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Sustainability of Solar-based Irrigation in India

Key determinants, challenges and solutions

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An interim report on 'Sustainability of Solar-based Irrigation in India – Key determinants, challenges and solutions'.

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About the Authors

SHALU AGRAWAL

Shalu Agrawal was Programme Officer at the Council on Energy Environment and Water, India, when this research was undertaken and the working paper was written. Currently, she is pursuing a masters degree at University College London in Economics and Policy of Energy and Environment. Her research interests include Solar Energy Policy, Finance and Applications, Energy Access, Water-Energy Nexus, and Integrated Energy Modelling. Shalu holds a B.Tech Degree in Electrical Engineering from Indian Institute of Technology (IIT) Roorkee.

In the past, Shalu has worked on a diverse range of research projects in collaboration with international associations with a focus on energy access and sustainability. These include efficacy analysis of LPG subsidy policy in India, impact assessment of DBTL scheme, roadmap to realise 100 GW of solar and re-energizing India's solar energy market through financing. Prior to joining CEEW, Shalu completed a course on 'policies, politics and practices of environmental management in developing world' at the Centre for Science and Environment (CSE), when she also served as the editor of the participants' environment magazine. Shalu also had short term project stints with organisations such as Schlumberger Asia Services Ltd. (Wireline segment) and Control & Switchgears Ltd (low voltage protection elements, assembly line).

ABHISHEK JAIN

Abhishek Jain is a Senior Programme Lead at the Council on Energy, Environment and Water. He leads the council's research and work in the area of 'energy access'. His research focuses on energy provision and use for consumptive, community, and productive applications, fossil fuel subsidies reform, and reforms in the power sector. He holds an MPhil in Sustainable Development from University of Cambridge (Chevening Scholar; Cambridge Trust Scholar) and a B.Tech in Mechanical Engineering from IIT Roorkee.

Over the last five years, Abhishek has worked on multiple issues at the confluence of energy, economics, environment and sustainable development. Most recently, he has co-led the largest energy access survey in India. He also conducted the first independent evaluation of the world's largest direct benefit transfer scheme. He has researched and published in the areas of energy access, clean cooking energy, rationalisation of LPG and kerosene subsidies, deployment strategies for solar pumps, and electricity sector reforms for India, to name a few. He regularly presents at various national and international forums, and writes op-eds in leading national dailies.

In his previous avatar, Abhishek has worked as an energy and environmental engineer with Nestle India.

Contents

1. Introduction

Sustainable agriculture is central to achieving several of the Sustainable Development Goals (SDGs) from poverty alleviation to food security to livelihood security (Drechsel, Heffer, Magen, Mikkelsen, & Wichelns, 2015; FAO & GIZ, 2015; UN General Assembly, 2015). Most of the future growth in agriculture is likely to come from intensification, in which irrigation would play a key role (FAO, 2011). However, only 20 per cent of the global cultivated land is currently irrigated and there is a need to significantly expand the irrigation cover, particularly in developing countries, to meet the rising food demand (FAO, 2011). Of the global irrigated land, 56 per cent requires energy and the share is increasing, with corresponding rise in GHG emissions (FAO & GIZ, 2015).

Provision of energy to ensure access to irrigation in a sustainable and resource efficient manner has become a global challenge, particularly in the context of climate change. Climate change induced variations in precipitation and temperature are likely to adversely affect agriculture and the impact would be disproportionately high on poor farmers in developing countries, who are already food insecure (Nelson et al., 2009).

In India, only 46 per cent of the cultivated land is irrigated (Ministry of Agricutlure, 2014). With more than 19 million agriculture electricity connections, irrigation accounts for more than a fifth of the country's total power sales (CEA, 2014; Planning Commission, 2014). Further, on account of unavailability of electricity connection or inadequacy of power supply, more than 9 million diesel pumps are also being used for irrigation, which are expensive to run as well as hazardous to human health and the environment (Agrawal & Jain, 2015; Raghavan et al., 2010). Millions of farmers continue to lack access to irrigation, particularly in the eastern region of the country, where farming is predominantly rain dependent (Ministry of Agricutlure, 2015; Task Force on Agriculture Development, 2015). Provision of affordable and sustainable irrigation services, is becoming a pressing concern in India and elsewhere. In this backdrop, solar pumps or solar powered irrigation systems (SPIS) are emerging as an alternative to conventional irrigation solutions such as electricity or diesel powered pumps.

Solar-based irrigation

SPIS is a commercially available irrigation technology, with low operational and maintenance costs (Yu, Liu, Wang, & Liu, 2011). In view of their declining capital costs and the potential to mitigate greenhouse gas (GHG) emissions, several government and development entities have been promoting SPIS deployment, particularly in South Asian and Sub-Saharan countries (FAO & GIZ, 2015; IDCOL, 2015; MNRE, 2014). In India, national and state governments have set ambitious targets for deploying SPIS, supported via incentives such as capital subsidy and concessional loans (Kulkarni, 2015; MNRE, 2014). On these accounts, global solar pump market is rapidly growing and is expected to reach 1.5 million units a year by 2022 (GVR, 2015).

Sustainability of solar-based irrigation

While SPIS are being promoted as a solution to India's irrigation challenges, lessons from the past experience indicate that indifferent promotion and use of irrigation technologies, supported by myopic policies, could have fiscal, socio-economic as well as environmental fallouts (Sarkar, 2011; Shah, Molden, Sakthivadivel, & Seckler, 2000). These include rising fiscal burden on account of state subsidies on agricultural electricity, inequity in access to irrigation, excessive groundwater depletion and land degradation. Even as solar-based irrigation has environmental advantages, the need to ensure long term sustainability of SPIS could not be undermined (Kumar, Kumar, Suresh, Mitavachan, & Shankar, 2015).

Assessing the multi-dimensional sustainability of technology is important to transform a competent technology into a sustainable solution (Assefa & Frostell, 2007; Evans, Strezov, & Evans, 2009; Stougie & Kooi, 2014). The importance of looking at all three dimensions of sustainability, viz. economic, environmental and social has been argued in the literature for two prime reasons. First, to identify and understand the factors, which need to be taken into account while promoting and deploying any technology (Gibson, 2006). Secondly, to avoid single objective decision making, which could have unintended consequences on other dimensions of sustainability (Assefa & Frostell, 2007).

A sustainability assessment of any technology under varying contexts needs a comprehensive understanding of factors, which influence these dimensions of sustainability. Each factor could influence more than one dimension, sometimes in conflicting ways. Understanding the key factors, their influence, and their inter-relationship is crucial to develop policies and enable a market ecosystem, which can ensure long term sustainability of SPIS. So far, in the case of SPIS, studies have focussed on different sustainability components, though often individually. Multiple studies have evaluated their techno-economic feasibility, without taking into account the social and environmental concerns. (Bassi, 2015) emphasises the need for a comprehensive analysis of SPIS across technical, economic, and equity dimensions, before their large scale promotion, particularly through heavy public subsidies.

