Solar Water Pumps: Technical, Systems, and Business Model Approaches to Evaluation

India, Myanmar, and Sudan

Comprehensive Initiative on Technology Evaluation at MIT
Product Evaluation Report, June 2017

Salt pan workers stand in front of their solar water pump system in the Little Rann of Kutch, Gujarat, india

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LIST OF ACRONYMS

3-S	Three S evaluation framework
A	Ampere
AC	Alternating current
BESCOM	Bangalore Electricity Supply Company
CITE	Comprehensive Initiative on Technology Evaluation
DA	Development Alternatives
DC	Direct current
GDP	Gross domestic product
HP	Horsepower
IBC	Intermediate bulk container
JNNSM	Jawaharlal Nehru National Solar Mission
kWh	Kilowatt hour (unit)
L	Liter
MIT	Massachusetts Institute of Technology
MNRE	Ministry of New and Renewable Energy
MT	Metric ton
NGO	Non-governmental organization
PVC	Polyvinyl chloride
Rs	Indian rupees
SD	System dynamics
SEWA	Self-Employed Women's Association
TDS	Total dissolved solids
TEL	Technology Exchange Lab
UP	Uttar Pradesh
USAID	United States Agency for International Development
USD	United States dollar
V	Volt
VFD	Variable frequency drive
W	Watt

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INTRODUCTION

The Comprehensive Initiative on Technology Evaluation (CITE) at Massachusetts Institute of Technology (MIT) is dedicated to developing methods for product evaluation in global development. CITE is led by an interdisciplinary team at MIT, and draws upon diverse expertise to evaluate products and develop a deep understanding of what makes different products successful in emerging markets. Our evaluations provide evidence for data-driven decision-making by development workers, donors, manufacturers, suppliers, and consumers themselves.

From September 2015 to March 2017, CITE researchers evaluated solar-powered water pump systems. These are the most technically complex products yet to be considered under CITE's "3-S" evaluation framework of suitability, scalability, and sustainability. While other products evaluated by CITE have been relatively simple, as in water filters and food storage technologies, solar pumps include components of power generation, power electronics, and pump components. In addition to partners in the United States, the team worked closely with partners in three locations in India and two locations in Myanmar, as shown in Figure 1. These partners have been instrumental in choosing the solar pump technology used by farmers in their communities.

Figure 1. Fieldwork Locations

WHY SOLAR PUMPS?

Across the agricultural sector in developing countries, access to irrigation is an important step in improving farmer livelihoods and productivity as it increases productive yields. The value of irrigation is dependent on rainfall patterns. For example, in a climate like India's where a four month long rain-heavy monsoon season is followed by eight months of little or no rain, irrigation makes the farmer's land available for cultivation for three seasons instead of two, significantly improving their productivity and income. Many other countries may experience a season that is drier than others and while their rainfall patterns allow them to cultivate year round, irrigation can significantly improve yields, and provide a wider variety of crop options.

Pumping water from either surface sources such as ponds, lakes, and canals, or from underground through open wells or deeper borewells, is the primary driver for irrigation. These pumps come in a variety of power sources, including hand pumps, diesel pumps, grid-tied electric pumps, and solar pumps.

In India, access to irrigation is seen as a policy priority for meeting important development objectives. Yet, significant roadblocks exist—for example, weak water markets and fragmented institutional coordination and implementation (Varma 2016). Further, the environmental impacts of expanding irrigation have raised concerns about over-extraction of groundwater, which has become the dominant irrigation source, especially in the presence of a lack of political and social incentives to institute efficient irrigation practices—namely, pricing water to reflect its true value (Agricultural Census 2011; Shah and Kishor 2012).

In this context, solar pumping has been identified as a desirable technological solution. For instance, one research group found that, out of four renewable energy technologies for irrigation, solar-powered pumps seemed to have the highest utilization potential across India as a whole (Kumar and Kandpal 2007). From a policy perspective, the Ministry of New and Renewable Energy (MNRE) has promoted solar pumps for irrigation under a national solar mission, the JNNSM, which provides large capital subsidies (generally 80 percent to 90 percent) to make such systems affordable to farmers. State-level governments have followed suit and provided similar and complementary policies. Also, while solar pumps have a high up-front cost, their operating costs are very low compared to widely used diesel pumps, reducing risk of price fluctuations to farmers.

With this context in mind, this report has the following objectives:

- To create a technical comparative evaluation of the pumps used in conjunction with solar panels
- To understand the socio-economic drivers and grassroots level insights association with solar pump use
- To analyze the complex interaction between water, energy, and food through system dynamics modeling
- To analyze the business models used by farmers to access and use solar pumps

- To create a tool to enable farmers and institutions supporting farmers to correctly size the pump needed for their particular application

How to Use This Report

This report contains comparative rating charts and key findings based on two years of rigorous research and analysis undertaken by CITE's multidisciplinary team at MIT.

The findings of this report are especially applicable for the following audiences:

- In India
  - Project implementers tasked with procuring solar pump systems or those interested in using the technology in their projects
  - Consumers in India looking for information about solar pump technologies
  - Government officials and development practitioners seeking to better address agricultural issues and policy development for solar pumps
  - Indian designers, manufacturers, suppliers, and retailers seeking to better understand consumer preferences, use patterns, and needs

- In similar contexts in other countries
  - Development practitioners outside of India who may be unaware of the availability and affordability of solar pumps for applications in their own regions
  - Global designers, manufacturers, suppliers, and retailers seeking to better understand consumer preferences, use patterns, and needs

The report is organized into three main sections:

- The **Scoping Study** which included a literature review, establishment of partnerships, informal discussions with partner management and end-users, and downselecting from an initial five use cases to two cases for further evaluation.
- The **Solar Water Pumps for Irrigation** evaluation focuses on larger scale systems in Jhansi, Utter Pradesh, India with Development Alternatives and Harobele, Karnataka, India with SunEdison and BESCOM (the local electricity distribution company). This evaluation included surveys and interviews with stakeholders in the two implementation sites, analysis of survey responses, and financial and systems modeling.

Methodology at a Glance

The solar water pump evaluation included three key components…

Scoping Study

Potential Use Cases
Case #1: Uttar Pradesh, India (Irrigation)

Case #2: Karnataka, India (Irrigation)

Case #3: Gujarat, India (Salt Production)

Case #4: Rakhine, Myanmar (Irrigation)

Case #5: Darfur, Sudan (Drinking Water)

Desk Review
42 reports and papers reviewed

Field Visits
India
Myanmar

Partnership Development
SEWA
MercyCorps

Downselect

Identify Final Use Cases
Case #1: Uttar Pradesh, India (Irrigation)

Case #2: Karnataka, India (Irrigation)

Case #3: Gujarat, India (Salt Production)

Identify Tools & Models
Pump Sizing Tool
System Dynamics Model

Evaluation Criteria

Technical Performance: How well does the product perform its function in the lab and in real world settings?

Availability: Is the product available in local markets? Is the supply chain dependable?

Ease of Use: How easy or difficult is the product to use by an untrained user in a non-lab setting?

Affordability: Is the full cost within the ability and willingness to pay for low-income users?

Demand Generation: How high is the demand, and can the supply chain actors increase demand?

Data Sources

Lab Testing
Five pumps were imported from India and tested in a dedicated lab at MIT

Field Testing
The CITE team took field measurements of flow rate, well depth, panel voltage and current and pump voltage and current

Sensors
SMS-based sensors were installed in pumps and panels being used for irrigation and salt production

Findings at a Glance

Findings at a Glance: Solar Water Pumps for Irrigation

Technical Performance: Proper system sizing is essential to both the financial and environmental sustainability of a project.

Ease of Use: All farmers considered the solar systems **very easy to use.** Solar pump systems provide additional benefits in terms of increased safety, ease of use, and comfort with the technology.

Affordability: We found that farmers have a high capacity to accept increases in monthly payments up to and maybe just slightly more than their current payments for diesel.

Findings at a Glance: Solar Water Pumps for Salt Production

Technical Performance: Of the 5 pumps tested, Falcon and Kirloskar brands offered the best performance at a price farmers can afford.

Ease of Use: Based on sensor data, the salt farmers appear to run their systems all day, every day.

Affordability: Before loan payback, profit margins are similar to diesel pumps, but after the loan is paid back, farmers can realize significantly increased profits from the same quantity of production compared to diesel pumps

Tools and Models

Pump Sizing Tool

While pumps increase marginally in cost with increased size, solar panels required to run larger pumps add significantly to the capital cost, without any additional benefit. Larger than necessary pumps with high flow rates can also contribute to groundwater depletion. This tool can help farmers "right-size" their pump systems.

Water Food Energy Nexus Model

When introducing state-level policies that increase the use of solar powered pumps, additional factors to curb groundwater usage must be considered. This System Dynamics model examines that effect on groundwater levels in Karnataka and Gujarat over a ten year period after the introduction of such policies, including factors such as efficient irrigation and grid feed-in tariffs.

