Received: 30 March 2018 | Revised: 16 July 2018 | Accepted: 24 July 2018
DOI: 10.1002/wene.325

WILEY WIREs ENERGY AND ENVIRONMENT

FOCUS ARTICLE

Sustainable deployment of solar irrigation pumps: Key determinants and strategies

Shalu Agrawal[1] | Abhishek Jain[2]

[1]Initiative for Sustainable Energy Policy, Alwar, India
[2]Council on Energy, Environment and Water, New Delhi, India

Correspondence
Shalu Agrawal, Initiative for Sustainable Energy Policy, Alwar, India.
Email: shaluagrawal.in@gmail.com

Funding information
Council on Energy, Environment and Water (CEEW)

Irrigation access is deemed critical to sustainable agricultural growth, which underpins the global food and livelihood security. Solar irrigation pumps (SIPs) have emerged as a promising technology to expand irrigation access and are being deployed rapidly across several developing countries. Even as the interest in SIPs is rising, the understanding about their sustainable deployment and use remains limited. Based on a detailed literature review and semi-structured interviews of key stakeholders, we identify and discuss 14 determinants of economically viability, socially acceptability, and environmental sustainability of SIPs, under any given context. These include crop water requirement, depth of water source, solar irradiance, scale of farming, utilization factor, cost of alternatives, system quality, after-sales service, water use efficiency, and technology awareness, among others. Drawing from the best practices and experiences in South Asia and Sub-Saharan Africa, we also put forward key recommendations on ways to incorporate sustainability concerns in the policies and programs for SIPs deployment. The study emphasizes that policies and programs for SIPs should focus on building awareness and trust, providing need sensitive support, priortizing areas for SIPs deployment, and ensuring long-term sustainability.

This article is categorized under:
Energy and Development > Science and Materials
Energy and Development > Economics and Policy
Energy and Development > Systems and Infrastructure

KEYWORDS
business models, climate smart agriculture, solar irrigation pumps, sustainable irrigation

1 | INTRODUCTION

Sustainable agriculture is central in achieving many of the sustainable development goals, including poverty alleviation, food security, livelihood security, and sustainable ecosystems (FAO & GIZ, 2015; UN, 2015). Most of the future growth in agriculture is likely to come from intensification, in which irrigation would play a key role (FAO, 2011). This is because, irrigated farms have significantly higher (double or more) crop yields than rain-fed farms. Further, rain-fed farms are more vulnerable to climate change-induced rainfall variability, such as delayed, insufficient, or excessive rainfall, which could adversely impact crop production (Turral, Burke, & Faurès, 2011). However, only 20% of the global cultivated land is currently irrigated, with this share being less than 5% in Sub-Saharan Africa (SSA) (FAO, 2011). Global development institutions have highlighted the need to significantly expand the irrigation cover, particularly in developing countries, to meet the rising food demand (FAO, 2011).

In irrigation expansion, energy access plays a key role, with 56% of the global irrigated area relying on energy (FAO & GIZ, 2015). Motorized tube-wells are the mainstay of irrigated agriculture in most of South Asia (Shah, Scott, Kishore, & Sharma, 2004). But lack of energy access can pose a critical challenge to irrigation access. In India, 54% of the cultivated land is rain fed (MoAFW, 2015) and more than 9 million farmers use diesel irrigation pumps (Agrawal & Jain, 2015; Raghavan et al., 2010), despite 19 million agriculture electricity connections (Central Electricity Authority, 2014). In SSA, given the low electrification rates, adoption of fuel-powered motor pumps for private irrigation is steadily rising, even though majority farmers rely on labor intensive, manual methods of irrigation (De Fraiture & Giordano, 2014).

In this context, solar irrigation pumps (SIPs) have emerged as a promising technology to expand irrigation access (see Box 1 for details). As an off-grid technology, powered by renewable energy, SIPs are particularly attractive for regions with low electrification rates and dispersed farmlands. Although solar pumps have high upfront costs, their zero operational costs, easy maintenance, and long lifetime make them attractive as compared to fuel-powered pumps (Kelley, Gilbertson, Sheikh, Eppinger, & Dubowsky, 2010). The drastic fall in solar module prices (75% fall over 2010–2015) has further strengthened the economic case for solar-powered irrigation, and several countries in Asia and Africa are implementing programs to facilitate its uptake (Bloomberg, 2016). The global solar pump market is rapidly growing and is expected to reach 1.5 million units a year by 2022 (Grand View Research, 2016). Yet, SIPs is a novel technology in most developing countries and faces several challenges pertaining to technology awareness, access to credit, and availability of skilled manpower in rural areas, besides the concerns related to their sustainable deployment.

Sustainable development is commonly understood as achieving economic, social, and environmental welfare for both the present and future generations. It is often argued that by facilitating irrigation access, SIPs could help promote socioeconomic development with much smaller carbon footprint than the alternative technologies. Yet, past experience indicates that indifferent promotion and use of irrigation technologies, supported by myopic policies, could have fiscal, socioeconomic as well as environmental fallouts (Sarkar, 2011; Shah, Molden, Sakthivadivel, & Seckler, 2000). These include rising fiscal burden on account of heavy state subsidies on agricultural electricity, inequity in access to irrigation, excessive groundwater depletion, and land degradation. The need to ensure sustainable deployment and use of SIPs cannot be overstated (Kumar, Kumar, Suresh, Mitavachan, & Shankar, 2015). This in turn requires an understanding of the factors, which influence the sustainability of SIPs.

