Solar pumps and South Asia’s energy-groundwater nexus: exploring implications and reimagining its future

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Abstract
South Asia’s groundwater economy stands at the threshold of a revolution in adoption of solar irrigation pumps (SIPs). This has potential to unlock the region’s perverse energy-groundwater nexus. In much of South Asia, the price of energy used in irrigation, the only surrogate for water price, fails to signal the abundance or scarcity of groundwater, resulting in myriad distortions. We analyse these in South Asia’s eight distinct energy-groundwater interaction settings. We then explore SIP promotion policies to ease pressure on scarce groundwater in South Asia’s ‘groundwater depletion zone’ and accelerate groundwater irrigation for poverty reduction in its ‘groundwater abundance zone’.

1. Introduction
South Asian irrigation is in the throes of a solar pump revolution. Although solar irrigation pumps (SIPs) have been installed in demonstration farms for several decades, it is only in the past few years that their numbers have begun to grow rapidly. Governments in the region have begun promoting SIPs for various reasons. SIPs represent an innovative irrigation solution. They use green and clean energy compared to diesel and thermal power (Hartung and Pluschke 2018). SIPs can reduce the huge oil import bill and help improve balance of payments. In off-grid areas, SIPs are superior alternative to diesel pumps (Shah et al 2014, Gupta 2017). SIPs can save the cost of connecting tubewells to the grid and, in many parts, the subsidy on grid power (Durga et al 2016). SIPs offer day-time uninterrupted power, offering reliability and convenience to farmers.

All these are important. However, rapid expansion of SIP’s will also have broad and deep economic and ecological impacts on the way the regional groundwater irrigation regime functions. Access to uninterrupted free solar power for irrigation during daytime can accelerate groundwater use in agriculture since energy pricing and supply conditions are the most important driver of agricultural groundwater demand in South Asia (Shah 2009b, Shah et al 2009). Spread of SIPs may be a welcome development in the Ganga–Brahmaputra–Meghna (GBM) basin where high diesel prices keep the agrarian poor from benefiting from abundant groundwater availability (Shah et al 2009). However, spread of SIPs may worsen ecological stress in the western corridor of South Asia where electricity subsidies have already created large and growing pockets of groundwater depletion (Briscoe and Malik 2006, Shah 2009a, Kumar et al 2011). As long as the spread of SIPs is driven by capital cost subsidies, governments will have power to regulate their numbers. However, once panel prices drop to a level where farmers begin to buy SIPs over the counter, governments may have no means to regulate groundwater draft (Shah et al 2017b). Policies for promotion of SIPs therefore need to be situated in the unique historical nexus between energy supply and groundwater irrigation in South Asia.

Innovations in different forms of energy use in lifting water have always had a powerful role in shaping the socio-ecology of groundwater irrigation in South Asia. Shah et al (2016). The arrival of the Persian Wheel from West Asia during the 13th century gave the first big boost to well irrigation by replacing the far less energy-efficient charasa, the leather bucket, requiring 'six to eight bullocks and two able-bodied
men to operate’ (Islam 1997). The next major boost came in the 1920s when William Stampe, a maverick British engineer, began installing small hydroelectric plants on Ganga canal bed to generate electricity for towns. Since domestic electricity demand did not ensure sufficient base load, Stampe established a network of electrically powered tubewells to irrigate up-lying areas not commanded by canals (Subramanyan 2016). In the following years, Stampe’s Ganges grid fell by the wayside, but tubewells survived, flourished, spread and, in time, made South Asia the world’s largest user of groundwater in irrigation (Shah 2009a). The arrival of SIPS has brought South Asia on the threshold of one more such energy innovation which arguably has the potential to reconfigure the region’s irrigation socio-ecology.

Until a few years ago, SIPS larger than 0.1–1 kWp1 were rarely deployed, thanks to high capital investment involved. With rapid decline in global prices of photovoltaic (PV) cells, however, large SIPS of 5–10 kWp have become increasingly attractive during the recent years. Indeed, though small, a non-subsidy market for SIPS has already emerged in the region. A 2016 study based on phone interviews with some 150 SIP suppliers suggested that non-subsidy SIP market was already 6%–10% of total sales in India (Shahul 2016). In Pakistan, similarly, well-off farmers have begun installing SIPS without any government subsidy (Hartung and Pluschke 2018). In India, from just around 180 00 in 2014–15, total SIP numbers, with and without subsidy have soared to 143 515 in 2017–18 (Ministry of New and Renewable Energy MNRE 2018), a growth rate of 68% yr−1. At this rate, India will have many more solar pumps in 2025 than electric and diesel pumps it has today! Pakistan, Sri Lanka, Nepal and Bangladesh, all with significant groundwater irrigation economies, are less aggressive than India in growing SIP adoption. However, given their high solar insolation and the many advantages of SIPS, it will be surprising if these countries do not start aggressively fueling their SIP boom especially as PV cells keep getting cheaper (Shah 2009a).