Comparison Chart

product Information			product attributes				
make/model	Unit cost USD (incl. shipping)	type	max head (m)	max flow (LPM)	daily max at 10m	priming ease	efficiency
Falcon FCM 115	$260 ($455)	3 Phase AC 120V	24.3	300	●	◕	◕
Harbor Freight (baseline)	$128	1 Phase AC 120V	32.2	81	○	●	◔
Kirloskar SKDS116++	$236 ($486)	3 Phase AC 120V	22.9	291	●	◑	◕
Rotomag MBP30	$535 ($730)	DC 30V	20.2	295	◕	◕	●
Shakti SMP1200-20-30	$1835 ($2018)	3 Phase AC 120V	32.0	162	◑	◔	◔

Scoping Study

Overview

The team first completed a detailed scoping study, focusing on India and Myanmar. These locations were chosen because they represented both a mature market for solar pumps (India) as well as a nascent market (Myanmar). The locations were further ideal because of our partnerships with the Self-Employed Women's Association (SEWA) and Mercy Corps in the two countries respectively.

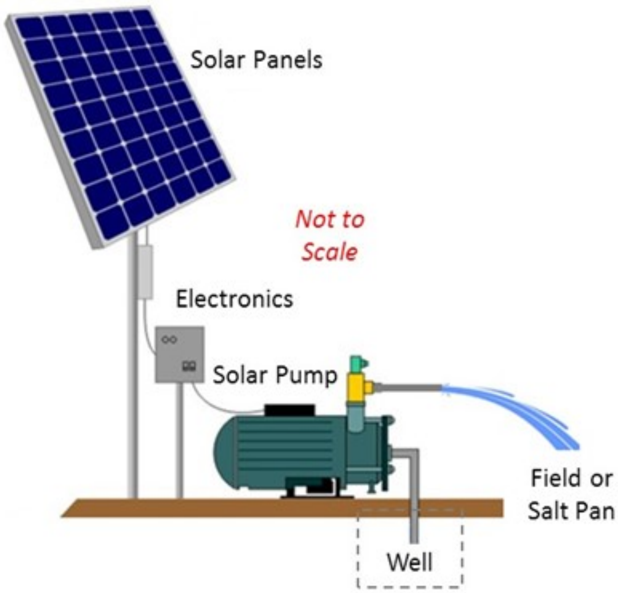
In keeping with the concept of lean research, the objective of the scoping study was to quickly ramp up knowledge within the team on the technical, financial, and social aspects of the adoption and use of solar pumps so that fieldwork could be done quickly and efficiently. By gaining a deeper understanding of the way solar pumps are used by farmers from both desk research and brief introductory field visits, the team was able to develop more appropriate and research questions that directed and focused the subsequent fieldwork, as well as aided the development of the use cases we used to evaluate the different kinds of solar pumps.

The scoping study began with a desk-based literature review which covered solar pump usage, the policy environment, water scarcity issues, irrigation coverage, the energy scenario including electricity grid coverage and diesel for distributed power, project economics of solar pumps, and the various delivery models for solar pumps.

Design of Solar Pump Systems

Solar pump systems come in many forms for many different applications, but are broadly divided into three components: the solar panels, the electronics, and the pump itself. Figure 2 shows the basic design of the solar pump systems included in this evaluation.

Figure 2: Sketch of Solar Pump Design



Panels

Solar panels are by far the most expensive component of the solar pump system. The size of the array is dependent on the power needed for the pump, so even a small change in the pump horsepower can have an outsized impact on the overall cost of the system. Panels can be either fixed or have manual single-axis tracking to ensure the highest levels of sunlight are hitting the panels during both morning and afternoon hours.

Figure 3: Solar Panel in the Little Rann of Kutch

Electronics

Most pumps used for agriculture are alternating current (AC) pumps, but solar panels produce direct current (DC) power. The electronics, usually housed in a weatherproof box under the panels, convert that DC power into AC that can be used with the pumps. The on/off switch is usually a part of the electronics box as well. The amount of access farmers have to the electronics varies from project to project. In Gujarat, India, salt farmers using solar pumps had full access to the electronics and often made small adjustments to maximize their use of the system including attaching additional pumps, and even diverting electricity for home-lighting and television.

Figure 4: Solar Pump System Electronics

Figure 5: Solar Pump System Electronics (detail)

Pumps

The pumps are the system component most understood by the farmers, because in almost all cases, they have already been using pumps of some kind. In several cases, we saw farmers use their existing electric pumps with the new panels and the majority of salt farmers interviewed pump using the solar panels during the day and using diesel generators at night.

Figure 6: Solar Pump

Figure 7: Diesel Pump

Scoping Study Use Cases

The scoping study consisted of gathering primary data from users who have adopted a solar-powered pump system. This was complemented by information gathered from interviews and meetings with project implementer staff and other relevant stakeholders such as suppliers and manufacturers.

Specifically, we developed our research understanding of three different use cases in India for solar pumps: shallow open well irrigation in Uttar Pradesh, deep bore well pumps for irrigation in Karnataka, and surface pumps for pumping brine for salt farming in Gujarat. Additionally, a site visit in Myanmar with our partners at Mercy Corps took place to ascertain the current solar pumping landscape in a nascent market and given an alternative political and economic context.

Case #1: Uttar Pradesh, India

Development Alternatives (DA) is a Delhi-based non-governmental organization (NGO) focused on sustainable development. In Orchha, Madhya Pradesh, DA has developed the TARAgram campus, a sustainable community that acts as a training facility and incubator for DA's new products and services for members. Orchha is only a few kilometers from Jhansi district in Uttar Pradesh and many of its energy programs, including the solar pump program are focused there because of the state's poor grid connectivity and power infrastructure.

Figure 8. Flood Irrigation Using Solar Energy in Uttar Pradesh

Each of the four solar pumps the team visited in Uttar Pradesh are used by between one and four farmer families in rural areas for irrigation of a range of revolving crops, including both horticulture and cash crops. The solar pump systems operate in open wells and replace previously used diesel pumps. As shown in Figure 8, the primary method of irrigation is by flood, but one farmer also had a sprinkler system she used occasionally.

This particular belt of central India has been hit hard by drought in the last several years, resulting in very low water levels in the wells in which the pumps are installed. We visited before monsoon season during which time water levels would ordinarily be low, but in years of normal rainfall, still operational. Because of the drought one of the wells was completely dry, and two others were only marginally functional.

The solar pumping systems implemented in this model were identical to each other and installed at the same time in 2015. Each system consisted of a three horsepower (HP) AC submersible water pump connected to a 3040W (16 x 190W) Solar Array through an electronic controller/inverter. The water level varied from 30 to 60 feet and the water was used for crop irrigation purposes with an average usage rate of three hours per day. Due to the ongoing drought in the region two of the four wells were at significantly low levels (a water depth of two to six feet). As a result, the farmers were limited in the time they were able to pump, one such farm was only able to pump for six minutes before shutting off the system due to lack of water.

The pumps belong to the local farmer federation and are financed using a revolving fund model. This model relies on initial grant funding from the Coca-Cola Foundation to catalyze the project. The grant funding was used to purchase the first four systems for farmers within the federation. The farmers then make payments on the solar pump systems to the federation, which in turn will be used to purchase future solar pumps for other members of the federation. So, although the grant does not get repaid to Coca-Cola, it does catalyze the financing for additional solar pumps in the future. Despite the availability of government subsidies for solar pumps, the facilitating NGO, Development Alternatives, has chosen not to access government money because of delays and complications associated with government subsidies.

When assessing the financial viability of solar pumps, it is necessary to also assess what they are replacing, in this case, diesel pumps. Diesel pumps have a low initial fixed cost, and a relatively high variable marginal cost of fuel. Solar pumps have a high initial fixed cost, but no fuel cost and very low maintenance cost. As with many high priced assets, the farmers pay monthly installments on the pumps. Assuming that the water well is functioning properly, these payments are equal or less than the equivalent cost of diesel for the same number of irrigation hours.

However, in drought conditions, water is not available in high enough volume for substantial irrigation. In summer months, this means that a great deal of a farmer's land is not cultivated at all. In this scenario, farmers using diesel pumps would have substantially lower diesel expenses because they are pumping for a shorter period of time. But those using solar pumps still have the same monthly payments to make on their solar pump systems. For those unable to cultivate, they are also unable to make the payments. This has implications for the revolving structure, effectively curtailing the federation's ability to plan for new pump systems because of the low ability of farmers to repay.

As facilitators of a pilot project, Development Alternatives prioritized engaging with community leaders and influencers. While these handpicked farmers were not involved in the technology selection, they were able to give feedback about the operation of the systems. The farmers took good care of the panels and understood their value. Their only complaint was a lack of water in the wells because of the drought. They were given very basic training on systems that were so easy to use that even small children could flip the switch to run the systems. Farmers were not trained, however, on the more intricate workings of the inverter, which will remain closed and locked for the duration of the project unless the system is being serviced by a representative of the installer company.

CASE #2: KARNATAKA, INDIA

The stakeholder ecosystem for the Karnataka project is more complex than the other cases examined in this report. The policy environment was extremely important in this case, as the project is essentially government-sponsored. USAID played an important role in the development of a “net-metering” policy for the payment for power fed back into the grid, and the Power Ministry was instrumental in engaging with the project to ensure its success. The local distribution company, Bangalore Electricity Supply Company (BESCOM) released a tender for the development of a pilot solar pumping project for the catchment area around one particular electricity substation, and SunEdison won the bid and was in charge of carrying out the implementation of the project. They engaged Selco, a for-profit social enterprise, for local community development and capacity building. This pilot would provide a proof of concept for this unique solar pump business model.

The pilot was chosen to be implemented in Harobele, a village 80 kilometers south of Bangalore, because of its water availability, pre-existing power supply, and support from both local and state government. In addition to the technical components of the project, BESCOM set up a famers’ cooperative to manage the finances from the project. BESCOM pays the feed-in tariff[1] to the cooperative’s bank account, which then transfers funds appropriately to individual farmers’ bank accounts.