Assessing the multidimensional sustainability of technology is important to transform a competent technology into a sustainable solution (Evans, Strezov, & Evans, 2009; Stougie & Van der Kooi, 2012). The importance of looking at all three dimensions of sustainability has been argued in the literature for two key reasons. First, to identify the factors, which need to be taken into account while promoting and deploying any technology (Gibson, 2006). Second, to avoid single objective decision-making, which could have unintended consequences on other dimensions of sustainability (Assefa & Frostell, 2007).

Several studies have looked into technoeconomic feasibility (Sarkar & Ghosh, 2017; Sontake & Kalamkar, 2016), impact on food security and poverty alleviation (Burney, Woltering, Burke, Naylor, & Pasternak, 2010), and technical potential for solar irrigation in various geographies (IFC, 2015; Schmitter, Kibret, Lefore, & Barron, 2018). Studies have also highlighted different concerns with SIPs, such as economic viability and environmental sustainability (Shah & Kishore, 2012). But a comprehensive analysis of different factors influencing their sustainability is missing in the literature. Bassi (2015) emphasizes the need for a holistic analysis of SIPs across technical, economic, and equity dimensions, before their large-scale promotion, particularly through heavy public subsidies. Against this background, this work attempts to answer the following research questions:

- What are the key determinants of sustainability of SIPs?
- What measures could help overcome the challenges to sustainability of SIPs?

The rest of the paper is structured as follows. Section 2 briefly discusses the solar pump technology. Section 3 outlines the research methods employed. Section 4, 5, and 6 presents the key determinants of economic, environmental, and social sustainability of SIPs and Section 7 discusses the study's implications for future programs of SIPs and concludes.

2 | METHODS

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

BOX 1

SOLAR IRRIGATION PUMPS

One of the first experimental use of solar photovoltaic (PV) cells for pumping water for irrigation dates back to 1977 in Nebraska (Pytilinski, 1978). During the 1980s and 1990s, there was a surge in studies exploring the technological feasibility and economic viability of solar-powered irrigation across different parts of the world (Sontake & Kalamkar, 2016). However, it was not until early 2000s, when solar pumps started receiving policy attention, in line with the growing discourse on clean energy solutions. The past decade has seen a rising uptake of solar pumps for irrigation in India, China, and more recently in Africa.

A typical SIP comprises solar PV panels (to convert solar energy into electricity), electric motor (AC or DC), inverter (with AC motor), power conditioning unit, water pump, and water delivery system (Meah, Ula, & Barett, 2008). Solar pumps can be used with both surface and ground water resources, and can pump water from up to 200 m head (Practical Action, 2010). They can also be combined with drip or sprinkler irrigation systems to achieve higher irrigation efficiency. As solar radiation drives both the irrigation water requirement and a solar pump, the system "passively self-regulates," with higher water discharge on hot sunny days (Burney et al., 2010). They do not use batteries in general, but are sometimes coupled with water storage systems, for cloudy weather or irrigation during night times.[3]

2.1 | Detailed review of existing literature

Given the multidisciplinary yet specific focus of the research questions, the literature review was conducted to identify factors influencing technoeconomic feasibility, environmental sustainability, or social equity aspects of solar-powered irrigation. The literature search was conducted by using the keyword "solar irrigation pump" along with keywords, such as "techno-economic," "economic," "social," "environmental," "feasibility," "sustainable," "challenges," and "potential." The relevant literature was critically assessed to identify the key determinants and understand their impact on relevant sustainability dimensions. A secondary round of literature search was conducted to identify the measures to address the sustainability concerns arising out of the use or promotion of solar irrigation, which are often common to other irrigation or renewable energy technologies.

2.2 | Stakeholder interviews

We conducted 12 semi-structured telephonic interviews with key stakeholders in India, including system suppliers/installers, pump manufacturers, civil society organizations working with farmers, and policy researchers working on solar pumps. The interviews were aimed at capturing the views and concerns of key stakeholders regarding sustainability of SIPs, exploring the measures being undertaken to address challenges to their sustainability.

2.3 | Field visits

We undertook field visits to validate our findings from the literature review and stakeholder interviews. We visited several solar pump installations in the Chomu block in Jaipur district, Rajasthan, and Kashi-Vidhyapeeth block in Varanasi district, Uttar Pradesh, India. The choice of location for field visit was determined through factors such as penetration of solar pumps, duration of experience that farmers have with solar pumps. In addition, the authors' network to identify solar pump suppliers and users also limited the choice of locations. In order to capture the farmers' perspective, concerns and experience with solar pump technology, we conducted semi-structured interviews of farmers', including both users and non-users of solar pumps.

3 | DETERMINANTS OF ECONOMIC SUSTAINABILITY

Conventionally, a technology's economic sustainability is assessed using the life cycle costs and benefits approach (Stougie & Van der Kooi, 2012). Accordingly, economic sustainability (viability) of SIPs would be determined by (a) the input costs for solar irrigation, (b) the expected additional revenues from cultivation due to use of solar pump, and (c) the cost of alternative irrigation solutions, such as diesel or electric pumps. These in turn are influenced by key factors discussed below.