Key research objectives

In order to fill the current gap in comprehensive understanding of sustainability of SPIS and its determinants, we conducted this study to answer the following research questions:

1. What are the key determinants of sustainability of solar-based irrigation? What is the impact of these determinants on each dimension of sustainability?
2. What could be the potential approaches or measures to overcome the challenges, which pose a hindrance to SPIS sustainability?

2. Research methodology

We used three research approaches, including: i) a detailed review of the existing literature on solar pumps, ii) semi-structured interviews of different stakeholders involved in the solar pump sector, and iii) field visits to multiple solar pump installations in India.

Detailed review of existing literature

Several academic as well as empirical studies were reviewed to:

a. Identify the factors which would affect different components of sustainability of solar-based irrigation under diverse local context.

b. Understand their significance and impact on relevant sustainability dimensions.

c. Identify the context under which these factors could pose a barrier to sustainable use of solar pumps and explore the potential measures to address such issues.

Stakeholder Interviews

We conducted semi-structured telephonic interviews of key stakeholders comprising system suppliers (5), pump manufacturers (2), civil society organisations working with farmers (2) and policy researchers working on solar pumps (3). The interviews focussed on the following:

a. Capturing the views, experience and concerns of the stakeholders regarding sustainability of SPIS across the three dimensions, verifying the determinants and their impact, as gleaned the from literature review, as well as understanding the relative importance of these factors in the Indian context.

b. Exploring the measures being undertaken to alleviate various barriers, which pose a challenge to systems' sustainability and their on-ground experience with such measures.

Field visits

We undertook field visits to multiple solar pump installations in the Chomu block in Jaipur district, Rajasthan and Kashi-Vidhyapeeth block in Varanasi district, Uttar Pradesh, India. We conducted these field visits to:

a. Witness the working of solar pumps under different contexts.

b. Enrich and validate our findings regarding the key determinants of sustainability, their influence, and the corrective measures deployed on ground to deal with some of these challenges.

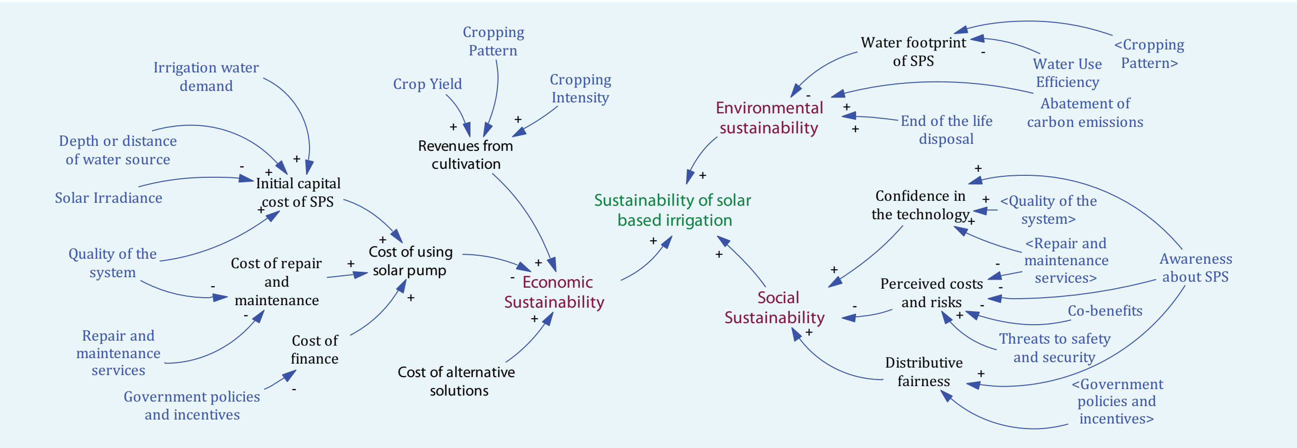
c. Capture the perspective of the most important stakeholder - the farmers. We conducted semi-structured interviews of farmers', who were using solar pumps (8) as well as those who were not (2). Our aim was to understand i) the factors which influence farmers' decision to adopt solar pumps, and ii) their experience with the technology. The chosen locations differed on account of factors such as agro-ecological regions, state policies, irrigation practices and service provider, which could impact the working of solar pumps and farmers' experiences.

3. Key determinants of SPIS sustainability

Based on the findings from literature review and their cross-validation through stakeholder interviews and field visits, we have identified eighteen key determinants of sustainability of solar-based irrigation in India. **Figure 1** depicts all the key determinants (shown in blue) and their influence on the three sustainability dimensions (shown in red) of solar-based irrigation, using a causal loop diagram (CLD).[1]

In the following section, we discuss the significance and impact of each factor on the relevant sustainability dimension and the associated concerns. We also discuss potential measures or approaches to address these challenges, to facilitate sustainable deployment and use of SPIS.

Figure 1: Sustainability of Solar-based Irrigation: Key Determinants and their Influence



Source: Authors' Analysis

3.1 Determinants of economic sustainability

Conventionally, a technology's economic sustainability is assessed using the life cycle costs and benefits (LCC) approach (Stougie & Kooi, 2014). Thus, i) the input costs for solar-based irrigation, ii) the expected revenues from cultivation and iii) the cost of alternative irrigation solutions (electricity and diesel powered irrigation pump-sets), would together determine economic sustainability of a SPIS.

Accordingly, we have identified ten factors, which would together determine the economic sustainability of SPIS, by influencing i) the input costs, ii) the revenues from cultivation and/or iii) the opportunity cost of solar-based irrigation. These key determinants (refer to Figure 1) are discussed below.

3.1.1 Irrigation water requirement (IWR)

The pumping capacity and, hence, the initial costs of SPIS directly depends on the irrigation water requirement (IWR) or the daily water discharge required from the SPIS for irrigating a unit area of land (Campana, 2015; Rahman & Bhatt, 2014).

1 The causal loop diagram is developed and interpreted on the basic premise of 'ceteris paribus' i.e. while looking at the relationship between any two variables, it is assumed that everything else in the system is constant. The polarity sign associated with the link indicates the nature of effect. A positive sign implies that increase in one variable would lead to increase in the dependent variable, while negative sign implies the opposite. Absence of sign implies an ambivalent relationship.