Rather than replacing diesel pumps, the farmers interviewed[2] in Harobele are replacing pumps powered by grid electricity. These farmers are cultivating a single crop throughout the year: mulberry bushes for silk production. The farmers generally have one pump per family and cultivate between two and four acres. These pumps are also much larger in size because they pump from a deep borehole well instead of an open well.

[1] The amount of money paid to a person generating electricity remotely and feeding it back into the electricity grid

[2] The total planned pilot was for 250 pumps, of which 149 were installed by the time of the field visit. Of these, 20 farmers were interviewed.

Figure 9. Grid-Powered Solar Pumping in Karnataka

The solar pumping systems installed in this area were specified and sized by SunEdison. The program was mid-installation at the time of the fieldwork and the systems were between one month to two weeks old. Each system consisted of a 5 or 7.5 horsepower (HP) AC borehole water pump connected to a 7,200W (24 x 300W) solar array through an electronic controller. The solar arrays were intentionally oversized by 150 percent as part of the financial model which is described below and to maintain a continuous baseline feed-in to the electricity grid (see Figure 9). The water level varied from 240 to 600 feet and the water was used for crop irrigation purposes with an average usage rate of 6.5 hours per day for 138 days during the year.

The financial model for this project relies on a key piece of policy called net-metering, which allows the electricity distribution company to pay farmers for excess electricity generated by the panels. It brings together the local electricity distribution company, the farmers, the project implementer, and debt financing. Government subsidies were also used: farmers pay a minimal part of the initial cost, approximately Rs. 5,000. Government subsidies cover 40 percent and debt financing covers the rest.

In this model, the farmers are paid Rs. 7.2/unit (kWh), of which Rs. 6 go toward debt servicing, Rs. 2 go to the farmer federation for the monitoring and operation of the model, and Rs. 1 goes to the farmer. After the debt is repaid in full, the farmer will receive Rs. 7/kWh. This incentivizes efficient use of the pumps including drip and sprinkler irrigation to ensure the maximum number of hours of solar production can be fed into the grid.

The farmers in Karnataka had the least amount of choice in project and system design. Because the pumps were situated in bore holes, the entire system was closed and not open to customization by the farmer. All farmers within the catchment area of the electricity distribution substation were enrolled in the project, suggesting either that it was an irresistible opportunity or more likely, that they were under at least minor pressure to join. SunEdison engaged Selco for capacity building among the participating farmers, but this training was either minor or incomplete because many of farmers, despite being more educated and in better financial situations than other farmers we interacted with during our project, did not have a full understanding of the intricate financial arrangements in place for the payback of these expensive systems.

CASE #3: GUJARAT, INDIA

SEWA, an organization whose membership consists of informal women workers and whose mission is to ensure their rights, is the driving force behind the solar pump project for the salt farmers in the Little Rann of Kutch. The salt farmers pump brine from underground into salt pans miles away from the nearest villages in a desolate stretch of desert. The farmers are beholden to salt merchants who set the price for salt each year and provide the salt pan workers only a very small margin on their produce.

SEWA's Hariyali program not only facilitates the promotion of solar pumps for the salt workers, but also has solar lantern and efficient cook stove programs. They first started installing the solar pumps four years ago. Today, 250 of the 286 solar pumps installed on the Rann were installed by SEWA. The introduction of solar pumps into the Rann has reduced the cost of production for salt pan workers, which can significantly improve their profit margins.

Figure 10. Solar Pumping for Salt Production in Gujarat

This final model is unique because the pumps are used not for agricultural irrigation, but for salt production. There are 40,000 salt farmers in the Little Rann of Kutch in Gujarat, of which 250 are working with the local NGO to purchase solar pumping systems. They pump underground brine into salt pans, which evaporate to produce rock salt (see upper right corner, Figure 4). The farmers want to maximize the amount of salt they can produce, so they run pumps anywhere from 12-24 hours per day pumping brine into the pans. The solar pumps they are using replace diesel power generators and greatly reduce the cost of fuel for the farmers during the salt season.

The solar pumping systems implemented in this model were sized and the specifications were chosen by SEWA Hariyali. The program was in its second year at the time of the fieldwork and the systems were between one month and two years old. Each system consisted of either a 1 HP or 1.5 HP AC water pump connected to a 1800W (6 x 300W) Solar Array through an electronic controller, some farmers had added an additional second 1 HP pump to their systems. The water level varied from 40 to 69 feet and systems were utilized for brine extraction and shifting from one pan to another with an average usage rate of 8 hours per day (all usable sunlight hours) for 180 days during the year.

The financing model for the salt farmers is debt financing facilitated through SEWA's microfinance lending arm. This model is very similar to a consumer finance model, where the farmer takes possession of the solar pump system and makes monthly payments for a specific period of time in order to pay off their system, after which they own it in full. This model work well for the salt farmers because, unlike agricultural irrigation, they are pumping as much water as possible, ensuring that the solar power generated is used in full.

SEWA has secured loans for the salt farmers and negotiated the purchasing of the solar water pumping systems. Additionally, SEWA have taken an active role to date in relation to maintenance and after sales support. This is motivated by a desire to continue the project and encourage more farmers to adopt the technology.

The desires and concerns of the end-users were strong driving factors on technology choice in Gujarat. The SEWA staff has an extended presence in the community and is trusted by the members to make decisions in their best interest. These users rely heavily on their pump systems (both diesel and solar) for their primary income generation activity, brine extraction, as a result they are much more dependent upon and invested in the technology. In addition, because of the remoteness of the salt pans, pumps and panels cannot be easily transported into town for maintenance or repair. Consequently, the farmers learn to maintain the systems and even make adjustments to improve performance.

CASE #4: RAKHINE, MYANMAR

In Myanmar, 65 percent of the workforce is involved in agricultural activities, and the sector accounts for 36 percent of GDP (gross domestic product). It is widely acknowledged by the government and the international development community that improvements within the agricultural sector are central to development and poverty alleviation in the country. Mercy Corp Myanmar are working with smallholder farmers throughout the country to introduce new farming techniques, which increase yields and diversify crops, and to create better linkages between the farmers and their potential markets. To complement the Mercy Corp agriculture focus, an investigation into the current state of solar water pump availability and usage in Myanmar was undertaken during the CITE evaluation process. This included a field visit to the site of new training farm in Rakhine State, during which various stakeholders were interviewed and local vendors were surveyed.

With 80 percent of the annual rainfall occurring during the monsoon season (mid-May to mid-October), most regions in country experience significant drought during the dry season and reduced productivity. Despite this shortfall, 80 percent of farmers rely solely on rainfall to supply water to their crops. By 2016, there were 600 irrigation facilities across the country covering about 23% of the net sown area. However, pumps contribute only a fraction to this irrigated land, with 7.2 percent of irrigated land from river pumps and 2.3% of irrigated land irrigated by deep well pumps.[3] Those who do have access to wells and boreholes primarily use hand pumps to irrigate their plots less than one acre in size for yard long beans, okra and pulses production during the dry season, while their rice fields lie dry and unusable.

Due to increased trade with China in recent years, an influx of diesel and petrol powered engines have entered the markets in Myanmar, in the form of motorbikes and generators. A wider availability of skilled mechanics to service such systems has consequently increased the market demand for diesel and petrol powered water pumps. Those with the available capital, still a small subset for farmers nationally, are investing in 5-6.5 HP portable petrol pumps (USD 100-120) and having a service provider dig boreholes close to their fields (USD 80-100). A strong advantage of the petrol pumps over hand pumping is the reduction in time needed to irrigate crops, allowing for a reduction in working hours, or diversifying crops to those that require more water, such as morning glory. Additionally, as the pumps are portable, we noted during our visit to Rakhine that enterprising pump owners were renting the pumps to neighbors for a fee (USD 2.50-3.50 per hour), enough to cover diesel costs and make a small profit. Without an extensive survey, it's difficult to estimate the frequency of this practice, but with farmers cultivating small plots close to each other, it is logistically straightforward. Word of mouth from neighbors was a significant driving factor when choosing which pump to purchase and from which supplier. The suppliers import the pumps from China and Japan.

With less than 26% of the population with access to grid electricity, diesel generators are commonplace. Solar panels, imported from both India and China, are available for domestic use and can be purchased in local markets at a cost between USD 0.38-0.61 per watt (Indian average: USD 0.45-0.75 per watt). Any electric pumps available in the local Sittwe shops were marketed for household use with the unanimous belief that rural farmers would not be interested in electric pump due to lack of grid connections. Farms in more urban areas that do have grid connections do not enjoy reduced rates when utilizing the electricity for agricultural purposes, as is commonplace in India. They are classified at the domestic tariff, with incremental increases in charges based on monthly usage limits.

While a number of suppliers of solar water pumps exist within South-East Asia, and have expressed interest in expanding into the Myanmar market, currently only 3 manufacturers have a presence in the country, and they each have only a handful of installations: Lorentz, a German Solar Pump Manufacturer through their local partners EcoSolutions (3 installations) and Salay (5 installations); SETEC, a Chinese electricity power supplier (1 installation); and Proximity Designs, a local NGO designing specifically for the Myanmar context.

[3] Than, Mu Mu. Roles and Efforts of the Irrigation Sector in Myanmar Agriculture Practice. 2nd World Irrigation Forum. 6-8 Nov 2016.