We argue in this paper that, instead of worsening, sound SIP promotional policies have the power to reform the perverse nexus between energy and groundwater that, over the past 50 years, has given rise to myriad distortions, macro-economic inﬁrmities and serious sustainability concerns (Shah et al 2017b). Harnessing this transformational power of SIPS requires a nuanced understanding of South Asia’s energy-groundwater nexus, the way it plays out in different geographies of the subcontinent, and how SIP promotion can be best designed to address specific objectives in each geography. Section 2 briefly traces the trajectory groundwater revolution in South Asia. Section 3 discusses South Asia’s groundwater depletion zone (GADZ) and groundwater abundance zone (GAZ). Section 4 briefly outlines eight energy-groundwater interaction settings (EGIS) within GADZ and GAZ. In section 5, we explore alternative policy models presently used by governments to promote SIPS and assess them against seven criteria. Section 6 explores the ways forward and conclude our analysis with recommendations for appropriate policies.

2. South Asia’s silent groundwater revolution

In the 40 years between 1973–2013, South Asia’s irrigated area almost doubled from 49.6–98.0 Mha (FAO Aquastat 2016), over 90% of this through the spread of private irrigation by groundwater that, according to oﬃcial statistics, reached 55.5 Mha in 2013. In India, mechanised irrigation pumps numbered just around 5000 in 1951 (Dhawan 1982); but their numbers soared to 19 million by the turn of the millennium (Rajan and Verma 2017) and between 22 and 25 million today. In Bangladesh, shallow tubewells (STWs) increased from 45 000 in the early 1980s to 1.2 million in 2013 (BADC 2013), with their share in irrigated area rising from 15% in 1980 to 77% (including low-lift pumps) by the turn of the millennium (BADC 2013). In Pakistan, tubewell numbers increased from less than 200 000 in 1980 to 1.2 million in 2010 (Qureshi 2014:135). Before 1960, pockets of irrigation were conﬁned to landscapes commanded by canals and tanks. By 2000, groundwater wells had taken irrigation throughout the subcontinent as suggested by the spread of well numbers in ﬁgure 1.

The socio-economic gains from this groundwater boom have been dramatic and extensively documented (Shah 1993, 2009a). Groundwater was so central to the success of Green Revolution in north-western India that Repetto (1994) asserted that the Green Revolution, often called a wheat revolution, might also be called a tubewell revolution. Groundwater also helped normalize the vast difference in access to irrigation between canal commands and dryland areas, between uplands and valleys, between large and small farmers, between areas underlain by alluvial and hard-rock aquifers (Shah 2009a). Around

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1 Kilo watt peak.
1960, vast pockets of canal commands in Pakistan and north–west India suffered acute problems of water logging and soil salinization for lack of drainage infrastructure. By mid-1980s, water logging all but disappeared, thanks to private tubewells doubling up as vertical drains (Dhawan 1982, Briscoe and Malik 2006). Adding 1.3 Mha of groundwater irrigated area annually for 40 years made South Asia more food secure than ever before and made famines history. Bangladesh was a perennial importer of rice; after its STW boom during the 1980s it became a rice exporter as did India and Pakistan. There is little doubt that, but for the groundwater revolution, South Asia would have been hard placed to feed a population that quadrupled since 1950—from 493 million to 1.89 billion in 2018. To put things in perspective, equally poor Sub-Saharan Africa, has been much slower in expanding groundwater irrigation among its smallholders at a rate of just 60 000 ha yr⁻¹ (Shah 2018a); as a result, every drought turns into a famine threatening countless starvation deaths (The World Bank 2018).