IWR, in turn, depends on the crop type, climatic factors (particularly effective rainfall) and irrigation efficiency (M. Ayub Hossain, Hassan, Mottalib, & Ahmed, 2015; Rao, 2002). Crop type determines the peak daily water needs (Critchley & Siegert, 1991), which is a prime factor determining the capacity of an irrigation system. Crops with high water requirement would require higher capacity SPIS, ceteris paribus. Secondly, climatic factors such as temperature, humidity, sunshine and wind speed, further influence the crop water need, which, for instance, is high in a hot, dry, sunny and windy climate (Critchley & Siegert, 1991). Thirdly, farm irrigation efficiency determines the gross irrigation water requirement.

Cultivation of locally (agro-ecologically) suitable crops and increasing the water use efficiency at farm level could help minimise the IWR and the overall input costs. For instance, in a field experiment using SPIS, (M. A. Hossain, Hassan, Ahmed, & Islam, 2014) found drip irrigation to be economical as compared to furrow irrigation for brinjal and tomato crops, due to reduced capacity requirement of SPIS.

While micro-irrigation solutions, such as drip or sprinkler irrigation systems, can be easily combined with SPIS (Burney, Woltering, Burke, Naylor, & Pasternak, 2010), their adoption depends on several factors such as nature of soil, crop type, availability of cash, education level, and social and economic status of the farmer (Namara, Nagar, & Upadhyay, 2007). In India, micro-irrigation is adopted in regions with high water-scarcity and adequate government support, primarily to increase the irrigation cover with limited water availability. To facilitate use of micro-irrigation through SPIS, adequate financial incentives, judicious system design, timely O&M, and continuous awareness generation would be required (Levidow et al., 2014).

The high upfront cost of SPIS necessitates optimisation of IWR. State support programmes to facilitate adoption of solar pumps could leverage this opportunity to promote cultivation of agro-ecologically suitable crops and use of efficient irrigation practices.

3.1.2 Depth or distance from water source

SPIS can be used with both surface and groundwater sources. In the latter case, the groundwater level and the seasonal fluctuations determine the required pumping head (Rahman & Bhatt, 2014), whereas, in the former case, it is the distance from the source. The system capacity required to meet a given IWR and hence, the initial investment is directly proportional to the pumping head (Kelley, Gilbertson, Sheikh, Eppinger, & Dubowsky, 2010). Thus, with doubling of groundwater depth, initial costs would nearly double[2], ceteris paribus, adversely affecting the economic sustainability of solar-based irrigation.

Further, a major threat to the economic sustainability of solar-based irrigation could be the unanticipated decline in groundwater level. As per SPIS suppliers, submersible pumps are kept 20 feet (~6 m) below the groundwater level. This implies that upon a 20 feet decline in groundwater level, the pump would have to be lowered. As the water discharge from SPIS (almost) linearly decreases with increase in pumping head (Benghanem, Daffallah, Alamri, & Joraid, 2014), falling groundwater level would reduce the irrigation potential of SPIS. Our interviews with SPIS suppliers reveal that the likelihood of future decline in GW levels is not factored in while designing solar pumps, even though most regarded it as a challenge for sustained use of solar pumps over their technical life. In regions experiencing rapid ground water decline, this challenge can adversely affect the economic sustainability of solar-based irrigation.

Given the influence of groundwater level and its fluctuation on economic sustainability of SPIS, it would be imperative to adopt measures to reduce IWR (see section 3.1.2), particularly in regions with high groundwater depth or those classified as 'critical' in terms of groundwater exploitation. In regions having low to moderate recharge rates, irrigation needs should be carefully planned and appropriate crops should be chosen (Kelley et al., 2010). In the long term, adequate water harvesting and management techniques would be critical to ensure sustainable access to irrigation, including through SPIS.

2 The capital cost of SPIS in India is of the order of INR 1,00,000 (USD 1,500) per HP, as per our interviews with the suppliers.

3.1.3 Solar irradiance

Even though the fuel cost for running SPIS is zero, solar irradiance is an important determinant of its economic sustainability. In SPIS, the size of the solar PV array is inversely proportional to the daily solar irradiance (Kelley et al., 2010). Since solar panel costs comprise ~45% of the total capital cost (M. A. Hossain, Hassan, Mottalib, & Hossain, 2015), economic viability of SPIS could vary with site location, higher in regions with high solar irradiance, ceteris paribus.

Majority of India's land is endowed with annual solar radiation of more than 5 kWh/m2/day (Ramachandra, Jain, & Krishnadas, 2011), favouring solar-based irrigation. However, during three winter months (November, December and February), the Northern to Western regions in India receive below 4.5 kWh/m2/day. This period coincides with the growing season of rabi (winter) crop, for which irrigation requirement is most crucial. The pump and panel selection should account for the IWR and solar irradiance during winter cropping season; otherwise the reliability of solar-based irrigation for winter crops will be affected. From our interviews with farmers in Varanasi (Uttar Pradesh) and researchers working in Bihar, we found that low discharge from SPIS during winter months, particularly during foggy days, has been a growing concern amongst the farmers. In regions with severe fog, SPIS might not work for days at length. This might adversely affect the crop productivity in absence of adequate backup for irrigation.

3.1.4 Quality of the system

Given a long technical life and capital intensive nature of SPIS technology, poor quality of system components could result in reduced or no water output over its operational life. For instance, in certain cases in India, water output from SPIS either significantly diminished or stopped altogether due to poor quality of the solar panels (KPMG, 2014). During interviews, SPIS suppliers expressed concern that spurious low quality products might enter the market to capitalise on the barrier offered by high upfront costs. Poor quality of components used could lead to frequent system breakdown and raise repair and maintenance costs.

Measures to regulate the quality of SPIS entering the market would be critical to maintain economic sustainability of SPIS, while keeping the O&M costs low. The Ministry of New and Renewable Energy (MNRE) in India has prescribed technical specifications and quality standards for each component to be used in SPIS (NABARD, 2014). The suppliers, who plan to install SPIS under state supported schemes, have to comply with these regulations, besides providing free service warranty for 5 year period. However, quality certification and enforcement mechanism is also required for out-of-scheme installations. Besides, measures such as awareness generation about quality assurance, post deployment monitoring of SPIS and a strong grievance redressal system would be crucial to protect farmers against poor quality products.

3.1.5 Repair and maintenance services

Though SPIS is a low maintenance technology, the solar panels require regular cleaning, as accumulation of dust can significantly lower the panel power output and hence the water discharge from SPIS (Abu-Aligah, 2011). Depending upon the climatic conditions and the rate of accumulation of dust, the required cleaning cycle for PV panels could vary from once in two weeks to daily (Mani & Pillai, 2010). However, SPIS can be easily cleaned by the farmers themselves, without incurring additional costs.

During our field visits, we found that most farmers were cleaning the panels in every 2-4 weeks, despite being aware about the need to clean the panels every week. Further, an on-field service provider remarked that a significant proportion of famers do not clean their panels regularly, leading to dust accumulation on them, to the extent that power generation is not enough to start the pump in low irradiance times. Therefore, periodic awareness generation would be necessary to ensure that farmers clean the panels regularly.