Pump Manufacturer	Installer	Specs	Installation
Lorentz	Ecosolutions	Submersible Flow rate: 100 m3/day 2.1kWp solar array	January 2016 Ayeyarwady
-	SETEC Power	Submersible 2.8kW solar array 2.2kW solar DC to AC inverter 1.5kW 3-phase AC pump	December 2013 Pond installation at President's farm
Proximity Designs	Proximity Designs	50L/min USD 350 per system	-

Availability of financing and limited household capital (82 per cent of households in the Mrauk U region of Rakhine State spend less than USD 118 a month) reduce the viability of individuals purchasing solar water pumps. One vendor in the Sittwe market recounted a recent visit to Yangon where he saw a solar water pump demonstration by a Chinese manufacturer. He declined to become a supplier as he deemed the cost of the system too high for his customers to afford (pump: USD 245, panels: USD 140).

The adoption of solar water pumps within India has been aided by government intervention schemes and in-country production capabilities. The swift rate of adoption has resulted in post-fact discussions on concepts such as grid feed in tariffs and water conservation issues. As Myanmar is a budding market with vast potential, lessons learnt from the Indian context can encourage the conversation to begin with the larger environmental and economic hurdles before critical uptake occurs.

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CASE #5: DARFUR, SUDAN

Two of CITE's partners are interested in solar pump applications related to the provision of clean drinking water in Internally Displaced Persons (IDP) camps, including the USAID Office of Foreign Disaster Assistance (OFDA) and Oxfam.

USAID/OFDA is currently supporting four NGOs—CARE, Mercy Corps Scotland, World Relief International, and World Vision—to convert diesel fuel-powered water pumping systems to hybrid, solar-powered systems in Darfur IDP camps. According to the January 11, 2016 Sudan Fact Sheet, "the NGOs have installed 14 solar-powered water systems in 13 IDPs camps in West Darfur and South Darfur and plan to transition nine additional fuel-powered water systems to solar power in FY 2016. The new solar-powered water pumping systems have reduced operational costs and increased access to safe drinking water in the Darfur IDP camps."[4]

Since 2010, the Oxfam team in El Fasher, North Darfur, Sudan has been looking into replacing the diesel-powered submersible pumps they are operating in the Al Salaam Internally Displaced Persons (IDP) camp as part of the extended response to the complex emergency that began in 2004. Currently Oxfam maintains five boreholes with their associated water tanks and water distribution equipment in the camp in partnership with the Government of Sudan (GoS) and local community water committees. In 2011 CITE Sustainability Lead Jennifer Green conducted an extensive review of the El Fasher water systems while employed at Oxfam America, and the CITE team met with the local Oxfam water and sanitation specialists to discuss how we could use this analysis as a basis for a solar pump focused evaluation in Darfur.

Following discussions with OFDA and Oxfam, the CITE team decided not to pursue the IDP drinking water use case further due to the following reasons:

- Security is a major factor in Darfur and MIT students are not permitted to travel there
- Sudan strictly limits the number of foreigners they allow into Darfur, and even though it was likely that the non-student researchers on the CITE team could get in to Sudan, we deemed it unlikely that we could get the additional permissions to conduct research in Darfur. Given the cost and logistical burden of the trip and the fact that the Darfur permissions can only be applied for in person in Khartoum, Sudan, the risk of not meeting our research goals was too high
- The situation in Sudan has been deteriorating due to a high influx of refugees from neighboring South Sudan and the country is also facing a major famine.

[4] https://scms.usaid.gov/sites/default/files/documents/1866/sudan_ce_fs02_01-11-2016.pdf [Accessed April 12, 2017]

- Our contact at USAID/OFDA left the Agency shortly after our discussions began and while we are still hoping to work with Oxfam in the near future, the current security situation in Darfur and lack of research funding impacted our ability to include this case in the overall report

SUMMARY OF USE CASE SELECTION

Solar pumps can be used in a variety of applications, for agriculture, drinking water, and for cottage industry/processing. The use cases provided a variety of applications as well as delivery models for solar pumps. Ultimately, the uses cases for this evaluation were chosen because they had strong local partners and were programmatic in nature, with a relatively larger number of installations. For example, while solar pumps for drinking water is a prevalent application across the world, each NGO or facilitating organization may only have a few pumps, and the pumps may have a significant geographic spread.

In order to facilitate collection of data and to create useful and robust evaluations, two primary use cases were chosen: solar pumps for irrigation and solar pumps for salt production.

OVERVIEW OF CITE EVALUATION CRITERIA

In past evaluations, the CITE team has defined six primary criteria to be used in our comparative evaluations, as shown in Figure 11.

Figure 11: CITE Evaluation Criteria

	Top Level Description
Technical Performance	The technical performance of a product is defined as how well it performs its primary function both in the lab and in real world settings. The indicators for this criteria are specific to each product type.
Ease of Use	Ease of Use refers to how easy or difficult a product is to use by a wide range of potential users, including those with no formal education. It also compares how well the product performs its primary function when used by a untrained user in a non-lab setting.
Availability	The Availability criteria evaluates whether a product is accessible to a wide range of potential users and whether the manufacturer's supply chain can continue to provide a high quality product in a dependable way at scale.
Affordability	The Affordability criteria evaluates whether the initial purchase price of the product is within the ability and willingness to pay for low-income users and whether the total life cycle cost including upkeep and maintenance is manageable. Credit mechanisms are also evaluated.
Demand Generation	The Demand Generation criteria evaluates whether there is an existing demand for a product and if not, whether the product manufacturers and retailers are marketing the product at a sufficient level to create new demand. Associated demand creation projects are also evaluated.
Environmental Impact	The Environmental Impact criteria evaluates whether the product has a negative impact of the environment and/or whether the commercial success of the product could be substantially impacted by climate change.

For both the irrigation case and the salt production case, we attempted to stay as consistent as possible with this six-criteria comparative system; however, we modified the approach in several ways in order to fit the more technically complex evaluation into CITE's lean research approach:

Irrigation Case

First, for the Irrigation Case, the pumps being piloted in in the areas where fieldwork was conducted were large (e.g., 5 or more Hp) and it was infeasible to purchase and test the pumps in the MIT lab due to their cost, size and power requirements. Therefore, in this Case, the "Technical Performance" criteria was combined with Ease of Use and is based solely on the perceived performance of the larger pumps as reported by the user surveys. Also, since the pumps used in the Salt Production Case were considerably smaller (~ 1 Hp) than those observed in the field in the Irrigation Case, we thought that any attempt to compare the two sets of pumps against each other would prove imbalanced. Given that there were only a few farmers using the larger systems in Utter Pradesh and a limited number in Karnataka, fewer than 30 surveys were administered in the irrigation case and therefore the sample size was too small to produce robust results. For this reason, we do not present a "Scorecard" summary of results in this Case. However, the results of the surveys are incorporated into our discussion of the pumps throughout the report and provided important input for the pump sizing tool that is discussed later in the report and available on the CITE website.

Salt Production Case

For the evaluation of the pumps sized for the salt production use case (~ 1 HP), we conducted interviews in April 2016 using the full survey with only 21 salt farmers. From those results and discussions with our partner SEWA, we decided to focus this evaluation on the technical performance of the pumps in the field and the MIT lab, the performance of the solar panels in the field, the reported and observed usability of the solar pump system, and a detailed analysis of the cost advantage of replacing or combining solar pumps with diesel pumps. For the technical performance criteria, we do present a "scorecard" style comparative table of pump performance in the MIT Lab. In this use case evaluation, we did not address the supply chain (availability) aspects, the demand for solar pumps with users other than SEWA members, or the environmental impacts of the salt production.

In the next sections, we present the results of the irrigation case and the salt production case separately and then make some final conclusions applicable to all the defined use cases.

Solar Water Pumps for Irrigation

Uttar Pradesh and Karnataka, India
Rakhine, Myanmar

Solar Water Pumps for Irrigation

Findings at a Glance

- **Technical performance:** Proper system sizing is essential to both the financial and environmental sustainability of a project
- **Ease of use:** All farmers considered the solar pump systems very easy to use. Solar pump systems provide additional benefits in terms of increased safety, ease of use, and comfort with the technology
- **Affordability:** Farmers have a high capacity to accept increases in monthly payments up to and maybe slightly more than their current payments for diesel

In order to increase self-reliance as well as food production, numerous programs exist in India to encourage smallholder farmers to irrigate their fields. These include free or low-cost electricity in some regions and, more recently, capital subsidies for purchasing solar water pumps. However, pumping water for agriculture use in India has a significant impact on the water table and long-term water resources.

The irrigation portion of the evaluation focused on two main sites, Jhansi in Uttar Pradesh and Bangalore in Karnataka. Both sites have a number of solar water pumps that are being used by local farmers for irrigation purposes but the implementation and demographics of the farmers differ greatly.

The systems in Jhansi, implemented by Development Alternatives, were installed by Punchline in a batch of six. Punchline is a system aggregator and does not manufacture the components themselves. From stakeholder interviews, it was determined that little-to-no site surveying was done prior to installation. Additionally, all six systems were identical and not tailored to individual locations. Conversely, the systems in Karnataka were both installed and the program implemented by SunEdison, the system manufacturer. Consequently, SunEdison had a team embedded in the community to ensure correct and efficient installation of the systems.

Because of the diversity of applications, pump sizes, and business models, a comparative evaluation chart has not been created for the irrigation use case, and instead the focus has been placed on the understanding of two important factors when considering solar pumping for irrigation – appropriate choice of pump size, and the impact of solar pumping on the water, energy, food nexus.