3. Groundwater depletion zone (GDZ) and groundwater abundance zone (GAZ)

South Asia has complex hydrogeology (Price and Mittra 2016). However, for our purposes, three geographies (1, 2 and 3 in figure 2) are critical for our analysis:

- **arid alluvial aquifer areas** (Indian Punjab, Haryana, western Uttar Pradesh, western Rajasthan, parts of Gujarat and Madhya Pradesh; Pakistan Punjab, Sind, Baluchistan and pockets of Khyber Pakhtunwa) which have copious aquifer storage but low monsoon precipitation. Canal networks using Himalayan rivers ramp up limited natural recharge in parts of this geography; as a result, groundwater needs careful demand management;

- **semi-arid hard-rock aquifer areas** (almost all of inland peninsular India) which has 600–1100 mm yr⁻¹. Average precipitation but poor infiltration and percolation rates and low aquifer storage; these too need

4 Besides these three large geographies, there are inter-montane aquifer areas in the lower and middle Himalayas, north-eastern India, much of Khyber Pakhtunwa and a thin coastal strip—all of which have their own distinctive hydrogeological features but have little groundwater irrigation. We therefore focus our analysis on the three geographies.

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3 http://worldometers.info/world-population/southern-asia-population/.
intensive demand management to ensure long-term sustainability of irrigated agriculture.

Humid alluvial areas (the GBM basin comprising eastern Uttar Pradesh, West Bengal, Assam, Bihar, coastal Orissa, Bangladesh, terai districts of Nepal). These have excellent aquifers with alluvium to the depth of 1000 m in places; have heavy summer rains augmented by snowmelt slosh these plains with over 1200 BCM of flood discharge that leave 15–18 million ha inundated for up to four months (Rasul 2015), causing annual loss of life and property worth billions (Priya et al 2017). The Ganges Water Machine doctrine of 1970s (Revelle and Lakshminarayana 1975, Amarasinghe et al 2016) argued that intensifying groundwater irrigation in winter and summer in the GBM basin could drastically enhance the capacity of alluvial aquifers to absorb large part of the floodwaters. Incentivizing millions of smallholders to irrigate with groundwater can not only improve their livelihoods and farm productivity but also potentially alleviate annual flood havoc.

The paradox of South Asia’s groundwater economy is that the full potential groundwater irrigation in the GBM basin—the ‘GAZ’ remains unrealised because its smallholders face high energy prices while in geographies 1 and 2, the ‘GDZ’, energy subsidies have driven uncontrolled groundwater draft resulting in a groundwater crisis. By far the most powerful factor in western India and much of Pakistan were flat electricity tariffs and subsidies which during the 1980s gave a strong fillip to demand for grid-connected tubewells as well as their utilization. Flat tariffs also catalysed pervasive groundwater markets which, no doubt benefitted the poor (Shah 1993) but stressed the resource (Shah 2009a). By the early 1990s, power subsidies had emerged as the pivot of populist electoral politics in India’s western states as also in Pakistan. Provision of free power to farmers from Indian Punjab down to Tamil Nadu turned western India in a groundwater-stressed landscape. Pakistan followed much the same trajectory until the late 1990s when the president of the time, General Musharraf, ordered the army to meter tubewells and recover the power tariff from farmers. Soon thereafter, farmers in Punjab and Sind turned en masse to diesel pumps (Shah 2009a:144).

Many GBM states—such as Uttar Pradesh, Bihar, Assam—too wanted to benefit their farmers by offering them power subsidies. However, they had low power generation capacities and poor rural electricity grid network. In fact, states like Uttar Pradesh and Bihar underwent an era of ‘rapid rural de-electrification’ during 1980–2010, with grid connected tubewells registering a significant decline. Bangladesh metered all electric tubewells (Shah et al 2009:

5 Groundwater depletion in vast areas of western India pushed water levels so low that diesel pumps could no longer operate in many parts. This increased the demand for subsidized electricity and helped consolidation of farming vote-banks around electricity subsidies in western India. In the GBM basin, groundwater was easily accessible by diesel pumps; as a result, there was no significant vote-bank politics around electricity subsidies in this geography.

![Figure 2. Groundwater depletion zone (GDZ) and groundwater abundance zone (GAZ) of South Asia.](image-url)
141–148) and kept its farm power subsidies small as did West Bengal (Mukherji et al 2009). Because of these, GAZ of GBM basin evolved a ‘high cost’ groundwater irrigation economy dominated by diesel-pumps while GDZ—especially western India—from Punjab down to Tamil Nadu—ended up with a ‘low-cost’ groundwater economy encouraging accelerated groundwater depletion. Figures 3(a) and (b) show that blocks in India where India’s Central Groundwater Board (CGWB) found groundwater resource over-exploited are in states which have electric tubewells availing free or subsidized power. South Asia’s areas dominated by diesel pumps have higher groundwater replenishment and lower withdrawals, thanks to high energy cost; these therefore show hardly any sign of groundwater depletion.