Unlike the regular cleaning, SPIS repair often requires skilled technicians (Yu et al., 2011). Lack of technically trained personnel and supply chain constraints in rural areas (particularly spare parts for DC motor based SPIS), often lead to delayed repairs and defunct systems (KPMG, 2014; Nathan, 2014). Two out of six solar pumps, studied during our field visits, were found defunct due to lack of maintenance response from service providers. Delay in repair and maintenance is a critical concern, as even a few days of system unavailability during peak growth season can significantly impact the crop yields, and thus the economic sustainability of solar pumps (Nederstigt & Bom, 2014).

Strengthening the local supply chain to improve availability of spare parts and training of local technicians is necessary to ensure timely repair services for SPIS in rural areas. Given the long technical life of SPIS, multi-year maintenance contracts, such as five year service warranty contract under state schemes in India, could provide farmers with economic and timely repair services.

3.1.6 Purchasing capacity of the farmers

Even though the lifecycle costs of SPIS are lower than alternative solutions, the ability to fund the high capital costs could be a significant barrier to solar-based irrigation (Kelley et al., 2010). In this regard, the purchasing capacity of the farmers is a key determinant of economic sustainability of SPIS, influencing it in a two-fold manner. First, it dictates the amount of capital available with a farmer and the need for external finance. Second, it influences the rate at which a farmer is able to raise external finance.

Usually the scale of farming determines the purchasing power. Small and marginal farmers having limited surplus capital to fund SPIS would prefer cheaper options or fee-for-service approaches (Nederstigt & Bom, 2014). Given low asset ownership, they also face difficulties in raising finance, both from private sources and public institutions. Farmers undertaking cultivation at commercial scale might be able to afford solar pumps, but even they might require external finance. As per our interviews with SPIS suppliers in India, given the high capital costs of SPIS, majority of installations have been under state supported schemes.

Interventions to reduce the capital costs of SPIS through its size optimisation and innovative financial products could help bring SPIS within the purchasing capacity of majority of farmers. For instance, state backed financial support schemes (by NABARD[3] in India and IDCOL[4] in Bangladesh) provide a combination of debt, equity and grant to facilitate solar pump uptake (IDCOL, 2015; NABARD, 2014). Further, new delivery models, such as solar-irrigation-as-a-service and community ownership of SPIS (through joint liability groups (JLGs) and farmer producer organisations (FPOs)) could be leveraged to provide affordable irrigation for small and marginal farmers using SPIS (Durga, Verma, Gupta, Kiran, & Pathak, 2016; KPMG, 2014).

3.1.7 Cropping pattern

Agriculture revenues vary significantly with cropping pattern (choice of crops), since different crops have different market values. For instance, cash crops and horticultural crops have high market price, as compared to cereals. Agriculture revenues have been found to increase with area under high value crops (Tahir & Habib, 2000).

Certain high value crops may have high IWR and would incur higher capital costs as well. The economic sustainability of SPIS would be higher for crops having higher revenues per unit of IWR. For instance, (M. Ayub Hossain et al., 2015) found solar-based irrigation was found economically viable for brinjal, tomato and wheat crops, but not for rice, in Bangladesh. Judicious choice of crops, in view of the IWR and crops' remunerative nature, could help improve the economics of solar-based irrigation.

3 National Bank for Agriculture Rural Development (NABARD)
4 Infrastructure Development Company Limited (IDCOL)

3.1.8 Crop Yield

Both the access to irrigation as well as its quality, have a strong impact on crop yields and in turn the crop revenues (Jin, Yu, Jansen, & Lansing, 2012). Irrigated land is 2.7 times more productive than rainfed land (FAO, 2011). Solar-based irrigation could significantly enhance crop revenues in unirrigated areas, particularly in remote and dispersed farmlands.

Further, adequacy and reliability of irrigation water significantly influence crop yield (Tahir & Habib, 2000). Irrigation via diesel or grid-electricity powered pumps faces both the challenge of fuel inadequacy and unreliability. The high cost of diesel also forces the small and marginal farmers to under-irrigate their farms in a bid to reduce costs, thereby affecting crop yields (Pullenkav, 2013). SPIS, if designed and maintained properly, could provide reliable irrigation service and positively impact the crop yields and revenues.

3.1.9 Cropping intensity

Around 65% of India's net sown area is cropped only once (Department of Agriculture and Cooperation, 2011). Most of India's cultivable land is endowed with three cropping seasons (Kharif, rabi and zaid) and solar-based irrigation could facilitate higher cropping intensity and hence higher revenues, in rainfed farms or those lacking access to reliable irrigation. SPIS can particularly facilitate zaid (summer) crops, such as vegetables, which are high value crops, but require adequate irrigation at regular intervals. During our field visits and interviews, we found that farmers, who were earlier growing only one crop a year, had begun cultivating three crops a year, after adoption of solar pumps, at zero operational costs.

3.1.10 Cost of alternative solutions

Several studies have shown that on a life cycle basis, solar-based irrigation is more economical than irrigation using diesel pump sets (M. A. Hossain et al., 2015; Narale, Rathore, & Kothari, 2013; Raghavan et al., 2010). In locations with high solar radiation and easy access to ground water, solar powered irrigation is economical as compared to both conventional alternatives (Kelley et al., 2010). This is particularly true for remote areas, where refuelling and maintenance of diesel generators is not cost effective and power lines are not readily available (Meah, Ula, & Barett, 2008). Moreover, the volatility in diesel prices often leads to price shocks for farmers, which could be avoided in the case of SPIS.

Table 1 illustrates the comparative input costs for irrigation through 5 HP capacity pump (70% pump efficiency) powered by grid-electricity, diesel or solar power, in India (discounting any state subsidies). Though SPIS require high initial investment as compared to diesel and grid-electricity powered pumps, the latter two have high fuel costs (Figure 2). Over a 25 year period (the technical life of solar panels), solar pumps are highly cost-effective than diesel pumps, but less attractive than electric grid-connected pumps. But this assessment doesn't include the costs associated with T&C loses, which are quite significant in India.