Approach & Methodology for Evaluation of Solar Water Pump Systems for Irrigation

The irrigation use case evaluation was divided into several activities:

- **User surveys** for social and economic factors, including perceived technical performance
- **Technical performance measurement** in the field both in person and through sensors

- **System Dynamics model** of the effect of solar water pump implementation policies (detailed in the Water, Energy, Food Nexus section of this report)
- **Development of pump sizing tool** (in conjunction with the irrigation use case, June 2016 onward)

USER SURVEYS FOR IRRIGATION

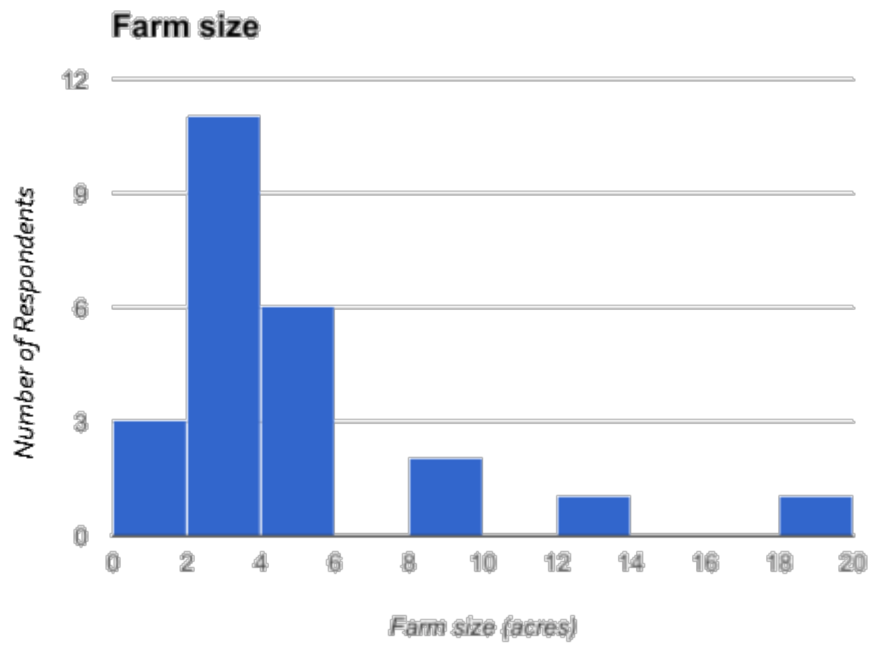
Surveys were developed to gather data on the use, perceived performance, availability, and affordability of solar pumps. Separate surveys were given to the end-user farmers (one survey for each pump), landowners, facilitating NGOs, system installers, and industry experts. All of the farmers with solar pumps in operation with the Development Alternatives program were surveyed, while the farmers with solar pumps in operation for the longest amount of time were surveyed from the SunEdison project, which was just getting underway.

Based on the data gathered from the user surveys, a demographic profile was developed, as shown in Table 1. In addition to the demographic data, a histogram of the reported farm sizes was also recorded, as shown in Figure 12. The farmers surveyed for the irrigation portion of the study had an average farm size between two and four acres and were mostly farming mulberry to host silk worms in Karnataka and a mixture of cash and horticulture crops in Uttar Pradesh. In Karnataka, the farmers had existing electric pumps, whereas those in Uttar Pradesh had previously relied upon diesel pumps, due to a lack of grid infrastructure that did not provide them reliable electricity for irrigation.

Table 1: Demographic Profile for Irrigation Case

Demographic Data of Survey Group (combined)	
Average Age of Respondent	48.5
Gender of Respondents	
Male	23
Female	5
Average Household Size	7.6
Education Level	
No school or Illiterate	11
Primary, Middle, or Secondary	15
Higher Secondary	2
Average Annual Income from Farming (Rs)	119,679
Average Annual Income from Farming (USD)	1,786

Figure 12: Size of Farm Owned by Respondents



Evaluation Criteria for the Irrigation Case

Table 2 shows the criteria used for the irrigation case evaluation.

Table 2: Evaluation Metrics for Irrigation Cases

Indicator	Description
Ease of Use	Ease of use refers to the ability of the end-user to operate the system as it was intended, as well as the system's ability to meet the farmer's pumping needs. Maintenance, convenience, user satisfaction, and required training were taken into account to evaluate ease of use for each pump.
Technical Performance (Perceived)	Perceived technical performance was evaluated based on farmer satisfaction with the solar pumps vis a vis their previous pumping method (either grid electricity or diesel). Technical performance was taken as a perceived measure gathered from survey data rather than actual technical data taken in the field, due to a small sample size and high variability in field-collected data.
Affordability	Affordability is measured both as the farmers' perception of system cost, as well as actual cost relative to income. We also gathered information on the financial model of each case study and the ability of the NGO and/or financing agency to pay for the system up front and over time.
Availability	The availability criterion includes access to trained personnel and physical parts. Technical support proves very important for systems as complex as these, while ease of repair also necessitates easy access to replacement parts in local markets.
Demand	Demand generation was calculated by evaluating the extent to which farmers endorse the systems they have been using, as well as the diffusion of knowledge about the systems throughout the greater community. While these systems are generally part of specific projects, and therefore not a "consumer" good in the sense that it can be readily purchased by individuals in local markets, awareness of their existence and of their value proposition is important in driving scale.
Safety	Safety was evaluated based on the availability of an automatic shut off valve. Overall perceived safety of the system to the user vis a vis their grid electric or diesel alternatives was also noted as well as actual reports of injury from either solar or alternate pumping systems.
Environmental Impact	Though solar pumps have a positive effect on energy balance, they can have a negative impact on groundwater resources. Rather than evaluating the environmental impact of specific systems, we chose to develop a System Dynamics model to evaluate the effect of different policies on the water-energy-food nexus. This is presented as a separate section in the document (The Water-Energy-Food (WEF) Nexus).

FINDINGS FOR THE IRRIGATION CASE

EASE OF USE

Despite the technical complexity of the solar systems, users overall found them overwhelmingly easy to use on a day-to-day basis, which consists primarily of cleaning the panels when they become dusty. One respondent demonstrated how easy the system was to operate by having his infant daughter toggle the on/off switch.

While day-to-day use proved easy, some respondents noted a desire to learn how to troubleshoot more complex problems, expressing concern that they were exclusively reliant on having to call technical staff to come inspect and fix the problems. Since pumping is not possible during more serious technical problems, having to wait for technical staff translates to lost income. On the other hand, several respondents also expressed hesitation at fixing any major issues by themselves and preferred that trained technicians handle problems as they arose.

TECHNICAL PERFORMANCE (PERCEIVED)

Researchers took measurements of flow rate and power input (panels to electronics) and output (electronics to pump). Technical performance measurements were taken using a flow meter and by measuring power input. However, these measurements proved uneven, as researchers were unable to take measurements at all sites visited due to numerous constraints, including frequent inability to access controller boxes and visiting farms on days when they were not irrigating. In the absence of reliable technical measurements, indicators drawing from end user surveys, which captured the qualitative experience of users, were developed.

Nearly all respondents were satisfied with the performance of their systems thus far, though it should be noted that several had only been using their systems for a very short time, especially in Karnataka where the project is in its early stages. Several respondents in Karnataka also expressed the view that the pumps, when run on grid electricity, had a higher flow rate. We were unable to substantiate this claim, but it is worth noting that several farmers mentioned this independently; regardless of its veracity, it is a commonly shared perception.

For the SunEdison project in Karnataka, the survey respondents had 5 HP submersible bore well pumps from either Falcon or CRI local pump manufacturers paired with a fixed 7200W array of SunEdison panels and Mitsubishi electronics including a net meter (which meters both the use and feed-in of generated electricity). The Development Alternatives project featured six solar pumping systems, of which four were in operation and whose users were surveyed. The DA systems were installed by a system integrator called Punchline Energy and featured a 3040W manual tracking solar array and a 3 HP submersible pump.

AFFORDABILITY

Though the cost of solar systems has come down significantly over the past decade due to a drop in the per unit cost of photovoltaic (PV) cells, they continue to represent a significant capital investment for smallholder farmers. At a cost of Rs 190,000 (about USD 2,800), the cheapest system we found was nearly double the average annual income from farming—approximately Rs 105,000 (about USD 1,500)—of our respondent sample. As a result, 96 percent of respondents said that they would not have bought their solar system had a financing or installment option not been offered.

With such an expensive product, it is perhaps not surprising that how long it would take to own the entire system was not a consideration that drove purchasing decisions—either between buying or not buying, or between one system and another. Given the significant risks and uncertainties associated with poverty, some studies have found that the time value of money (net present value, or NPV) is skewed toward the present with less regard for long-term financial considerations among lower-income individuals.[5]

AVAILABILITY

Systems are provided to program participants, or those residents within the jurisdiction of an implementer's project, and so availability of products on the market is not an issue per se—though the ability of farmers to procure small replacement parts in local markets proved important. However, a key dimension of availability that emerged during interviews with implementing partners was the importance of skilled technicians at the local level. This would be required as solar systems scale in a region, and would become more and more important as the systems age and require greater maintenance and increase in their likelihood of needing repairs. In the absence of a skilled, local workforce, solar systems may scale and yet may underperform or fall into disrepair, misuse, or disuse.