4. EGIS of South Asia

In short, since the mid-1970s, differences in energy pricing and supply have been the key driver of the shape that groundwater economies have taken in GDZ and GAZ. The difference and implication gets put in bold relief when one notes that the energy cost a farmer pays in groundwater stressed Punjab is US $ 0 MWh$^{-1}$ and that paid by a resource poor water buyer in perennially flood-prone north Bihar can be as high as US $ 600 MWh$^{-1}$ (see annexure 1, available online at stacks.iop.org/ERL/13/115003/mmedia on workings of energy cost). This anomaly is of concern to policy makers in GDZ as well as GAZ states with policy responses creating varying dynamics in different states/countries (see figure 4). Energy-groundwater nexus has perverse impacts in other sectors too. Western Indian states—from Punjab down to Tamil Nadu—have been weighed down by the deadweight of farm power subsidies that have brought many electricity utilities to the brink of bankruptcy (Infrastructure Development Finance Company Limited IDFC 2012). Many states offering free power to farmers witnessed veritable anarchy on rural electricity grid, with rampant power theft and all-round deterioration of rural power supply (Shah and Verma 2008). Free power for tubewells also encouraged farmers to abandon traditional sources of gravity flow irrigation like public canals and community tubewells (Shah et al 2009). As their importance declined, so did their performance (Shah et al 2016). Power subsidies also created asymmetries between cropping patterns and water resource endowments. Water-short Punjab began growing water-guzzling rice in vast areas just as western Maharashtra emerged as a sugarcane hub of India. Had energy been priced near commercial rates in these regions, these crops would have been far less profitable. On the other hand, thanks to high energy cost of irrigation, water-abundant GBM basin failed to take full advantage of intensive summer cropping which is lucrative but requires several rounds of irrigation (Mukherji et al 2009, Shah et al 2009, Kishore et al 2015).

Policy responses include energy as well as non-energy interventions that can ease the perverse impact of the nexus. For example, to provide farmers relief from high irrigation cost especially during a dry spell, Bihar and Bangladesh have both tried diesel subsidies,
without visible success to provide relief to diesel pump irrigators (Kishore et al 2015). To curtail subsidy burden and cap groundwater draft, Gujarat rewired the country-side separating feeders supplying power to farmers from those serving non-farm rural consumers and then imposed a farm-power ration (Shah and Verma 2008). Punjab, Madhya Pradesh and Maharashtra followed suit (World Bank 2014). Many states in peninsular India have taken enthusiastically to distributed groundwater recharge in the hope that this will reduce energy-footprint and diminish the impacts of power subsidies associated with irrigation. In the newly formed state of Telangana, the government launched Mission Kakatiya (Kakatiya’s are 13th century rulers of the territory that is now Telangana; Kakatiya’s mobilised peasantry to dig over 45 000 irrigation tanks that transformed agriculture in this otherwise dry landscape.

Figure 4. Energy-groundwater interaction settings (EGIS) of South Asia.
with the dual objective of augmenting tank irrigation and improve groundwater recharge (Bharti 2016, Shah et al 2017a). Maharashtra launched a similar Jala Yukta Shivar program (Anvesha et al 2017) as did Rajasthan (Verma and Shah 2018). Gujarat began doing distributed recharge since the 1980s expecting to gain from reduced energy footprint and lower power subsidies while increasing the reliability of groundwater irrigation.

5. Promotion of SIPS in South Asia

In sum, the overall groundwater governance challenge of South Asia varies widely between GDZ and GAZ. In the former, policy makers are in search of instruments of groundwater demand management without having to take politically suicidal measures like metering grid connected tubewells and charging farmer consumption-linked commercial tariff for power consumed in irrigation (Kumar et al 2011, Bassi 2018). In contrast, in GAZ, the search is for interventions that can transform monopolistic irrigation service markets into pro-poor service markets that enables poor smallholders to use groundwater for productivity-enhancing irrigation rather than mere life-saving one used sparingly to save a crop during dry spell (Shah et al 2009, Shah et al 2009, Kishore 2004). It is against this wider backdrop in South Asia that upcoming solar revolution in irrigation needs to be considered.