3.1 | Peak daily water requirement

The solar pump capacity and, hence, its capital costs (capex) directly depends on the peak daily water needs of a crop (Campana, 2015; Rahman & Bhatt, 2014). For instance, peak daily water needs of crops such as crucifers and onions are 20% lower than that of sugarcane or paddy (Brouwer & Heibloem, 1986). Thus, the former would need a smaller capacity system, with lower capex. An experimental study in Bangladesh found that solar irrigation is economically viable for brinjal, tomato, and wheat crops, but not for rice (Hossain et al., 2015). The use of solar pumps would be more economic for crops having higher revenues per unit of peak water requirement.

As crop water requirement is also influenced by climatic factors and water holding capacity of the soil, solar irrigation costs can be minimized by cultivation of local (agro-ecologically suitable) crops. Besides the choice of most suitable crops, the peak crop water need can be optimized with the use of micro-irrigation solutions, such as drip or sprinkler systems, which can be easily combined with SIPs depending upon the type of crop (Burney et al., 2010).

3.2 | Depth or distance from water source

The capacity of solar pump components is also determined by the pumping head (Kelley et al., 2010), which in turn depends on the distance from or the depth of the water source. The discharge rate from a solar pump declines almost linearly with the increasing pumping head (Benghanem, Daffallah, Alamri, & Joraid, 2014). Thus, regions with lower water table will need solar pumps with higher capacity and capex, ceteris paribus. While this holds true for diesel pumps as well, the capex difference between solar pumps and diesel pumps increases with depth of water. This makes a large-sized solar pump more difficult to acquire, particularly due to financial constraints.

Besides the current water availability and seasonal variations, the long-term water trends will also influence the techno-economic viability of SIPs (Practical Action, 2010). Poor water recharge rates could lead to falling groundwater levels, in turn reducing the water discharge from solar pumps and irrigation capacity over time. In order to ensure long-term economic sustainability of SIPs, it would be essential to link their deployment with water management and harvesting schemes (Kelley et al., 2010). For instance, in Rajasthan, a water scarce state in India, financial incentives for SIPs are tied to adoption of micro-irrigation technologies and possession of water harvesting/storage structures at farm level (Kishore, Shah, & Tewari, 2014). However, pumping in areas with low water table should be carefully considered as it can lead to a further decrease in the water depth and overexploitation of the aquifer if the recharge is not sufficient.

3.3 | Solar irradiance

The water discharge from SIPs varies with the solar radiation, which in turn varies with the time of the day, month, and location. Figures 1 and 2 illustrate the daily and monthly variation in SIPs water output with solar radiation.

Monthly variation in solar radiation necessitates that the solar irradiance during the month with peak irrigation needs is factored in while deciding the size of solar array. This is crucial as solar panels contribute around 30–45% to the total solar pump cost (Hossain, Hassan, Mottalib, & Hossain, 2015) and optimal sizing of solar array is essential to contain the system costs. In this regard, the use of efficient pumps (say, subsystem efficiency of around 70%), could help reduce the size of solar array required and hence, the total system costs (Practical Action, 2010).

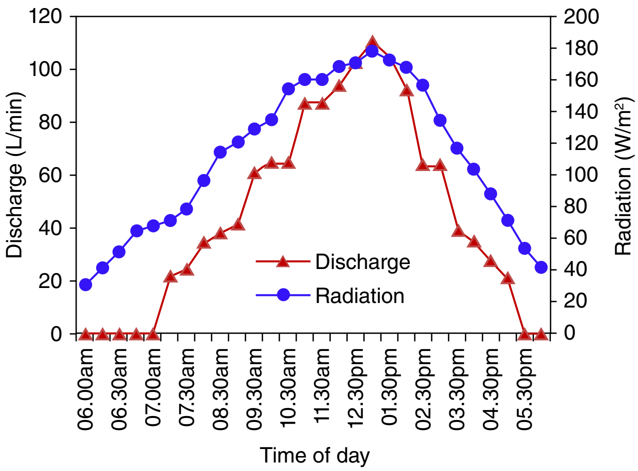

FIGURE 1 Daily variation in discharge of 2.2 horsepower (HP) solar pump with solar radiation on June 12, 2014, in Gazipur (Bangladesh). Source: Hossain, Hassan, Ahmmed, and Islam (2014)

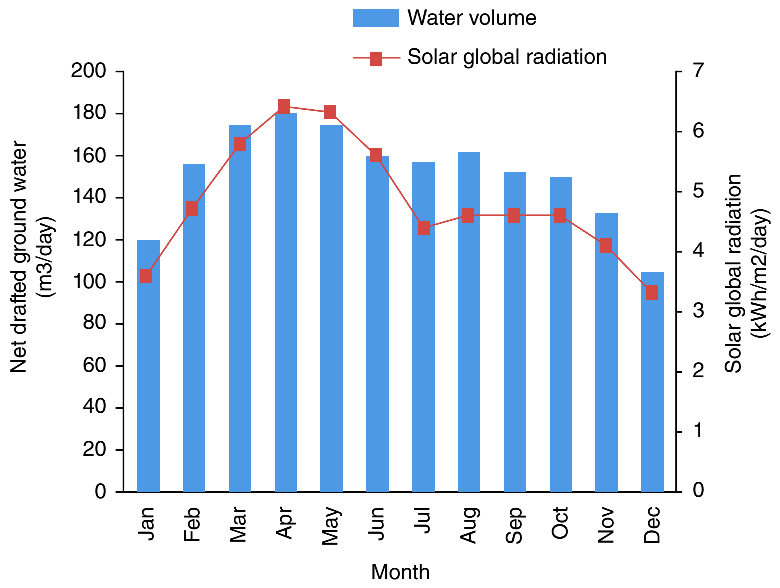

FIGURE 2 Mean monthly daily water output of a 3-HP solar pump along with solar global radiation for different months in Patna, India. Source: Rahman and Bhatt (2014)

Also, the daily variation in solar radiation can limit the pumping hours, particularly in regions with fewer peak sunlight hours or higher incidence of cloudy cover. In regions with severe fog, solar pumps might not work for days at length. Even though the irrigation requirements are lower during such periods, low irradiance can pose challenges in irrigation of certain winter crops, as has been observed in case of wheat cultivation in North Indian states. Use of water storage structures, such as overhead tanks, lined-ponds, etc., can help overcome these concerns and ensure reliable access to irrigation.