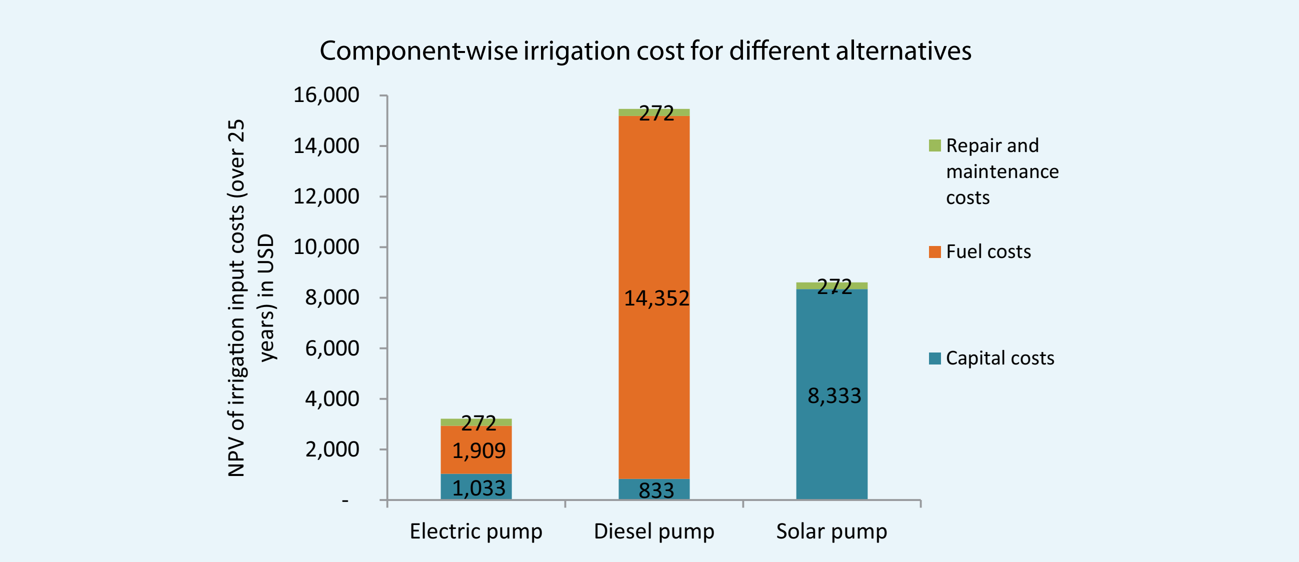
Even from a farmers perspective, SPIS would be economically attractive than diesel pumps, but highly uneconomical than grid powered pumps, due to heavy state subsidies on both agricultural electricity connection as well as consumption (Agrawal & Jain, 2015). However, factors such as long waiting time for new connections, unreliable and poor quality power supply as well as specific social hurdles could improve the economic attractiveness of SPIS over electric pumps. Almost half a million farmers in India have been waiting for electricity connection and a delay of just two years could imply an opportunity cost of INR 1,00,000 - 1,50,000 (USD 1,666 – 2,500 (Agrawal & Jain, 2015). Similarly, restricted hours of power supply often forces farmers to supplement irrigation requirement through diesel irrigation pumps or tractors (Kishore, Shah, & Tewari, 2014), while poor quality power supply could increase the cost of repair and maintenance (Kannan, 2013). Specific factors such as lack of consent from neighbouring farmer, who owns the land through which the electric feeder line for grid connected electric pump has to pass, have also acted as economic drivers for adoption of solar pumps by farmers in India (as confirmed during our field visit).

Table 1: Cost of irrigation through different irrigation systems of 5 HP pump capacity

	Grid electricity powered pumps	Diesel powered pumps	SPIS
Capital cost (INR)	INR 1,50,000 (initial connection cost) and INR 50,000 (pump cost)	INR 50,000 (pump cost)	INR 5,00,000 (system cost)
Fuel consumption	4.5 kWh/hour	1.23 litre/hour	0
Fuel price	INR 6/kWh	INR 55/litre	0
Rate of fuel price hike per annum	2%	2%	0
Annual repair and maintenance cost (INR/year)	2,000	2,000	2,000
Hours of operation per year *(6 hours*200 days)*	1,200	1,200	1,200
Discount rate	10%	10%	10%
NPV of total input costs* *(over 25 year period)*	**INR 5,60,000 (USD 9,330)**	**INR 9,27,400 (USD 15,460)**	**5,16,300 (USD 8,600)**
Cost of pumping (INR/hour)	18.7	30.9	17.2
Irrigation cost (INR/m³) *Flow rate of 96 m3/hr at pumping head of 10 m*	0.19	0.32	0.18

Source: Author's Analysis **Rounded off to nearest zero*

Figure 2: From a life cycle perspective, solar-based irrigation is highly cost-effective than diesel powered irrigation.



Source: Author's Analysis

3.2 Determinants of environmental sustainability

Environmental sustainability is generally understood as meeting the resource and services needs of current and future generations without compromising the health of the ecosystems that provide them (Morelli, 2011). Extending this definition to solar-based irrigation, we have identified following as the key determinants of environmental sustainability of SPIS.

3.2.1 Water use efficiency

Concerns have been raised about water use efficiency of solar-based irrigation. As SPIS have zero operational costs, once installed, there is little incentive for farmers to conserve water, which could lead to excessive water exploitation (Kishore et al., 2014). However, SPIS by their very design can check water-wastage, as they work only when the sun shines, providing peak output during peak sunlight hours (max. 5-6 hours per day). This limits the daily amount of groundwater that can be extracted. However, high state subsidies to facilitate SPIS adoption (of higher capacity then that required) could lead to groundwater exploitation. Such exploitation at large scale, without adequate groundwater recharge could lead to unsustainable water consumption patterns, particularly in semi-arid to arid agro-ecological regions.

Besides policies and incentives to promote size optimisation of SPIS, measures to enhance water-use efficiency such as proper irrigation scheduling, efficient irrigation techniques and conservation farming could also play an important role in enhancing environmental sustainability of SPIS.

Deployment models, such 'solar-irrigation-as-a-service', could also promote water-use efficiency by way of water supply through an efficient conveyance system at a pre-determined tariff. This model has been successfully piloted by GIZ in collaboration with VASFA (Vaishali Area Small Farmers Association) in Bihar, India (Kohler, 2014). However, a robust institutional design cognisant of the local socio-economic context would be critical for successful implementation of such an approach, besides adequate policy and financial support.

Researchers have also proposed grid integration of solar pumps, offering feed-in tariff to the farmers for surplus power generated, which could incentivise farmers against excess water use (Durga, Shilp, & Shah, 2014). Farmers' behaviour under such an approach as well as its cost-effectiveness is yet to be determined and proven. Moreover, challenges such as higher initial investment of grid-extension, metering of agricultural electricity connections, tariff for gross metering, settling of bills, and grid energy balancing also remain.

3.2.2 Cropping pattern

Cropping patterns not suitable to the agro-ecology of a particular region might pose multiple environmental challenges. Use of SPIS for cultivation of water intensive crops, indifferent to the soil characteristics or annual recharge rates could lead to issues such as waterlogging, salinization and land degradation, besides groundwater depletion. For farmers, pursuing such cropping patterns might be economically profitable in the short run. In the long run, environmental degradation and depletion of water resources would adversely affect the water discharge from SPIS as well as crop yields. Further, the cost of depletion is disproportionately borne by the resource-poor farmers, who lack access to groundwater irrigation (Sarkar, 2011).