Growing popularity of SIPS in South Asia is destined to change the energy-groundwater interaction in all eight EGIS of GDZ and GAZ. The arrival of every new technology opens up a new institutional pathway in its wake (Camilla 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 in at present. Studies show that SIPS meet the needs of smallholders admirably well in the GAZ (Kishore et al 2014, Durga et al 2016) as well as the GDZ (Anchal and Thakur 2016, Gupta 2017).

The worry is that SIPS are today promoted with the sole objective of reducing power subsidies where as they can achieve multiple objectives effectively (Shah et al 2017). Over 90% of India’s SIPS are installed in states where power utilities are nearly bankrupt offering free grid power to farmers (International Energy Agency IEA 2015). SIPS have many advantages as compared to electric and diesel pumps. At 5–6.5 KWh m$^{-2}$ d$^{-1}$ (Shukla et al 2017), South Asia has amongst the highest solar irradiation levels in the world. But SIPS have two major downsides, one economic and one ecological. SIPS enjoy near-zero operating cost but currently require 10–12 times the capital investment compared to diesel or electric pumps (Bassi 2018). Without 70%–95% capital subsidy, SIPS would have few takers in India. Such capital-intensive assets becomes viable only with a high utilization rate whereas Indian farmers find diesel pumps viable even at annual use of just 450 h (Rajan and Verma 2017). A 5 KWp SIP costing INR 500 000 (US $ 7692) in mid-2017 and operated for just 500 h yr$^{-1}$ in irrigation—against its potential of 2200–2500 h—is a poor investment for the farmer and the society more broadly. 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 western India’s parched aquifers. Free electricity is blamed for groundwater over-exploitation from Punjab down to Tamil Nadu, but its negative impacts are limited by restricted hours and unreliable, often nightly supply. With reliable daytime free solar power, SIPS can be much more lethal for ramping up groundwater over-draft than free grid power (Gupta 2017, Shah 2018b).

In comparing SIP promotion models, policy makers would be interested in multiple criteria. For instance, would a chosen model:

(a) offer farmers more reliable and affordable energy for irrigation than at present;
(b) ensure that energy price correctly signals scarcity or abundance of groundwater;
(c) reduce power subsidy burden on government;
(d) minimise carbon-footprint of irrigation;
(e) maximize farmer contribution to investment in irrigation equipment;
(f) enhance small-holder incomes; and
(g) offer rapid scalability.

South Asia is experimenting with several promotional models for SIPS, each addressing one or two of the above criteria but not all. These models can be grouped into following seven major categories:

5.1. Subsidy-saving model

India offers capital cost subsidy on SIPS in lieu of grid power connections to ease the subsidy burden on power utilities. This will accelerate adoption but with little contribution from farmers. As a result, the subsidy budget will limit how fast SIPS spread. Moreover, studies in India show that: (a) this subsidy is captured mostly by rich and influential farmers (Kishore et al 2014, Durga et al 2016, Gupta 2017); and (b) SIPS are often used as stand-by pumps to complement diesel/electric pumps rather than replacing them, resulting in increased total energy use in pumping more groundwater (Durga et al 2016, Gupta 2017). This model will address criteria (a) and (c) and partially (d) but contribute little or nothing to achieving (b), (e), (f) and (g).
5.2. Developer-centred farmer-dedicated solar plant
Piloted in Maharashtra, this model invites private investors to build tail end solar power plants (1–2 MWp in size) on government land to energise an entire separated agricultural feeder. The Utility offers investors Feed-in Tariff (FiT) on total generation, while farmers get free day-time solar power. Surplus power would flow back into the grid; and the deficit would be provided by the grid. This model, preferred by Utilities, offers cost-savings, upsizing potential and mobilizes private capital but it provides no incentive for energy and water conservation. In sum, it will address criteria (a), (d) and, with attractive FiT, even (g), and contribute moderately to (c) but will not address (b), (e), and (f). If anything, by offering better quality power supply free, it will intensify groundwater depletion (Gupta 2017).