3.4 | System quality and after-sales services

The economic viability of solar irrigation is also influenced by the system quality as well as timely repair and maintenance. While poor quality components may lead to frequent breakdowns, lack of technically trained personnel or spare parts can result in delayed repairs and defunct systems (KPMG, 2014; Nathan, 2014). Even a few days of system unavailability during peak growth season can significantly impact the crop yields (Nederstigt & Bom, 2014). Spurious and low-quality solar pumps are a particular threat, as there exists a high incentive to capitalize on the barrier offered by the high upfront costs of solar pumps (Agrawal & Jain, 2018). Lack of timely after-sales service has been cited as a major challenge faced by smallholder farmers, particularly in SSA (Gebregziabher et al., 2016).

This underscores the need for regulating the quality of SIPs available for consumers, training of local technicians, and incentivizing suppliers to provide service warranty and timely services. In India, the national government prescribes technical specifications and quality standards for variety of solar pumps eligible to receive support under state schemes (NABARD, 2014). Eligible suppliers have to comply with these regulations, besides providing free service warranty for 5-year period. To ensure timely after-sales service, the state government of Uttar Pradesh (India) has established a toll-free complaint redressal helpline for solar pump customers, and the suppliers are bound to address the complaints within 72 hr (Sambodhi & Dalberg, 2018). In parallel, private suppliers also offer product warranty varying from 2 to 5 years. Similarly, the recently launched Regional Certifications Scheme in West Africa aims to support off-grid deployment by creating a trained solar force and regional renewable energy (RE) standards (ECREEE, 2018). Adoption of such best practices could help ensure availability of quality solar pumps and reliable after-sales service.

3.5 | Scale of farming

Even though SIPs are cost-effective as compared to diesel pumps on life time basis, farmers' ability to fund their high capital costs would be a critical factor in their adoption (Kelley et al., 2010). In this regard, the scale of farming becomes important, as it determines the capacity of solar pump required (and hence, the system costs), the revenues from cultivation, purchasing power of the farmer as well as his ability to access credit facilities.

While the scale of farming may not directly determine the economic viability of SIPs, it influences the possibility of SIP adoption, particularly for smallholder farmers. Very few smallholder farmers have been the beneficiaries of subsidized solar pumps in Rajasthan (India), as they find even the subsidized products expensive (Kishore et al., 2014). In SSA, majority motor pumps are used by the richest 20% farmers, often due to lack of finance (Namara, Hope, Owusu, De Fraiture, & Owusu, 2014). It would be essential to devise alternative business models and financial products to make solar irrigation accessible to even smallholder and resource poor farmers. Table 1 illustrates the different types of business models for solar irrigation being tried and employed in different parts of the world. However, each of these models would require tailored financial, technical, and policy support, the discussion of which is beyond the scope of this paper.

3.6 | Access to inputs and crop markets

Irrigated land is 2.7 times more productive than rain-fed land (FAO, 2011). Solar irrigation could significantly enhance crop yields and revenues in unirrigated areas. However, effectiveness of irrigation depends on the availability of complementary inputs, such as fertilizers, improved seeds and extension services (You et al., 2011). Across many developing countries, farmers generally lack access to high-quality inputs, market information about crop prices, and crop markets, key barriers to profitable irrigated farming (Mwamakamba et al., 2017; Pittock, Bjornlund, Stirzaker, & van Rooyen, 2017). In fact, access to market and extension services are found to be important determinants of adoption of lift-irrigation technologies (Gebregziabher, 2012; Wakeyo & Gardebroek, 2017). This underscores the need for convergence between solar irrigation program and other market linking and extension programs. This, however, might face challenges related to institutional coordination between different government departments overseeing relevant programs. In this context, role of development partners and market actors also becomes important. For instance, suppliers like SunCulture in Kenya (REEEP, n.d.) and partner organizations in Bangladesh[2] also provide extension services and market information to their customers for adopting better cropping practices.

3.7 | Utilization factor

While the capital cost of SIPs is significantly higher than the diesel or electric pumps, their marginal cost of water pumping is zero. This makes utilization factor, the fraction of time for which the systems is in use, a key determinant of economic viability of SIPs. For instance, some farmers in northern West Bengal (India) need irrigation for an average of 8 hr/day for 30 days in a year. Ownership of SIPs by such farmers would imply the system lying idle for majority of the year, potentially making it economically unviable.

