry of Water Resources, Government of India.

Chlebna, C. and Simmie, J. 2018. New technological path creation and the role of institutions in different geo-political spaces, *European Planning Studies*, 26(5): 969-987 https://www.tandfonline.com/doi/pdf/10.1080/09654313.2018.1441380?needAccess=true

Dhawan, B.D. 1982. *The Development of Tubewell Irrigation in India*. New Delhi: Agricole Publishing Academy.

Dossani, R. and Ranganathan, V. 2004. Farmers' willingness to pay for power in India: Conceptual issues, survey results and implications for pricing. *Energy Economics* 26(3):359-369

Durga, N., Verma, S., Gupta, N., Kiran, R. and Pathak, A. 2016. Can solar pumps energize Bihar's agriculture? Anand: IWMI-Tata Program, Water Policy Research Highlight #3.

IAI, FICCI and Grant Thornton. 2016. Accelerating growth of Indian agriculture: Micro irrigation an efficient solution. Strategy Paper – Future prospects of micro irrigation in India. Irrigation Association of India (IAI), Federation of Indian Chambers of Commerce & Industry (FICCI) and Grant Thornton India LLP. Available online: http://www.grantthornton.in/globalassets/1.-member-firms/india/assets/pdfs/micro-irrigation-report.pdf

Government of Bangladesh (GoB) 2001. National Minor Irrigation Census and National Minor Irrigation Development Project (Dhaka, Ministry of Agriculture).

Government of Bangladesh (GoB) 2003. Irrigation by Methods, 1979-80 to 1999-00", Bangladesh Bureau of Statistics, accessed October 2007 GoB, 2003

Gupta, E. 2017. Extending Solar Water Pump Subsidies: Impact on Water use, Energy use and Cropping Patterns in Rajasthan: Difference in Differences Analysis. Working Paper Kathmandu: SANDEE

Hardiman, D. 1998. Well Irrigation in Gujarat: Systems of Use, Hierarchies of Control. *Economic and Political Weekly* 33(25): 1533–44.

IEA. 2015. World Energy Outlook 2015. Paris: International Energy Agency (IEA).

IEA. 2016. World Energy Outlook 2016. Paris: International Energy Agency (IEA).

Impact Energy and TERI. 2017. Promoting energy efficient agricultural pump sets in India. Impact Energy and The Energy and Resources Institute (TERI).

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

Rajan, A. and Verma, S. 2017. Evolving Nature of India's Irrigation economy: Insights from the Fifth Minor Irrigation Anand: IWMI-Tata Program, Water Policy Research Highlight # 7

Reddy, B.D. 2018. A boon for farmers, Telangana's 24/7 free power scheme may hit discoms hard. *Business Standard*, 02-Jan. Available online: https://www.business-standard.com/article/economy-policy/a-boon-for-farmers-telangana-s-24-7-free-power-scheme-may-hit-discoms-hard-118010100742_1.html

Shah, M., Bharti and Verma, S. 2017. Reviving Minor Irrigation in Telangana: Midterm Assessment of Mission Kakatiya. Anand: IWMI-Tata Water Policy Research Highlight, 8.

Shah, T. 2009. *Taming the Anarchy: Groundwater Governance in South Asia*. Washington D.C.: Resources for the Future Press.

Shah, T. 2018. Kick-starting KUSUM. *Economic and Political Weekly* (Forthcoming).

Shah, T. and Verma, S. 2008. Co-management of Electricity and Groundwater: An Assessment of Gujarat's Jyotirgram Scheme. *Economic and Political Weekly*, Vol.43(7): 59-66

Shah, T., Mehta, M., Sankar, G. and Mondal, S. 2012. Organizational reform in Gujarat's electricity utility: lessons for revitalizing a bureaucratic service delivery agency. Anand: IWMI-Tata Water Policy Research Highlight, #6.

Shah, T., Singh, O.P. and Mukherji, A. 2006. Some aspects of South Asia's groundwater irrigation economy: analyses from a survey in India, Pakistan, Nepal Terai and Bangladesh, *Hydrogeology Journal*, Vol. 14(3):286-309

Shukla, A.K., Sudhakar, K. and Baredar, P. 2017. Renewable energy resources in South Asian countries: Challenges, policy and recommendations. *Resource Efficient Technologies*, 3(3): 342-346`

The Express Tribune (2017). 'Balochistan farmers owe Rs150b in electricity bills'. 05-Oct, The Express Tribune. Available online: https://tribune.com.pk/story/1523147/balochistan-farmers-owe-rs150b-electricity-bills/

Verma, S., Kampman, D.A., Van der Zaag, P. and Hoekstra, A.Y. 2009. Going against the flow: A critical analysis of inter-state virtual water trade in the context of India's National River Linking Program. *Physics and Chemistry of the Earth*, 34 (4-5), pp: 261-269.

Whitcombe, E. 2005. Irrigation. In *The Cambridge Economic History of India, c 1757–c 1970*, volume 2, edited by D. Kumar and M. Desai. Hyderabad, India: Orient Longman, 677–737.

About IWMI-Tata Water Policy Program

The IWMI-Tata Water Policy Program (ITP) was launched in 2000 as a co-equal partnership between the International Water Management Institute (IWMI), Colombo and Sir Ratan Tata Trusts (SRTT), Mumbai. The program presents new perspectives and practical solutions derived from the wealth of research done in India on water resource management. Its objective is to help policy makers at the central, state and local levels address their water challenges – in areas such as Sustainable groundwater management, water scarcity, and rural poverty – by translating research findings into practical policy recommendations.

Through this program, IWMI collaborates with a range of partners across India to identify, analyse and document relevant water management approaches and current practices. These practices are assessed and synthesized for maximum policy impact and published as IWMI-Tata Policy Papers, Water Policy Research Highlights and IWMI-Tata Comments. The research underlying these publications was funded with support from IWMI, Tata Trusts, CGIAR Research Program on Water, Land and Ecosystems (WLE) and CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). The views expressed in the publications are of the author/s alone and not of ITP's funding partners. All IWMI-Tata publications are open access and freely downloadable from the Program's blog: http://iwmi-tata.blogspot.com

IWMI Headquarters
127 Sunil Mawatha, Pelawatte, Battaramulla, Colombo, Sri Lanka
Mailing Address
P. O. Box 2075, Colombo, Sri Lanka
Tel: +94 11 2880000, 2784080 **Fax:** +94 11 2786854
Email: iwmi@cgiar.org
Website: www.iwmi.org

IWMI-Tata Water Policy Program
"Jal Tarang"
Near Smruti Apartments, Behind IRMA Gate
Mangalpura, Anand 388001, Gujarat, India
Tel: +91 2692 263816, 263817
Email: iwmi-tata@cgiar.org
Blog: http://iwmi-tata.blogspot.in

IWMI International Water Management Institute

IWMI is a CGIAR Research Center and leads the: CGIAR

RESEARCH PROGRAM ON Water, Land and Ecosystems