5.3. Developer-centered distributed generation model
Piloted in Karnataka under Surya Raitha scheme, 220 farmers surrendered their free grid power connections in lieu of free solar pumps on their fields with 1.5 times more panels than the rated pump capacity (Shah et al 2014). Farmers get free solar power for irrigation during 8 am–4 pm all through the year. Surplus solar power is sold to the utility at INR 9 kWh⁻¹ (US $134 MWh⁻¹) of which for the first 10 years, INR 8 kWh⁻¹ (US $123 MWh⁻¹) is to be applied to recovering the capital cost, interest and developer profit. In effect, farmers get free solar power instead of free grid power but have no incentive for energy and water conservation nor does it offer any income flow to farmers. This model addresses (a) and (e) but contributes nothing to other objectives and will arguably increase groundwater withdrawals, thanks to improved power supplied free.

5.4. Farmers as land-leasers to solar companies
This model saves the governments the trouble of land acquisition for solar parks and gives farmers with barren wasteland a source of rent-income. In a pilot in Uttarakhand 150 acres are leased for 27 years at a rent of INR 16 700 (US $257) /acre/year (Patridge 2018); on the land so leased, crops are replaced by solar arrays. Farmers and solar companies are happy; but the government is unhappy because, instead of wasteland, prime agricultural land has been taken out of farming for solar generation, Gujarat too has such a scheme afoot (Acharya 2018) as has government of India under its ambitious KUSUM scheme. This model contributes only to (f) and nothing to other criteria.

5.5. Non-subsidy market model
Pakistan has so far left solar pump promotion to market forces without any subsidy (Ayaz 2015). As a result, adoption is slow and restricted to large, commercial farmers. Given high diesel-dependence of groundwater irrigation in the Pakistan Punjab, SIPs will grow as PV cell costs fall even without subsidy and aggravate concerns about resource depletion (Watto and Mugera 2016). An alternative market model deployed by Sri Lanka may address depletion concerns better. Under its Soorya Bula Sangramaya (Battle for Solar Energy) scheme, all distributed solar generators —rooftop and ground-mounted—are treated on par, net metered and offered a FiT of SLR 22.0 (US $140 ) MWh⁻¹ for the first 7 years and SLR 15.5 (US $100 ) MWh⁻¹ from the 8th to 20th years with no capital cost subsidy. Both the Pakistan as well as Sri Lankan options are designed to attract 100% farmer investment in SIPs (objective e) but while the Sri Lankan policy would incentivise energy-water conservation (objective b), the Pakistan policy would do the opposite. Solarization of diesel pumps in Pakistan will deepen its groundwater stress.

5.6. Solar irrigation service provider (S-ISP) model
Bangladesh, Nepal terai and eastern India have abundant groundwater which diesel pumps make costly for the poor to use (Shah et al 2009, Kishore 2014). High energy costs create highly monopolistic water markets in which resource poor marginal farmers end up paying up to a third of their irrigated crop as irrigation service charge (Shah and Ballabh 1997, Shah and Chowdhury 2017). NGO’s in Nepal and Bangladesh have responded by offering small SIPs of 0.5–0.8 kWp for irrigating kitchen gardens and small plots. However, the challenge here is to create pro-poor irrigation service markets, which right-sized SIPs (5–8 kWp) can meet admirably when SIP-owners are encouraged to sell irrigation service to other farmers. In a fee-for-irrigation-service model, IDCOL, Bangladesh offers private companies or investors 50% government subsidy and 35% loan to get a 8 KWp SIP expressly to sell irrigation service to small farmers for a fee. 300 such SIPs were in operation in 2016. A similar pilot in Bihar by the International Water Management Institute (IWMI) goes a step further in creating a pro-poor water market. The IWMI model has five distinct features: (a) identify young men/women in a village with entrepreneurial qualities and prior experience in selling diesel-pump irrigation service; (b) saturate the village with SIP irrigation by setting up 6–8 S-ISPs with overlapping command areas; (c) help each of them own and operate 5–6 kWP SIP instead of 1–2 kWp being subsidized now; (d) ensure SIP are mounted on a borewell deep enough to work at full capacity during summer; (e) augment the command area of each SIP with the help of 1000–1500 feet of buried distribution pipe. In both Bihar and Bangladesh cases, there is

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7. https://pib.nic.in/newsite/PrintRelease.aspx?relid=177489.
8. http://energy.gov.lk/Solar/.
9. http://blogs.worldbank.org/endpovertyinsouthasia/solar-irrigation-pumps-new-way-agriculture-bangladesh.
evidence of 40%–60% fall in water prices charged earlier by diesel pump owners, crowding out of diesel pumps and rapid expansion in pro-poor irrigated agriculture (Development Management Institute DMI 2017, Kumar and Goel 2018, Rai 2018). In both these, the key motive is to promote affordable groundwater irrigation for the poor in a geography with abundant water resources. This model addresses, to greater or lesser degree, all seven objectives.