DEMAND

While there exists strong interest in solar systems for use in agriculture and beyond (for example, household lighting) among farmer households, demand is relatively weak and requires a "push" strategy. This is partly due to the systems' cost, but is also a function of how they are promoted more generally. Solar systems are rarely found as an off-the-shelf product that residents can purchase on their own. Rather, most systems are made available only through participation in specific programs, often government initiatives under the aegis of the Ministry of New and Renewable Energy (MNRE).

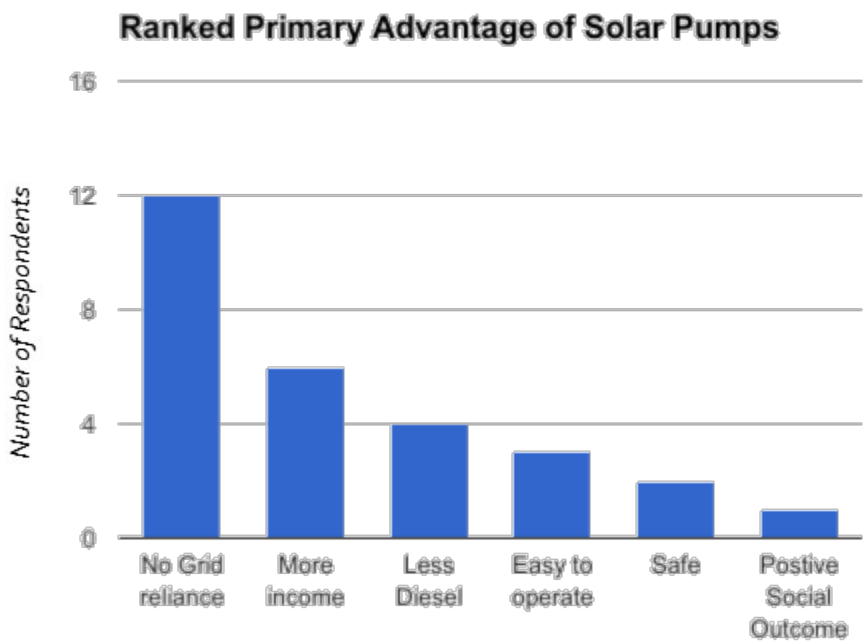
Moreover, demand for pump systems is skewed toward those that include higher horsepower pumps. This is because many farmers use horsepower as a proxy for system performance: the higher the horsepower, the better the system. Several organizations we interviewed noted the challenging nature of convincing farmers to use a lower horsepower pump with their systems. This points to the importance of addressing issues such as social norms and ingrained perceptions in the promotion of technologies.

Figure 13 shows the cited advantages grouped into these categories. Most farmers surveyed cared about the reliability of solar versus the grid. Grid power, while free or very low cost, was also unreliable

[5] Nielsen U. 2001. "Poverty and attitudes towards time and risk – experimental evidence from Madagascar." Working paper, Royal Veterinary and Agricultural University of Denmark

and available at inconvenient times. Solar powered pumps are seen as advantageous because they work during daylight hours, when farmers prefer to be working.

Figure 13: Farmers' View on Solar Pump Advantages



SAFETY

In terms of safety, beyond the threat of possible shock from wires, no real perceived danger was communicated to researchers by respondents. There seemed to be a general consensus that, in safety terms, solar pump systems are superior to both diesel- and electric-powered pumps. With diesel pumps, respondents shared problems of clothes getting stuck in the belt and getting pulled into the motor, burns from touching the belt when it is running, chest and back pain related to its use, and coughing resulting from inhalation of the exhaust smoke. With electric-powered pumps, the primary complaint was of timing: in Karnataka, because grid electricity is provided to farmers for free, it is provided at non-peak hours, often during the middle of the night. Several respondents noted how dangerous it was to irrigate at night, not only because it is dark and easy to lose your footing, but also because of the presence of dangerous nocturnal animals.

When the respondents were asked about the primary advantage to owning a solar pump, the majority spoke about a reduced reliability on other energy sources, such as the electric grid or diesel. While only a small number explicitly mentioned improved safety, they did mention that when the grid electricity was only available at night, farmers did worry about the danger from snakes, other wildlife, and possibly dangerous strangers. This, combined with the improved reliability, made the lack of grid reliance the most cited advantage.

ENVIRONMENTAL IMPACT

While solar water-pumping systems have been heralded as the environmentally friendly alternative to grid or fossil fuel powered pumps, caution needs to be taken when implementing this technology if it is to be truly environmentally sustainable.

Because solar pumps often provide farmers a more reliable, stable supply of water, the impulse to extract more water presents itself. In the absence of an incentive to conserve water, the adoption of solar pumps may therefore exacerbate existing water scarcity. Few programs incorporate such incentives, the case study presented in this report from Karnataka being a notable exception.

Changing minds is an important step. Several farmers use a visual inspection of the flow rate from their pump as an indication of whether it is performing well or not: the higher the rate, the better. And yet, few farmers interviewed adjusted the time they irrigated their land to compensate for higher flow rates. For the same reason, farmers tended to prefer pumps that have a higher horsepower: more horsepower means more power means a higher flow rate. Convincing farmers that they need to be conscious of their water use in the first place, and that they may likely be able to use less water than they currently do, is an important educational step in realizing the sustainable use of solar pumps. In addition, while larger diesel pumps do not get significantly more expensive as they get larger (for example, from 1 HP to 2 HP), the cost of a larger solar array to run a solar pump has a significant impact on the total price of the system. Therefore, educating farmers about the link between pump horsepower, panel size, and the relative cost of the total system is crucial for the future of solar pumping for agriculture to be done in a sustainable manner.[6]

During standard operation, solar panels are considered a benign technology and do not require additional fuels or emit chemicals or fumes. However, the manufacturing and disposal processes of solar panels can involve the use or exposure of toxic materials. As a result, they require diligence in following environmental and safety guidelines.

The economic advantage of a solar powered system results in a potential increase in groundwater extraction. When converting from fossil fuel powered systems, the farmers do not pay for incremental pumping (i.e. no ongoing fuel costs) and therefore incur no additional financial burden for increasing the hours spent pumping water. This increase, while advantageous in numerous cases, results in a dangerous precedent and can result in over-pumping and damaging the local water table.

In combination with solar water pumping, the use of drip irrigation as a primary irrigation method should be considered. It reduces the required amount of water and, when pumping to a storage tank, provides the freedom to irrigate at any time, even on cloudy days.[7]

[6] See our pump sizing tool discussed later in this report for more information
[7] See our section on the Water, Energy, Food Nexus later in this report for more information

The Water-Energy-Food (WEF) Nexus

Throughout the world, there exists a strong interdependency between natural and human systems in the production of agricultural crops (FAO 2015; Gulati et al. 2012; Shah and Giordano 2012). The production of food requires several inputs, two primary ones being water and energy. Access and availability of such inputs is predicated on both the local environmental context (natural system) and the local policy context (human system), which aims to promote or dissuade certain behaviors, such as technology adoption or efficient water use. Farmers' natural resource use affects the environment—in India, increased use of groundwater as an irrigation source is of particular concern (Kimmich 2013; Shah, Giordano and Mukherji 2012)—which can then stimulate responses on the individual and policy levels.

Agriculture can thus be viewed as an intimate, interconnected nexus of three systems impacted by policy and farmers' actions: water, energy and food, or WEF. Conceptualizing agricultural production as a WEF nexus promotes a holistic approach, which serves as an important and useful analytical framework (FAO 2015). Acknowledging the linkages between these three subsystems collectively makes possible the investigation and understanding of how changes in one subsystem impact outcomes in the other two. This is in distinction to more conventional analysis and management of agricultural systems as operating largely in isolation from one another, which masks the linkages inherent in the system. A nexus approach not only allows one to more explicitly state and examine the relationships between environmental and human system, but it also has utility as a frame for measuring and achieving broad policy goals, such as the global Sustainable Development Goals, or SDGs (Rasul 2016).

In this section, we investigate the WEF nexus as applied specifically to the case of solar pumps for irrigation in India. This is in distinction from other WEF studies that tend to view water as an input to energy production (Endo et al. 2016). In this case, both water and energy—in the form of solar energy that is replacing more environmentally harmful sources such as diesel-powered or coal-powered electric pumps—are used as direct inputs to agricultural production.

Modeling WEF Nexus in India: Solar Pumps

We draw on fieldwork and case studies from two states, Gujarat and Karnataka, to demonstrate the importance of local environment and policy contexts. In particular, we focus on the environmental impact of solar pump technology adoption under different policy scenarios, which are described in more detail below. We use a modeling approach that allows us to investigate the macro-level feedbacks inherent to the WEF nexus. Indeed, as Shah and Kishor (2012) note, "solar pumps are widely seen as an 'energy' solution; however, in the Indian context, they need to be viewed as a composite energy-and-water intervention that will affect both energy as well as groundwater economies."

In the next section, we describe our modeling approach, the model structure and results.

Modeling Approach: System Dynamics

System Dynamics (SD) is a quantitative modeling tool that employs macro-level thinking to analyze the impact of complex feedbacks in dynamic systems, such as agricultural processes and groundwater management. It is built on the belief that the structure of a system determines subsequent behaviors, and captures two essential features of many systems: that they are self-regulating and exhibit non-linearity over time. Such systems are common in both environmental and social systems.