Returns on solar pump investment can be enhanced by increasing its utilization factor. In areas with good groundwater recharge rates, this could be done by assisting the farmers to grow multiple irrigated crops in a year, particularly those with high value and requiring frequent irrigation, such as vegetables. Additionally, farmers can use their solar pumps to sell water

TABLE 1 Different types of business models for solar irrigation

Business models	Examples of deployment
Individual ownership models	
Retail and pay-as-you-go (PAYG): Suppliers provide individual SIPs to farmers, along with provisions of service warranty for 2–5 years.	In Kenya, suppliers such as FuturePump and SunCulture provide customized SIPs to farmers, on retail (Kunen et al., 2015) and recently on PAYG basis (Nichols, 2014).
Equity cum subsidy model: Suppliers provide SIPs at benchmarked costs to farmers, of which a share is borne by the government/donors as capital subsidy. Suppliers have to meet prescribed technical standards and provide multi-year service warranty.	In India, more than 140,000 SIPs have been deployed under this model, with a generous subsidy support from national and state governments (Agrawal & Jain, 2018).
Rent-to-own: Suppliers provide SIPs on loans to farmers, with the SIP acting as collateral. Farmers have to pay a fixed monthly fee and interest is charged on the declining principal balance. After the balance is paid in full, the customer owns the equipment.	In Nepal, Sunfarmer provides SIPs on rent-to-own basis. Farmers have to pay a small down payment and the remaining amount can be paid in installments over a 3-year period. Farmer cooperatives identify the interested farmers and collect monthly payments on behalf of the supplier (Kunen et al., 2015).
Shared models	
Group sharing: A group of farmers jointly owns and share a SIP to meet their irrigation needs.	In India, GIZ along with SIP suppliers, is enabling the farmers to form joint liability groups (JLGs) and secure collateral free bank loans, to purchase SIPs.
Renting: A provider owns, maintains and rents the SIPs to interested farmers. The provider could be a SIP supplier, any private entity or farmers association.	Claro energy in Bihar (India) has this model at several locations. A portable trolley-mounted SIPs is offered on a fixed hourly rent to small farmers within a local area (Kakkar, 2017).
Water-as-a-service: Under this, a SIP is used to pump and sell water for a fee to a group of farmers. The system can be owned, operated, and maintained by a SIP supplier, farmers association or any other third party.	In Bangladesh, more than 600 SIPs have been deployed under this model. With the help of low cost finance and partial grants, NGOs and MFIs own and operate SIPs to sell water for irrigation to farmers (Sarkar & Ghosh, 2017).
	In India, farmers' associations, such as Vaishali Area Small Farmers Association (VASFA) in Bihar, own and operate multiple solar pumps to provide irrigation water for a fixed fee to their members (Kohler, 2014).

GIZ, German Agency for International Cooperation; SIP, Solar irrigation pump.

to the neighboring farms, as is widely prevalent in many parts of India (Durga, Verma, Gupta, Kiran, & Pathak, 2016). Alternatively, SIPs can be promoted via different business models facilitating its shared use (see Table 1). In other areas, utilization could be improved through use of surplus electricity from solar panels for household/productive purposes (Raymond & Jain, 2018), though further innovation would be needed to leverage this opportunity.

3.8 | Cost of alternative solutions

The cost of alternative solutions, such as diesel and electric pumps, is also an important determinant of economic attractiveness of solar pumps. Several studies have shown that on a life cycle basis, solar-based irrigation is more economical than irrigation using diesel pumps (Hossain et al., 2015; KPMG, 2014; Narale, Rathore, & Kothari, 2013) This is particularly true for remote areas with limited access to fossil fuels or electricity infrastructure (Meah et al., 2008). For instance, there has been a rapid uptake of diesel irrigation pumps in SSA. Here, farmers spend USD 400 per hectare as one-time capital investment on diesel pumps, and incur USD 330 per year as operation and maintenance costs per hectare (De Fraiture & Giordano, 2014). In comparison, a solar pump of 1 HP, adequate to irrigate 1 ha land from shallow water sources, would cost around USD 1,700.[3] As compared to diesel powered pumps, a 1-HP solar pump investment would have a payback of around 4–5 years, post which the farmers can use solar pumps with negligible operation and maintenance (O&M) costs and a moderate pump replacement cost, over 15 years. It should be noted that the payback years and economic viability of SIPs can significantly vary with utilization factor.

Further, in regions with cheap or subsidized electricity costs, such as India, SIPs are less economical than electric pumps (Agrawal & Jain, 2015). However, despite 20 million subsidized agricultural electricity connections in India, around 9 million farmers use diesel pumps for irrigation, mostly due to lack of connections or inadequate power supply. Solar pumps would be more economical than diesel pumps for such farmers, who should be targeted for the technology's early adoption. However, economic viability does not necessarily translate into affordability. Given the high upfront cost of SIPs and long payback years, many farmers might find it unaffordable, particularly due to limited access to long-term finance. Innovative financial products would be required to facilitate the SIPs adoption by interested farmers (Agrawal & Jain, 2018).

4 | 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). Environmental sustainability of SIPs could be discussed in terms of their impact on the surrounding environment by way of depletion of water resources and pollution load. In this context, three key factors are discussed below.

4.1 | Water use efficiency

As SIPs are used for water pumping, a key sustainability concern is their impact on freshwater resources. Once installed, the marginal cost of pumping with SIPs is near-zero. On the one hand, this serves as an incentive to increase the cropping intensity to reap higher crop revenues. On the other hand, this could lead to excessive water withdrawals and depletion, particularly in regions with low water recharge rates (Shah & Kishore, 2012). Groundwater depletion is already a major problem in several countries of Asia. For instance, more than 60% of irrigated land in India relies on groundwater resources and groundwater levels are decreasing across most parts of the country. It would be critical to ensure that SIPs are used for irrigation in an environmentally sustainable manner. There are three key considerations in this regard.