5.7. Solar power as a remunerative crop (SPaRC)
Another IWMI pilot in Dhundi village in water-stressed Gujarat has an opposite motive, to promote solar energy that farmers can ‘grow’ on their fields as a new cash crop. Under this pilot: (i) tube well owners in a village gave up grid power connections for subsidized SIPs of equivalent capacity; (ii) SIPs are formed into a micro-grid managed by a cooperative of their owners; (iii) the Utility buys, at a remunerative FiT of INR 7.13 KWh⁻¹ (US $ 109.7 MWh⁻¹), all surplus solar power of the cooperative at a single metered point. The working hypothesis was that offering attractive power buyback option will reduce energy and groundwater demand (criterion b) for irrigation by creating positive ‘substitution’ and ‘output’ effects (Wolcowitz 2014). Such a policy can promote ‘green’ irrigation, reduce farm power subsidy, curtail technical and commercial losses in serving grid power, give farmers additional source of risk-free income and, above all, incentivize farmers to economise on energy and groundwater (criteria a, b, c, d, e, f, g). In sum, promoting SIP as a device to ‘grow’ one’s own solar energy to run irrigation pumps as well as to sell the surplus for cash income can correct or moderate many perversities of prevailing energy-groundwater nexus and become a potentially important demand-management tool in a groundwater governance toolkit.

Figure 5 summarizes indicative operating results of the Dhundi solar cooperative from January 2016–June 2018. Before solar power purchase began in May 2016, farmers used all solar generation for irrigating own and neighbours’ fields; but thereafter, they began selling as much power as they could and used only 35% of their solar generation for pumping groundwater on annual basis (Jayan 2018). The moot question is: would Dhundi farmers let 65% of their quality, daytime energy generation go waste if it was not purchased by the utility. Chances are they would have used much of it to pump more groundwater and sell it at a lower price or to grow water-loving crops, as free power leads farmers to do in Indian Punjab. Though indicative, results of the Dhundi pilot do suggest that offering a remunerative buy-back guarantee for solar power would confront farmers with a structure of incentives that is more consistent with the objective of sustainable groundwater management than providing them subsidized grid power at zero marginal cost. An important spill over benefit of transition from the present regime of unmetered grid power supply to metered buy-back of grid connected SIPs on Dhundi pattern is real-time measurement and auditing of energy and water consumption in agriculture, the first step to managing these two crucial resources.

6. Way forward: choosing the right sip promotion strategy
Figure 6 compares all seven models of SIP promotion in use in South Asia in terms of the seven criteria.
outlined earlier. Clearly, each model has something to offer to at least one or two objectives. But model 6 strikes the best balance among multiple objectives for groundwater abundant GBM basin (ITP 2018). Similarly, model 7 (SPaRC) has something to offer on all seven objectives, assuming of course that farmers respond to significant incentives. True, criteria need not have the same weightage for policy makers; and this would make choosing difficult in case of trade-offs. However, models 6 and 7 meet seven criteria better than other models. Model 6 emerges as ideal for EGIS #2 and 3 whereas model 7, with FiT calibrated to the needs of each context, offers best promise for EGIS 4, 5, 6, 7 and 8.

In its 2018 Union Budget, the Finance Minister of India announced KUSUM10, a mega-scheme entailing a total outlay of US$ 21.5 billion over coming 10 years; a large component of this will solarize 7.5 million grid connected electric pumps with a provision for utilities to buy surplus solar power at a remunerative price (Economic Times ET 2018). In quick pursuit, the western state of Gujarat launched a more detailed SKY pilot scheme on feeder-level solar cooperatives at an investment of US $ 120 million11 (The Indian Express 2018). Under SKY, farmers will contribute 5% of the capital cost upfront, get a 30% subsidy on SIP and take a loan to cover the remaining 65% over 7 years (objective e). Utilities will buy surplus solar power @ INR 3.50 KWh−1 (US $ 53.85 MWh−1) and will offer an incentive payment of INR 3.50 KWh−1 (US $ 53.85 MWh−1) of surplus solar energy sold (objectives b, f and g). This latter would be used to repay farmer’s loan component. At least 70% of tube-well owners on a feeder have to join the scheme and form a representative feeder-level committee that will oversee smooth evacuation of surplus solar power and ensure that farmer malfeasance is under check.