In order to ensure environmentally sustainable irrigation assisted cultivation, it would be essential to link SPIS promotion to adoption of cropping patterns which are suitable to the local ecological context. In regions with declining groundwater levels, measures for water harvesting and management would be necessary to improve recharge rates.

3.2.3 Abatement of carbon emissions

SPIS could considerably reduce GHG emissions and other pollutants as compared to electric or diesel pumps, both of which are highly carbon intensive (Vasilis M Fthenakis, Kim, & Alsema, 2008; Gopal, Mohanraj, Chandramohan, & Chandrasekar, 2013). As a comparison, 5 HP (3.73 kW) capacity irrigation pumps (average capacity in India) powered by solar, diesel and grid-electricity, and running for 1250 hours per year would emit zero, 5.2 and 4 tonnes CO2 annually (Jain et al., 2013). Replacing just half of the 10 million diesel pumps in India by SPIS could help abate 26 million tonnes of CO2 emissions annually (Jain et al., 2013). This would be equivalent to 1.2 per cent of India's total carbon dioxide emissions in 2010 (MoEFCC, 2015).

In the context of climate change, solar-based irrigation not only offers an opportunity for mitigating GHG emissions, but also to make farmers more resilient against the erratic rainfall patterns caused by climate change (Colback, 2015). Going forward, as the national and international carbon credit markets mature, the opportunity to abate carbon emissions through SPIS could help improve their economic sustainability further.

3.2.4 End of the life disposal

Solar pumps have several components with varying technical life. Effective management strategies for each component at its end of useful life would be imperative to ensure environmental sustainability of SPIS from a lifecycle perspective. The issue is pertinent for components such as solar panels, controllers and invertors, which are classified as e-waste, and their improper disposal could adversely affect the environment (V M Fthenakis, 2003; PV Cycle, 2014; Rajya Sabha Secretariat, 2011).

Interestingly, recycling rates of up to 97% have been achieved for solar PV panel waste in Europe (PV Cycle, 2016). A few entities have initiated take-back and recycling services such as PV Cycle (in Europe and recently in Japan) and First Solar (in USA) (PV Cycle, 2016; Wesoff, 2011). However, currently recycling of solar panels is not a universal phenomenon. Moreover, recycling of solar waste is relatively expensive at dispersed scale (V M Fthenakis, 2003). Waste generated from individually owned solar pumps in rural areas would be highly dispersed and, thus, expensive to collect and recycle.

Under the business models such as 'solar-based irrigation as a service', enterprises would likely manage multiple SPIS with higher aggregated capacity. At aggregated level, it would be easier and economic to both regulate and manage the effective disposal of SPIS components. As the deployment of SPIS increase, in the coming few decades, their effective disposal at the end of useful life would become a critical concern for their environmental sustainability. Devising guidelines and enforcement mechanism for ensuring effective disposal of SPIS waste would be critical going forward.

3.3 Determinants of social sustainability

In the literature, social sustainability of energy technologies is approached from multiple perspectives, such as social or public acceptance, social equity and social impact (Assefa & Frostell, 2007; Bassi, 2015; Evans et al., 2009; Huijts, Molin, & Steg, 2012). Public or social acceptance is crucial for the introduction of new energy technologies in the society and is influenced by factors such as perceived costs, risks and benefits, trust and distributive fairness (Huijts et al., 2012). We have identified following as the key factors, which could influence the public acceptance, social equity and hence, the social sustainability of SPIS.

3.3.1 Awareness

Lack of knowledge and information about new energy technologies can pose barrier to public discussion and decision making about alternative solutions (Assefa & Frostell, 2007). As per our interviews with SPIS suppliers, low levels of awareness amongst farmers about the benefits, costs and performance of SPIS and the government support schemes have been a major barrier to its adoption. Lack of exposure to real-life installations also leads to low confidence in this new technology. The bankers in rural branches are also not well-versed with SPIS and are hesitant in disbursing loans for them, which impedes the technology's adoption. Filling these information gaps through awareness campaigns, technology demonstration and training exercises would be crucial to enable farmers as well as other stakeholders to take informed decision about SPIS as an alternative irrigation technology.

During our interviews with farmers and researchers, we found that the mode of awareness is also a determinant of distributive fairness. Our field visit in Jaipur revealed that in absence of active awareness campaign, majority farmers having solar pumps had invested on the advice of SPIS installers, who also happened to be their relatives. For a few others, newspaper advertisements were the source of information. This trend has also been observed in Patna (Bihar), where majority of the farmers who received state subsidised solar pumps, happened to be inter-related. An empirical study in Pakistan also indicates that educated, younger, and wealthier farmers are more likely to adopt SPIS for irrigation (Ali, Bahadur Rahut, & Behera, 2016).

(McCullough & Matson, 2011) have discussed the role of local knowledge networks in spreading information and increasing acceptance of new agricultural technologies amongst farmers. Local public institutions, which are equally accessible to all farmers, need to be leveraged for awareness generation, in order to ensure that the benefits of state support can be availed by all farmers, irrespective of their educational and economic background. One such locally available institution in rural India is that of Kisan Counselors (also known as Kisan Mitra or farmers' friend), who are responsible for spreading latest information about farming techniques (PTI, 2012; UNI, 2010). During our field-visit to Varanasi, farmers having solar pumps reported that their respective Kisan Counselors were a main source of information about SPIS. Moreover, none was found related to either the SPIS installers or the Kisan Counselors, which indicates a fair process of information sharing for the intended beneficiaries.

3.3.2 Quality of the system

Apart from influencing the economic sustainability, the quality of SPIS would also impact their social sustainability. SPIS is a relatively new technology with low market penetration. Poor quality products can adversely influence the consumer perception about the technology's performance and long term resilience. During interviews with SPIS suppliers, we found that the gaps in system design, such as poor bore-well design or lack of consideration of soil type and water quality, have led to poor performance or defunct SPIS, adversely affecting farmers' confidence in the technology. This calls for measures to regulate the quality of product as well as installations (for details refer to section 3.1.1.6). It would also be crucial to minimise the technology risks faced by the financing agencies.

3.3.3 Repair and maintenance services

Apart from determining the economic sustainability, access to timely and economic repair and maintenance service is critical to farmers' confidence and public acceptance of SPIS as a reliable solution for irrigation in the long run. During interviews as well as field visits, we found that farmers having defunct SPIS, due to lack of repair or maintenance, perceive the technology as unfit for irrigation and adversely influence the perception of other farmers as well.