The high capital costs of SIPs make it essential that their capacity (size) is optimized to meet the peak crop water needs. This in turn, puts an upper limit on the amount of water that SIPs can extract on a daily basis, as they can operate at optimal levels only when the sun shines. In this way, optimal sizing of SIPs can ensure judicious water use and needs to be promoted. In fact, it has been observed that solar pumps increase water use efficiency, as crops can get water in smaller quantities at shorter intervals (Kishore et al., 2014). When farmers do not need to irrigate their farms, they can sell the water to nearby farmers, expanding irrigation opportunities for poor farmers. Prevalence of such water markets could further incentivize farmers to irrigate their lands in a judicious manner. Policymakers have a key role in promoting adoption of optimally sized SIPs.

Adoption of SIPs under sharing or service-based business models (see Table 1) might also promote more efficient water use, as compared to individually owned systems. However, deployment of SIPs under such models would require a higher financial, organizational, and training support from government or developmental agencies.

Finally, in regions with limited water resources, it would be essential to promote additional water-management mechanisms. These may include use of drip and sprinkler kits, mulching, conservation farming, etc., which could help conserve water at the point of application. Additionally, rain-water harvesting structures like ponds and check-dams could help recharge water sources. Overall, agricultural planning and water resource management would be crucial to ensure long-term sustainability of water resources as well as the use of SIPs.

4.2 | Abatement of carbon emissions

SIPs could considerably reduce green house gas (GHG) emissions and other pollutants as compared to electric or diesel pumps, both of which are highly carbon intensive (Fthenakis, Kim, & Alsema, 2008; Gopal, Mohanraj, Chandramohan, & Chandrasekar, 2013). For comparison, a 5-HP irrigation pump operational for 1,250 hr/year, would emit 5.2 and 4 t of CO_2/year, where powered by diesel and grid-electricity, respectively (Jain et al., 2013). Replacing just 5 million diesel pumps in India by SIPs could help abate 26 million tons of CO_2 emissions annually (Jain et al., 2013).[4] This is equivalent to 1.2% of India's total carbon dioxide emissions in 2010 (MoEFCC, 2015). In the context of climate change, SIPs not only offer an opportunity for mitigating GHG emissions, but also to make farmers more resilient against the erratic rainfall patterns caused by climate change.

4.3 | End of life management

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 SIPs from a lifecycle perspective. End-of-life management is particularly important for components such as solar panels, controllers, and invertors, which are classified as e-waste, and their improper disposal could adversely affect the environment (Fthenakis, 2003; PV Cycle, 2014).

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 United States) (PV Cycle, 2016; Wesoff, 2011). But recycling of solar panels is currently limited to few regions only. Moreover, recycling of solar waste at dispersed scale is relatively expensive (VM Fthenakis, 2003). As the deployment of SIPs 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 SIPs waste, along with user awareness and involvement, would be critical going forward.

5 | 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). 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, Molin, & Steg, 2012). Accordingly, we have identified following as the key determinants of public acceptance, social equity and hence, the social sustainability of SIPs.

5.1 | Technology 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). A recent survey of 1,600 farmers in Uttar Pradesh, India reveals that only 27% farmers were aware about SIPs technology (Jain & Shahidi, 2018). Same survey indicated that less than 2% farmers had information about supportive government schemes. Separate interviews with SIP suppliers in India also indicate that low levels of awareness among farmers have been a major barrier to its adoption. Moreover, such information hurdles significantly limit access to technologies for women and resource poor farmers (De Fraiture & Giordano, 2014). Limited awareness among bankers, particularly field-level staff, is also a concern, as it increases the perception of risk in financing SIPs and hinders access to loans for farmers (Agrawal & Jain, 2018).

A key determinant of social acceptability and adoption of SIPs would be awareness about the technology among potential customers. This warrants intensive awareness campaigns, technology demonstration and training exercises to enable farmers and other stakeholders to take informed decision about SIPs. For this purpose, local knowledge networks, such as farmers' cooperatives, should be leveraged to spread information and increase acceptance of new agricultural technologies among farmers (McCullough & Matson, 2011).

5.2 | System quality and after-sales service

Besides being important factors for economic viability, system quality and timely after-sales service are also crucial determinants of social acceptability of SIPs. SIP is a relatively new technology with low market penetration. Availability of cheap but poor quality products can severely affect consumer perception about SIPs technology, as has also been observed in case of solar lighting products in several countries (Lighting Africa, 2010). Similarly, lack of timely access to after-sales service can also reduce farmers' confidence and interest in solar irrigation systems. Though SIP is a low maintenance technology, the solar panels require regular cleaning, as accumulation of dust can lower the panel power output and hence the water discharge from SIPs (Abu-Aligah, 2011). While it is easy to clean the panels, at times farmers do not follow the prescribed schedule,[5] which often results in low water outputs and frequent complaints of poor-performance. These concerns call for stringent measures to regulate the quality of systems, training of local technicians and periodic awareness campaigns for farmers on identifying certified systems as well as on following procedures for SIPs maintenance.