Agriculture can be considered a coupled social-environmental system, where farmers rely on environmental inputs—namely water, but also seeds, soil nutrients, and sunlight—public policies that influence the availability of these inputs (e.g., capital in the form of pumps) and market conditions that govern how much income can be made. Feedbacks within this system are many: poor rains in one year may serve to increase government support to farmers in the next year; subsidies for new irrigation pumps may lead to increases in cultivated land; cash incentives for farmers to use efficient amounts of water for their crops can help stymie groundwater over-extraction. As such, SD modeling proves suitable as a means to investigate the dynamic issues inherent in agriculture.

SD models consist of two main components: 1) stocks, or accumulations over time of people, goods, or other items of interest; and 2) flows, or rates of change. Stocks and flows interact through a system of causal loops, which form the basis for the system's structure. These high-level diagrams serve to represent overall systemic feedback structures. As a consequence of self-regulation, a change in one area of the system generates ripple effects throughout the entire system through these feedback loops.

In the model we develop here, we consider the environmental impact of solar pump technologies in two States in India, Karnataka and Gujarat. From our fieldwork in 2016, we observed and heard from several actors across the solar pump value chain that promotion of the technology under heavy capital subsidies may lead to environmentally suboptimal outcomes. It is this relationship we sought to model and capture, and to consider various policy prescriptions that seek to mediate and ameliorate this relationship.

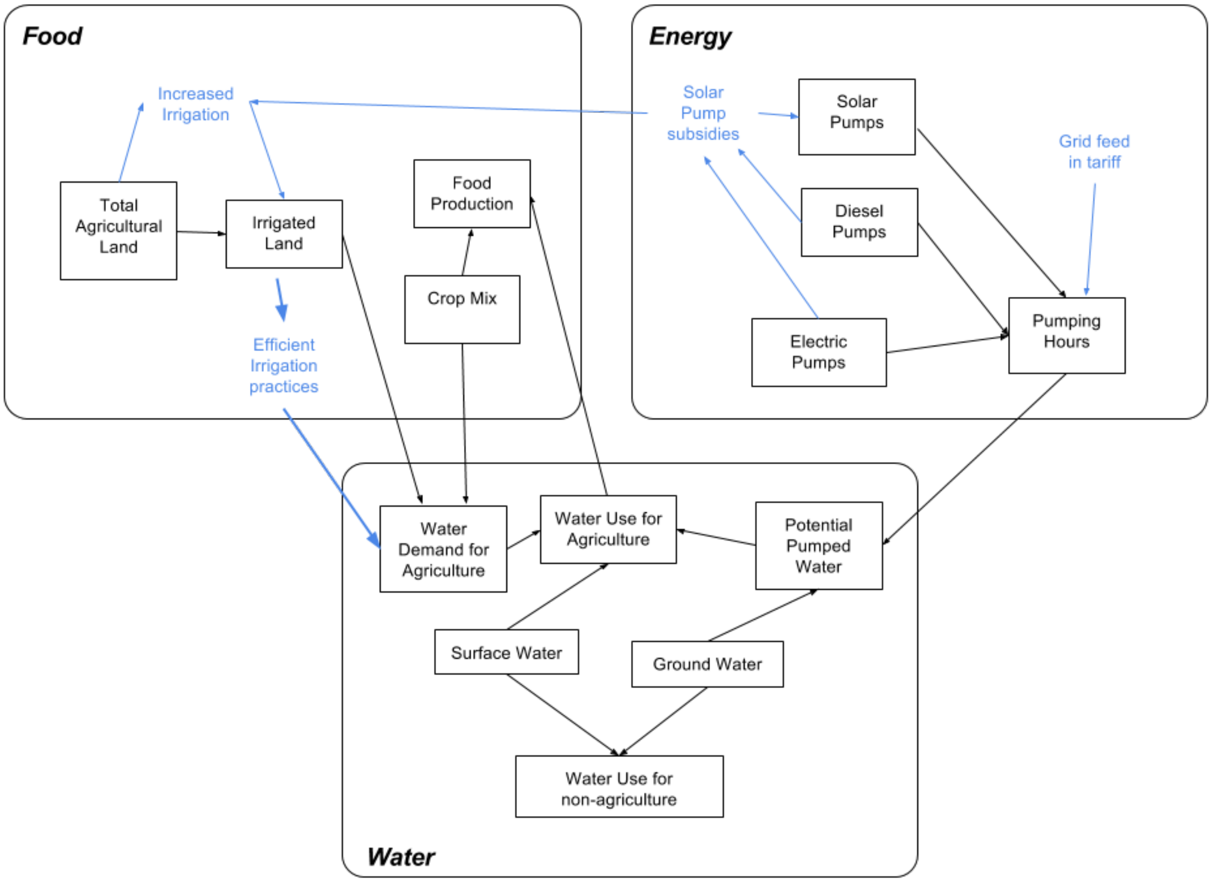
Model Structure

The model's structure draws from SD models developed by other scholars investigating the relationship between agricultural production, natural (especially water) systems and policy environments (Sohofi, Melkonyan, Karl and Krumme 2015; Zhuang 2014; Wang 2011; Ahmad and Prashar 2010) and is premised on the existence of a WEF nexus. Figure 14 shows the key relationships captured by this model.

One key aspect of the model is the feedback loop between irrigated agricultural land, solar pump adoption and water-and-energy use. In the absence of demand-side incentives and policies, greater solar pump technology translates to greater potential water supply, which leads to greater water demanded and used, which then leads farmers to further expand the area of land they are able to cultivate, and/or to irrigate for a longer period of time (day-to-day, or during the dry season).

The model is simulated over a 10-year period, beginning in January 2017, with a monthly time step (120 time steps total).

Figure 14: Schematic of SD Model Structure (Blue: Policy Interventions)



Model Inputs and Outputs

To ensure the SD model is as accurate as possible, variables were researched and included in the system. These included rainfall data from the India Meteorological Department; agricultural data from various central and state ministries; and water availability and use data from Ministry of Water Resources, Central Groundwater Board and state agricultural policy documents. Key variables from Karnataka and Gujarat, their values and sources are listed in Table 3.

Table 3: Data Sources and Inputs

	Karnataka	Gujarat	Sources
Total arable land (acres)	47.1M	48.4M	Indian Agriculture Census 2010-2011
Cropping intensity	1.03	1.06	
Irrigated area (acres), 2010-2011	8.1M	10.1M	
Agricultural land, total (acres), 2010-2011	30.0M	24.4M	
Agricultural land, total (acres) 2000-2001	30.4M	24.4M	Indian Agriculture Census 2010-2011
Irrigated area (acres) 2000-2001	4.3M	4.7M	
Water used for irrigation (bcm per acre per month)	6.4	3.2	Calculated from Water Policy reports 2016

The assumptions used in the Baseline scenario are outlined in Table 4, along with the sources of some the of the data used in the simulations:

Table 4: Assumptions for the SD Model Baseline

	Gujarat	Karnataka	Assumptions
Solar System Adoption Rates	pumps /month	pumps /month	Between 2001 and 2010 the total number of pumps, by Hp, was known. Combined with total figures for solar pumps in the two states, the adoption rates for solar are assumed to follow the same proportions.
0-3 HP	34	30.48	
4-5 HP	0.03	0.03	
6-8 HP	3.8	3.36	
9-10 HP	1.48	3.76	
< 10 HP	0.4	3.76	
Average hours of pumping	percentage of available hours	percentage of available hours	During the 2016 Field work, the survey results showed that when connected to the electric grid, farmers pumped on average 5 hours per day for 7 months of the year. 5/24 x 7/12 = 12% utilization. While the same data was not directly available for diesel the assumption was made that utilization is less due to the cost of purchasing diesel, opposed to free grid electricity. Average hours of grid connectivity in each state was also included in the model. Again from the 2016 field work, farmers reported solar pumping for 6-8 hours per day (or as long as the system would run) for 16 days a month, for 9 months of the year. 16/30 x 9/12 = 40% utilization.
Solar	40%	40%	
Diesel	10%	10%	
Electric	12%	12%	
Irrigation efficiency	percentage of land with drip or equivalent	percentage of land with drip or equivalent	Canal irrigation is known to be 60% efficient when it comes to water usage, versus drip irrigation can be up to 95% efficient. As a baseline figure 10% of land using drip irrigation in both regions was assumed.
	10%	10%	

Additional variables related to the various crops grown in Karnataka and Gujarat are shown in Table 5.

Table 5: Crop Mix Variables

Crop	Crop Mix		Productivity (kg/acre)		Crop Coefficients
	Karnataka	Gujarat	Karnataka	Gujarat	
Rice	16.83%	8.20%	1,665.99	770.45	1.13
Wheat	2.06%	11.05%	396.76	1,084.21	0.85
Jowar	10.50%	2.03%	403.24	424.29	0.80
Bajra	3.54%	9.29%	183.00	498.38	0.85
Maize	11.34%	5.28%	1,004.86	389.88	0.83
Ragi	7.12%	0.25%	666.80	302.83	0.85
Gram	3.35%	1.17%	244.13	382.59	1.05
Total Pulses	19.52%	6.62%	189.47	184.21	0.40
Groundnut	6.35%	18.77%	238.46	390.28	0.78
Sunflower	3.90%	0.00%	134.82	0.00	0.80
Tur	9.73%	2.43%	197.17	366.80	1.05
Sesamum	0.63%	2.20%	173.28	144.13	0.80
Castor	0.05%	3.78%	275.30	798.38	0.85
Cotton	5.03%	25.49%	111.74	206.88	0.85
Rape & Mustard	0.03%	3.44%	119.43	640.08	0.94
Sources	Indian Agriculture Census 2010-2011		Directorate of Economics and Statistics, Karnataka Directorate of Agriculture, Gujarat		USAID Journal of agrometeorology FAO Pereria et al (2014)

To determine the environmental effects of introducing various policy initiatives into the states the following key output variables were tracked over time:

- Groundwater Storage (in bcm)
- Agricultural Water demand
- Water use for agriculture
- Demand for water for agriculture, which is calculated as:

$$Ag.\,Water\ demand = \frac{(crop\ evapotranspiration - Effective\ precipitation)\ Irrigated\ Land}{Agricultural\ irrigation\ efficiency}$$

Where crop evapotranspiration is the measure of water absorbed by different crops during the growing season and is weighted by the crop fractions from x. Effective precipitation is determined by average rainfall and weighted by the amount that will go into agricultural processes, some is lost due to falling in cities or collected for other uses. Irrigated land is measured in acres and agricultural irrigation efficiency is determined by the use of efficient irrigation systems and is discussed in **Error! Reference source not found.**.