3.3.4 Co-benefits

Besides providing access to irrigation, SPIS offer multiple co-benefits, which could improve both the economic and social sustainability of SPIS from the perspective of farmers as well as the state. First, SPIS provide an opportunity to extend irrigation services in poorly or as yet unirrigated regions, particularly remote and dispersed farms and thus, enhance geographical equity in access to modern irrigation.

Second, SPIS could also service households' water needs, where the houses are close to farms, as was confirmed during our field visits. As typically the chore is conducted by women, SPIS could contribute towards gender empowerment, by eliminating their burden of fetching drinking water from large distances.

Third, during periods when irrigation is not required, solar panels of SPIS could be used for running chaff-cutters (for cutting fodder) and farm-machinery such as threshers, etc. However, innovation to facilitate use of SPIS for such purposes is required. Models such as grid connected solar pumps, in which power distribution companies could buy back excess power produced by SPIS, have also been suggested for incentivising farmers against inefficient water use and for enhancing the capacity utilisation of solar panels (Durga et al., 2014). This could help farmers supplement their incomes through additional flow of revenues for the power fed in to the grid. However, grid-connected SPIS model might not be cost effective for farms lacking access to grid electricity, whereas the strategy of replacing grid-powered electric pumps with grid-connected SPIS would imply overlooking the needs of unirrigated farms and negatively influence the equity of access to irrigation.

3.3.5 Government policies and incentives

Solar pumps being a new technology with high upfront costs, facilitating adoption of solar pumps would require government support in terms of subsidy, financing and market support (KPMG, 2014). As of August 2016, ~ 77,000 SPIS have been deployed in India, mainly on the back of high subsidy support by the National and the state governments (Wali Ahmad, 2016).

During our field visits to Jaipur and Varanasi, we found that five out of eight farmers, who installed state subsidised SPIS, already possessed at least one (subsidised) electric connection for agriculture. In a separate field study conducted in Rajasthan, it was found that most of the state subsidies on SPIS have been availed by medium and large farmers (Kishore et al., 2014). Thus, the content and spirit of government policies and incentives would significantly determine the equity in access to solar-based irrigation, besides influencing farmers' outlook towards the technology.

In order to ensure equitable access to solar-based irrigation, government policies and programmes for solar pumps would need to focus on deserving beneficiaries and facilitate innovative financial products (those aligned with farmers' capacity to pay) and business models (such as community owned SPIS or irrigation-as-a-service).

3.3.6 Threats to safety and security

Solar panels, which comprise almost half of the total system costs, run the risk of theft and physical damage, either of which could reduce public acceptance of SPIS. Instances of theft of solar panels have been recorded in India as well as countries such as USA and UK (Amar Ujala, 2015; Lawson, 2012). During our interviews, SPIS suppliers in India reported certain instances of damage to civil structures holding the solar panels, due to strong winds. These risks have to be taken care of while designing and deploying SPIS.

Devising innovative insurance products could help manage the risks due to extreme events. Measures such as fencing, security fasteners, alarms and system monitoring tools could be used to secure SPIS against risks of theft (Lawson, 2012). As per our interviews with SPIS suppliers, most arrays use anti-theft bolts and fasteners to discourage the easy removal of panels, while fencing and mobile linked alarm systems are also being employed in India.

4. Discussion

The eighteen determinants of SPIS sustainability, as discussed in the preceding section, need a cognisance while evaluating the suitability of solar-based irrigation under any given context. Further, the measures suggested to ameliorate certain barriers could impact multiple dimensions of sustainability, in reinforcing and/or adverse manners. For instance, regulating the quality of SPIS would improve both economic and social sustainability. However, financial incentives aimed at addressing the challenge of low purchasing capacity of farmers, if designed incognisant of factors, such as water source, water use efficiency, etc., could adversely affect the environmental and social sustainability of SPIS. Unconditional disbursal of subsidies could reduce the incentive to improve irrigation efficiency, while a universal incentive regime could increase inequity in access to irrigation. Thus, solutions to improve one aspect of sustainability could lead to problem shifting between different dimensions. Accordingly, effective strategies to ensure sustainability of solar-based irrigation would be the ones, which augment at least one dimension of sustainability and deteriorate none.

Table 2 qualitatively synthesises the measures and approaches, which would be required to address all the potential barriers posed by different factors (as discussed above), and enhance the overall sustainability of SPIS. The influence of each measure on each of the three dimensions of sustainability is depicted with the colours, while the text explains the effect. The table can serve as a decision support tool, for formulating or assessing the policies and guidelines for promotion and deployment of SPIS. **Annexure 1** illustrates the use-case of approach by taking an example of the guidelines to promote SPIS in a state (Rajasthan) in India. It highlights the extent to which these guidelines incorporate the measures proposed in Table 2 and potential reforms to strengthen them further.

Table 2: Measures and approaches to ensure sustainability of solar-based irrigation

Measures / Approaches	Impact on Sustainability Dimensions		
	Economic Sustainability	Environmental Sustainability	Social Sustainability
Legend:			
Diminish sustainability	Augment sustainability	Augment or diminish sustainability	No significant effect
Immediate (to enable conductive ecosystem for scaling-up of SPIS)			
Regulating the quality of SPIS [awareness, guidelines, grievance redressal]	Ensure reliability of solar-based irrigation; Keep O&M costs low.		Enhances farmers' confidence and public acceptance of SPIS as a reliable solution
Ensuring timely access to repair and maintenance services [awareness, local repair services, annual maintenance contracts]	Ensure reliability of solar-based irrigation; Keep O&M costs low.		Enhances farmers' confidence and public acceptance of SPIS as a reliable solution
Ensuring security and safety of SPIS [guidelines and incentives]	Safeguard against major economic loss due to physical damage or theft, at marginal additional cost		Ensure public acceptance and confidence in the technology's resilience and use.
Short term (While scaling up SPIS installations)			
Promoting efficient irrigation practices [awareness, guidelines, financial incentives]	Reduce the IWR and hence the capacity and capital cost of SPIS; positively impact the crop yields and hence the revenues.	Increase irrigation efficiency and sustainable water use.	Increase public acceptance of SPIS by slowing GW decline and enabling sustained use of SPIS;
Targeting farmers waiting for grid-powered irrigation or those reliant on diesel pumps	SPIS would be economically more attractive for such farmers.	SPIS will help abate carbon emissions from grid or diesel powered pumps.	Enhance equitable access to irrigation.
Solutions to bring SPIS within purchasing capacity of farmers- such as innovative business/ financial models, state support, etc.	Overcome the barrier of high upfront cost and bring SPIS within the purchasing capacity of different farmers.		Ensure equitable access to solar-based irrigation.
Promoting size optimisation of SPIS [guidelines and incentives]	Reduce the capital cost of SPIS.	Limit the pumping capacity of SPIS and hence, the scope for non-judicious use of water.	
Medium Term (When solar pumps market has stabilised)			
Promoting water harvesting and management	Improve GW recharge rates and sustained use of SPIS	Improve GW recharge	Reduce competition for water from different sectors
Promoting agro-ecologically suitable crops [awareness and incentives to minimise SPIS capacity per unit area]	(+) Reduce IWR and initial investment; Sustained availability of GW water; (-) Possibly lower revenues than other high value crops, though input costs would be lower as well.	(+) Reduce IWR and enable ecologically benign farming.	
Promoting crops with high market value to IWR ratio [awareness, access to market]	Increase the crop revenues per unit of initial investment.	(-) Certain high value crops might not be suitable to the local agro-ecology.	
Effective disposal of SPIS [guidelines, regulations]	(-) Recycling dispersed SPIS is expensive; (+) For models such as 'water-as-a-service', disposal could be easier and economic.	Adequate disposal of SPIS components (several are classified as e-waste) would minimise environmental degradation.	