5.3 | System security

Solar panels, which comprise almost half of the total system costs, run the risk of theft and physical damage, which can severely affect economics and public acceptance of SIPs. Instances of solar panel theft have been recorded across many countries, such as India, South Africa, Zimbabwe, Mali, etc. (Amar Ujala, 2015; Azimoh, Wallin, Klintenberg, & Karlsson, 2014). These often compel the users to frequently move the panels indoors for safety, leading to nonoptimal positioning of the panel and reduced system performance (Azimoh et al., 2014). Measures such as fencing, security fasteners, anti-theft bolts, alarms and system monitoring tools are being used to secure solar panels against risks of theft (Lawson, 2012). Use of mobile racks or containers for mounting solar panels can also reduce the risk of theft, without affecting performance (Boyd, 2016). Several prototypes of portable solar pumps are now available India and East African market (Ibrahim, 2017; Kakkar, 2017; Mumo, 2017).

5.4 | Co-benefits

Besides providing access to irrigation, SIPs could offer multiple co-benefits, which make them attractive on both economic and social dimensions, for users as well as other stakeholders. First, they are often used to supplement drinking water requirements, particularly in water scarce regions, such as Rajasthan in India (Sambodhi & Dalberg, 2018). Second, they could significantly contribute toward gender empowerment. Across most parts of the world, it is women, who fetch water for domestic purposes and food production. SIPs, which are much easier to use then diesel alternatives, could alleviate this burden and allow women more time for productive and leisure purposes (IRENA, 2016). Third, during periods when irrigation is not required, solar panels could be used for meeting household electricity needs, or for running chaff-cutters and farm-machinery, with additional socioeconomic benefits. However, this would incur additional expenses for battery and inverter (for AC pumps). These co-benefits enhance the social impact of SIPs and need to be acknowledged in policy discourse around sustainable irrigation.

6 | DISCUSSION AND CONCLUSION

Ensuring access to irrigation in a reliable and affordable manner continues to be a policy imperative across most developing countries. SIPs have emerged as a promising alternative to conventional diesel and electricity powered irrigation pumps. In view of the past irrigation experiences and the imperatives of sustainable agricultural development, it is important to ensure that SIP deployment happens in a sustainable manner, before supporting their scale-up. We have identified 14 factors, which together determine, whether the use of SIPs in any given context would be economically, socially, and environmentally sustainable. Figure 3 depicts these factors (in blue) and their influence on the sustainability dimensions (in red), using a causal loop diagram (CLD).[6]

As illustrated in Figure 3, each sustainability dimension is influenced by multiple factors. Accordingly, while planning for sustainable deployment of solar pumps, all factors would need to be considered concurrently. For instance, the input costs of a solar pump can be minimized through optimal design or subsidy support. But in order to ensure its economic viability, it would also be important to ensure that the concerned farmer can obtain timely after-sales service and has access to agricultural inputs and crop markets, without which he might not be able to realize the benefits of solar-powered irrigation.

The impact and importance of each factor would vary with the local context. For instance, in regions with poor water availability or low groundwater recharge rates, factors such as peak water requirement, depth of water source and water use efficiency would assume a much greater influence on both economic and environmental sustainability of SIPs, than in regions

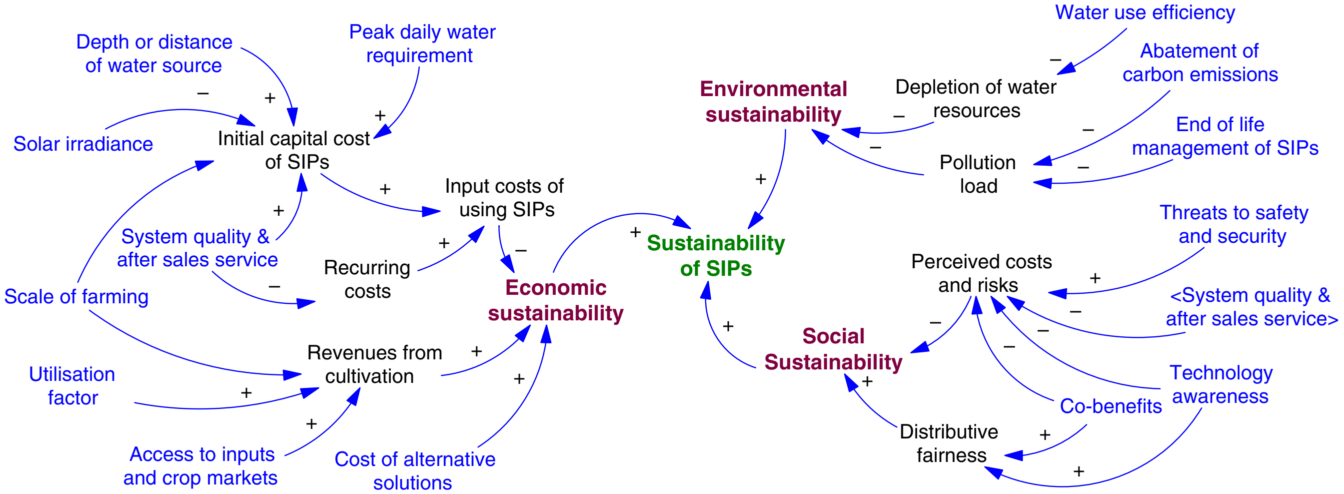

FIGURE 3 Sustainability of solar irrigation pumps—Key determinants and their influence. Source: Authors' Analysis

with good water availability. Accordingly, a higher focus on efficient irrigation practices and water resource management would be needed in the former case. This highlights the need to identify the factors, which wield higher influence in a given context, to design context-specific policies and programs.