Designing the right financial product for models 6 and 7 in different EGIS will likely need much experimentation and multiple iterations. The process should also be nimble enough to respond to new knowledge gained over time. The scheme should be attractive enough to generate strong demand pull from farmers but not so attractive that it is captured by non-farmers. Some capital cost subsidy will be needed to entice all tubewell owners on a feeder to join, until SIP costs (panels, pump, connection cost) drop to around US $ 500 KWp−1. For groundwater demand management, more important is the level of FiT which will shape farmer behaviour in groundwater use. Keeping FiT too low, at say around INR 2.50 KWh−1 (US $ 38.5 MWh−1) or less, as some Indian utilities have been proposing, will create a weak pull for maximizing solar surplus for sale and will have little traction in groundwater demand management12. Keeping it too high at INR 9 kWh−1 (US$ 139 MWh−1) or more, as Karnataka originally offered in its Surya Raitha pilot will create perverse incentives and lead to capture by non-farm investors/developers (Prasad 2017). Offering very attractive capital cost subsidy as well as FiT, as Uttarakhand did in its land-lease for utility-scale solar

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**Table: SIP promotion objectives**

| 1. Utility-centric (Subsidy Saving Model) | 2. Developer-centred Farm-dedicated Solar Plant | 3. Developer-centred Distributed Solar Model | 4. Farmers as Land-leasers to solar companies | 5. Open Market solar pump promotion | 6. Solar Irrigation Service Provider model | 7. Solar Power as a Remunerative Crop (SPaRC) |
|------------------------------------------|-----------------------------------------------|---------------------------------------------|--------------------------------------------|------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| Example | Prevaling model in all Indian states | PRAYAS model Maharashtra | Suryarathna, Karnataka | Uttarakhand’s MW-scale solar plant on farmers’ land | Pakistan & Sri Lanka | IIOCOL in Bangladesh; Chakravati model in Bihar | Dhundi model; Gujarat Government’s SKY scheme |

(a) Will it offer reliable and affordable solar energy for irrigation to rich and poor alike? 
(b) Will it correctly signal scarcity or abundance of groundwater resource? 
(c) Will it reduce farm power subsidy burden? 
(d) Will it reduce carbon footprint of irrigation? 
(e) Will farmers share capital investment in solarisation? 
(f) Will it offer new income source to farmers? 
(g) Does it offer rapid scalability?

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10 Kisan Urja Suraksha evam Utthaan Mahaabhiyan. 
11 Suryashakti Kisan Yojana (SKY).

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12 Although simulations by Amjath-Babu et al (2018) and Franklin (2015) for Indian Punjab show that even a low tariff would incentivize move away from water-guzzling rice crop; and that the higher the pumping lift, the lower the tariff needed to force change in cropping pattern.
plants, will push farmers and productive farmland out of farming which may not augur well for food production.

Even in GAZ, there is a case for grid-connected solar pumps with buyback guarantee for surplus solar power at a low reserve price of INR 2–3 KWh⁻¹ (US $ 30.8–46.2 MWh⁻¹). This can make SIP investment attractive and prevent low-value off-season irrigation driven by free power without tightening the local water market. It may also spur investment in grid development. Investing in rural electricity network in many far-flung, thinly populated poor communities is unviable because of very low domestic load it will carry. Connecting clusters of tail-end net-metered solar pumps to such networks for buying surplus solar power can increase traffic on such networks and improve viability of such investments.

In summary, solar pumps are widely preferred as a ‘green’ solution; but we have argued in this paper that they herald a possible alternative future for South Asia’s energy-groundwater nexus more benign and equitable than its perverse present. Actualizing it will take much effort experimentation, resources and political energy. The redeeming aspect is that, in western India, SIP promotion under approach 7 is now driven by political leadership because it promises to benefit farmers while also mending perverse incentives. Likewise, in EGIS 2 and 3, approaches akin to model 6 are likely to attract political energy because it may be the quickest way to expand access to affordable irrigation to the poor.

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See e.g. https://medium.com/@steinahunt/energy-tariffs-reflective-of-which-costs-on-whom-9dbd04ae1fb.