Source: Authors' analysis

5. Conclusion

Ensuring access to irrigation in a reliable and affordable manner continues to be a policy imperative in India. Given the fiscal and environmental constraints with conventional irrigation alternatives, the national and various state governments in India have started promoting solar pumps. This study, based on extensive literature review, field visits and interviews with all the key stakeholders, argues for a more comprehensive approach towards promotion and design of SPIS, in order to ensure long term sustainability of solar-based irrigation. The study identifies eighteen key determinants of SPIS sustainability and underlines several pertinent strategies to ensure the same.

The study could be useful for different stakeholders such as policy makers, SPIS manufacturers and suppliers, as well as researchers. It could help in designing better policies for deployment of SPIS as regards to identification of priority areas, streamlining of regulations, designing financial incentives, facilitating business models, etc.

The framework to promote solar pumps in a sustainable manner would help the policy makers adopt a holistic deployment strategy and avoid the pitfalls of the past approaches to pumping assisted irrigation extension in the country. The study would also be informative for the SPIS suppliers in understanding the likely barriers to SPIS adoption under different contexts and accordingly devise innovative business models and deployment approaches.

The study tries to bring together all the key factors, which could influence sustainability of solar-based irrigation. Future research could explore, which factors amongst those identified are most critical, for instance in determining i) technology adoption by farmers (through surveys) and ii) economic viability of solar pumps (through simulation and sensitivity analysis under various contexts). Future research efforts could also focus on validating the effectiveness of the proposed solutions under varied contexts and the extent to which they could address the concerns highlighted.

We hope that the study will not only help policymakers and businesses to make more informed decisions towards scaling up adoption of solar pumps in a sustainable manner, but will also encourage researchers to validate the aspects, which strongly influence the sustainability of solar-based irrigation in India and elsewhere.

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7. Annexure

Annexure 1: Review of solar pumps guidelines for the state of Rajasthan against the sustainability framework

Measures to ensure sustainable solar-based irrigation	Relevant provision	Cons/weaknesses	Reform needed
Legend:	Best Practice	Scope for improvement	Significant reform needed
Awareness generation about costs, benefits and risks of SPIS	One time advertisement in newspaper.	Inadequate to ensure information dissemination amongst rural areas. Dealers have to spread the word about SPIS, which has implications for equity in access to SPIS.	Need for more concerted efforts for awareness generation; could leverage local institutions- such as kisan mitras, for spreading awareness.
Regulating the quality of SPIS [awareness, guidelines, grievance redressal]	Eligibility criteria for suppliers: i) empanelled by MNRE ii) should have installed at least 100 SPIS in the state in the past; Release of subsidy to the supplier after physical verification of the installed pumps, within 7 days; Firm to be black listed upon - failure of 5 or more SPIS.		
Ensuring timely access to repair and maintenance services [awareness, local repair services, annual maintenance contracts]	10% of total project cost to be reserved as bank guarantee, in order to ensure compliance of service warranty contracts of 5 years. Suppliers' responsibility to i) establish a customer care centre, toll free number and service centres – sharing this information with all the stakeholders, ii) maintain enough spare parts to ensure repair within 5 days of receiving the complaints and iii) monitoring all the installed SPIS every quarter and sharing the information with district units.		
Measures to ensure security and safety of SPIS [guidelines and incentives]	Fencing of SPIS system mandatory and cost for this included in total project cost.		
Promoting micro and smart irrigation solutions [awareness, guidelines, financial incentives]	Mandatory to use drip/mini-sprinkler/sprinkler	No provision for subsidy for micro-irrigation kits, if farmer doesn't have it already.	Incentives for SPIS should be extended to cover micro-irrigation kits, where absent
Targeting farmers lacking access to grid powered irrigation or those reliant on diesel pumps	Farmers not having agriculture connection or willing to withdraw application for new agriculture connection eligible to receive higher subsidy (60-75%), than those having electricity connection (30%). Further, recipients of subsidised SPIS would be ineligible for subsidised agriculture connection in future.		
Solutions to bring SPIS within purchasing capacity of farmers- such as innovative business/financial models, state support, etc.	Capital subsidy up to 75% of capital cost of solar pumps available. Under the NABARD scheme, farmers can avail 40% subsidy and 40% credit for SPIS.	20-25% of upfront payment will not be affordable for many farmers.	Need for diverse financial products, such that small farmers can also avail of SPIS benefits.
Promoting design optimisation of SPIS [guidelines and incentives]	Suppliers responsible to conduct field Survey and design the SPIS required, on the basis of GW level, while ensuring water discharge as per the specifications.	Only 3 and 5 HP SPIS are eligible for incentives, which prevents optimisation of SPIS and most applicants go for 5 HP SPIS by default.	Make other HP pumps available under the scheme; incentives should progressively decrease with pump size.
Promoting crops with high market value to IWR ratio [awareness, guidelines/ incentives]	Mandatory to use a minimum of 0.5 Ha and 0.75 Ha land for horticulture via micro-irrigation, for getting subsidy on 3 HP and 5 HP solar pump, respectively.	Specifics of how this mechanism would be enforced are missing;	

Measures to ensure sustainable solar-based irrigation	Relevant provision	Cons/weaknesses	Reform needed
Promoting agro-ecologically suitable crops [awareness and incentives to minimise SPIS capacity per unit area]	NA		Provision and awareness for cultivating agro-ecologically suitable crops
Promoting water harvesting and management	NA		Measures to this effect under other schemes, should be extended to the regions where solar pumps are being deployed.
Effective disposal of SPIS [guidelines, regulations]	NA		Guidelines need to be formulated

Source: Author's Analysis

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