It should also be noted that the measures suggested to improve one dimension of sustainability could impact dimensions other than the targeted one, positively or adversely. For instance, high capital subsidies, aimed at improving the economic viability of SIPs, could adversely affect their environmental sustainability, by promoting oversized pumps and excessive water withdrawals. Similarly, unconditional disbursal of subsidies could reduce the incentive to improve irrigation efficiency, while a universal incentive regime (i.e., not targeted to specific beneficiaries) may get captured by better-off farmers and increase inequity in access to irrigation. In short, solutions to improve one aspect of sustainability could lead to problem shifting between different dimensions.

Effective strategies to ensure sustainability of solar irrigation would be the ones, which augment at least one dimension of sustainability and deteriorate none. Therein lies the utility of this work, which could allow the policymakers and other key stakeholders to take cognizance of all relevant issues and adopt a holistic approach to SIP technology diffusion. In many countries policies tend to address only one key issue with one policy. This is understandable as it presents itself as an easy fix, but most countries have different local situations and requirements. Therefore, policymakers should take cognizance of the diversity of local factors and support different technological options, business models, incentives, and regulations to sustainably facilitate irrigation access through solar pumps.

We propose four comprehensive action tracks, which could guide future programs to support adoption and scale up of SIPs in socially acceptable, economically viable, and environmentally sustainable manner, under varying contexts.

- **Building awareness and trust:** Policymakers along with solar pump suppliers should focus on awareness generation about the solar pump technology, its costs and benefits, as well as limitations, through information campaigns and field demonstrations. Robust standards, regulation and strict enforcement would be essential to ensure availability of high-quality systems and timely after-sales service, which is critical to build and maintain users' trust in a new technology. Besides targeting farmers, education drives need to focus on key supporting stakeholders, including financiers and local knowledge networks, which in turn could facilitate wider acceptance and adoption of SIPs.
- **Prioritizing areas for deployment**: As the sustainability of solar irrigation depends on several local factors, it is important that policymakers, financiers, and suppliers assess the suitability of solar irrigation for a given context. It would be economically and environmentally prudent to prioritize regions with sufficient water availability and solar radiation during irrigation months. Also, areas with rising use of diesel-powered irrigation, availability of crop inputs and market linkages would find more takers for SIPs, and should be prioritized. In regions where such factors are weak, SIPs deployment strategies would need to be augmented with additional support mechanisms.
- **Providing need sensitive support and incentives:** As farmers have varying irrigation needs and purchasing capacities, different support mechanisms and business models for solar irrigation would be required. Policymakers and financiers should facilitate access to credit for farmers as well as suppliers/service providers, while being sensitive to the needs of the business models. While initial subsidy support might be required in many regions, particularly for demand stimulation, it should be properly targeted toward resource poor farmers.

- **Ensuring long-term sustainability**: Policies supporting SIPs must incentivize optimal sizing of pumps, support development of efficient and portable SIPs, and promote efficient irrigation practices. Broader policies on agriculture should incentivize locally suitable crops, which are ecologically suitable. Finally, a regulatory framework to manage the SIPs at their end of life and focus on water harvesting strategies would be imperative to the long-term sustainability of solar irrigation.

SIPs offer an unprecedented opportunity to facilitate irrigation access to millions of farmers, and contribute toward food and livelihood security in developing countries. Even as the governments and developmental organizations are increasing efforts to promote their uptake, this study puts forward key determinants and strategies for sustainable deployment of SIPs. The work could be useful for different stakeholders, such as policymakers, SIPs manufacturers and suppliers, as well as researchers, across different countries. It could help in designing better policies for deployment of SIPs as regards to identification of priority areas, streamlining of regulations, designing financial incentives for both suppliers and consumer. It could also help the suppliers of SIPs to better understand the likely barriers to adoption of SIPs under different contexts and accordingly devise innovative business models for different customer segments. This study puts forward broad measures to ensure sustainable deployment of SIPs. Future research could focus on identifying region/country specific challenges to sustainability of SIPs and adapting the measures proposed in the study to the local context. Another key research area would be to identify business models, which could facilitate access to solar irrigation in a sustainable manner for a targeted region, along with measures to create supportive ecosystem for their diffusion. Finally, a key concern regarding use of SIPs at scale is their impact on water consumption pattern and sustainability of water resources. But there exists limited evidence on this subject, which calls for empirical research.

ACKNOWLEDGMENTS

This research was conducted at and with the funding support from the Council on Energy, Environment and Water, a not-for-profit policy research institution based in New Delhi, India.

CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

ENDNOTES

[1]In case of solar pumps, overhead water storage has been found to be more economic than battery storage.

[2]Based on interviews with senior management at IDCOL (Bangladesh).

[3]Free on Board (FOB) price for imported systems, based on interviews with Indian suppliers.

[4]This does not include additional CO_2 emissions on account of use of solar pumps, which have an energy payback time of 1–4 years (KPMG, 2014).

[5]Observed during a field visit to Chomu village in Jaipur, India.

[6]The causal loop diagram is developed and interpreted on the basic premise of "ceteris paribus," that is, 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.

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How to cite this article: Agrawal S, Jain A. Sustainable deployment of solar irrigation pumps: Key determinants and strategies. *WIREs Energy Environ*. 2018;e325. https://doi.org/10.1002/wene.325