SCENARIOS

Once the model was constructed the outputs were monitored while manipulating the simulation in 3 distinct scenarios and in a number of combinations of scenarios. Table 6 provides a short overview of each scenario and the corresponding input variables affected.

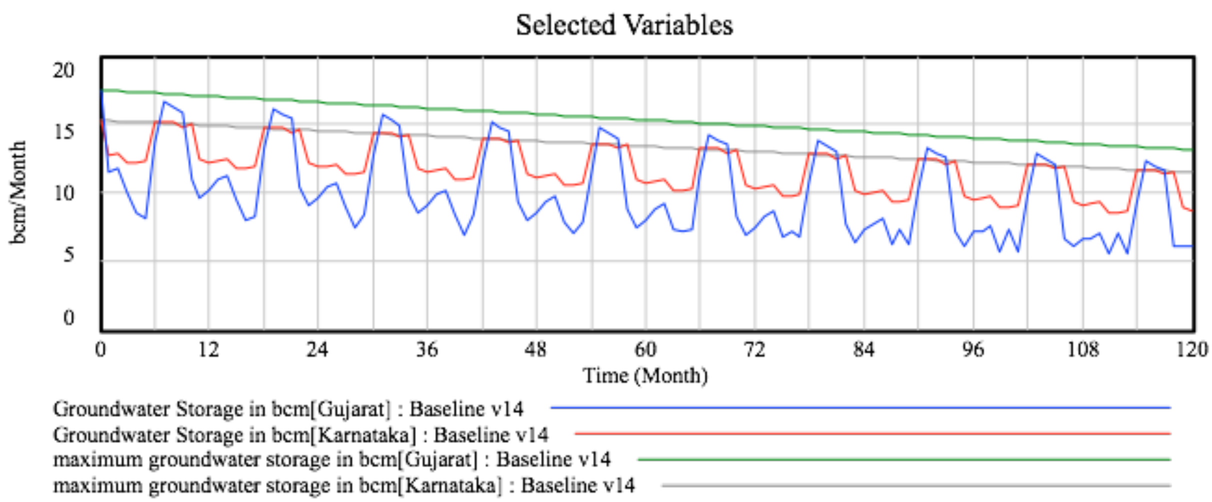
Table 6: Outline of the Scenarios Simulated Using the SD Model for the WEF Nexus

<table>
<tr><th></th><th colspan="2">Description</th><th>Variables affected</th></tr>
<tr><td>1: Baseline</td><td colspan="2">This scenario is run to determine baseline values for the outputs. None of the input variables are altered from the values found in literature.</td><td>None</td></tr>
<tr><td rowspan="4">2: Policy Interventions</td><td rowspan="4">The scenario runs through three potential policy interventions that state governments could introduce. These policies are already seen with varying success throughout India. They are explained in more detail in the corresponding section.</td><td>Policies:</td><td></td></tr>
<tr><td>Capital subsidies on solar pumps</td><td>Adoption rate for solar pumps is increased.</td></tr>
<tr><td>Grid feed-in tariff</td><td>Overall pumping time is decreased.</td></tr>
<tr><td>Efficient irrigation usage</td><td>Higher percentage of land uses efficient irrigation.</td></tr>
<tr><td>3: Ban Diesel Pumps</td><td colspan="2">In order to determine the overall effect of converting to 100% solar powered water pumps a scenario was considered that assumed a ban on diesel pumps. As this does not exist as a policy in India, it is was simulated as its own scenario.</td><td>Number of diesel pumps is set to zero and adoption rate for other pump types increases.</td></tr>
</table>

SCENARIO 1: BASELINE

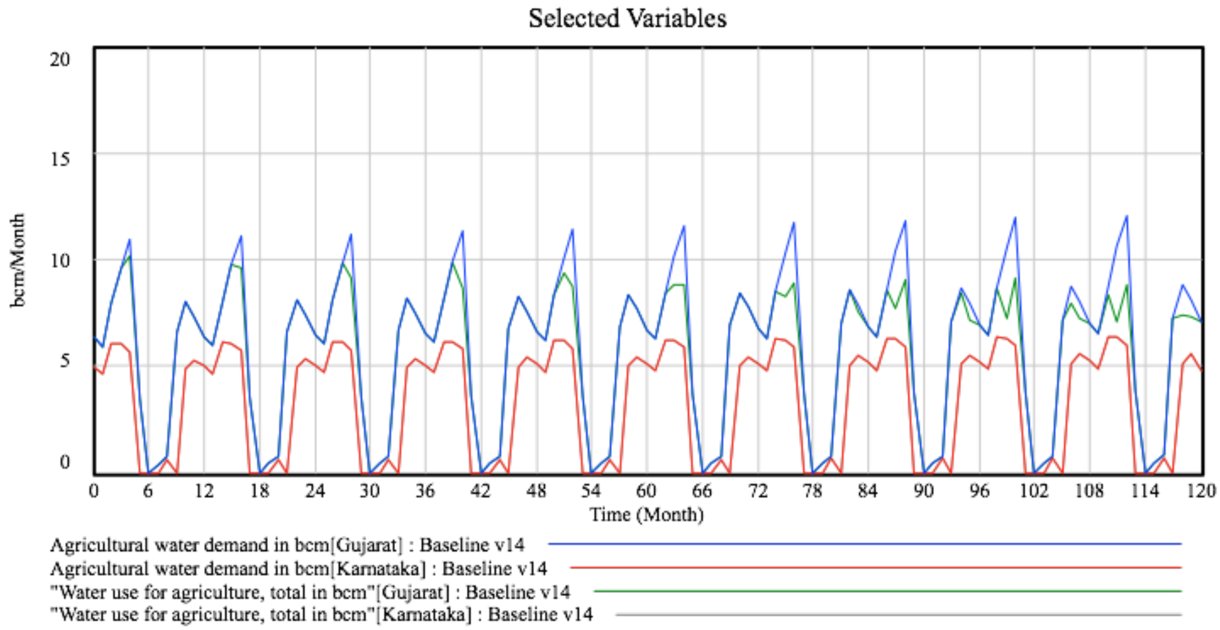
Due to changes in climate, groundwater levels are steadily decreasing and are expected to decrease across India in the next 10 years. Figure 15 shows the projected ground water levels over this time period for both Gujarat and Karnataka. The green and grey lines show the annual maximum potential water levels predicted in literature, whereas the red and blue reflect the monthly levels, due to water extraction for irrigation and non-irrigation uses, simulated by the SD model. Ideally, the Storage levels should match as closely as possible the theoretical maximum levels. According to the simulation, Karnataka is capable of replenishing its groundwater levels during the monsoon months whereas Gujarat falls short every year.

Figure 15: Baseline Groundwater Storage Levels, Including Theoretical Maximums.



The agricultural demand for water in both states is met by both surface and groundwater sources. Looking at the projected demand versus use of all water sources in Figure 16, the simulation predicts (with no additional policy interventions) that Gujarat will begin to see a shortage during the hottest months over the next 10 years. Whereas, Karnataka will have sufficient water resources to maintain current levels of agriculture in that same time period. This difference in sensitivity to groundwater reduction is due to the level of dependence on groundwater. In the Western arid Region, where Gujarat is located, 96 percent of the groundwater has been developed, versus 61 percent in the Southern Peninsular States, where Karnataka sits.

Figure 16: Supply versus Demand, Water for Agriculture



Scenario 2: Policy Interventions

In an attempt to decrease carbon emissions and a dependence on fossil fuels, policies to encourage the adoption of solar pumps for irrigation have been introduced at the national level. This is executed through a capital subsidies program. Additionally, a number of states have introduced their own aggressive subsidy programs, in some places reducing the cost to the farmer by 90 percent of the capital cost. In order to simulate similar programs within the SD model, increased adoption rates were set to double, when capital subsidies were in place. This assumption is based on values seen in other states in India. Figure 17 shows the results on the Groundwater Storage in Karnataka when capital subsidies are introduced versus the baseline scenario. While the effect is minor over 10 years, it is clear that the introduction of capital subsidies has a negative effect on the ground water storage as additional farmers are using groundwater for their crops and may have a more significant effect in the long term. This is logical as you decrease the cost to farmers of purchasing water pumps they are more able to pump additional water, whether required or not. The effects of capital subsidies in Gujarat, Figure 18, show minor changes to the groundwater storage over 10 years, and certainly not an improvement.

Figure 17: Introduction of Capital Subsidies in Karnataka

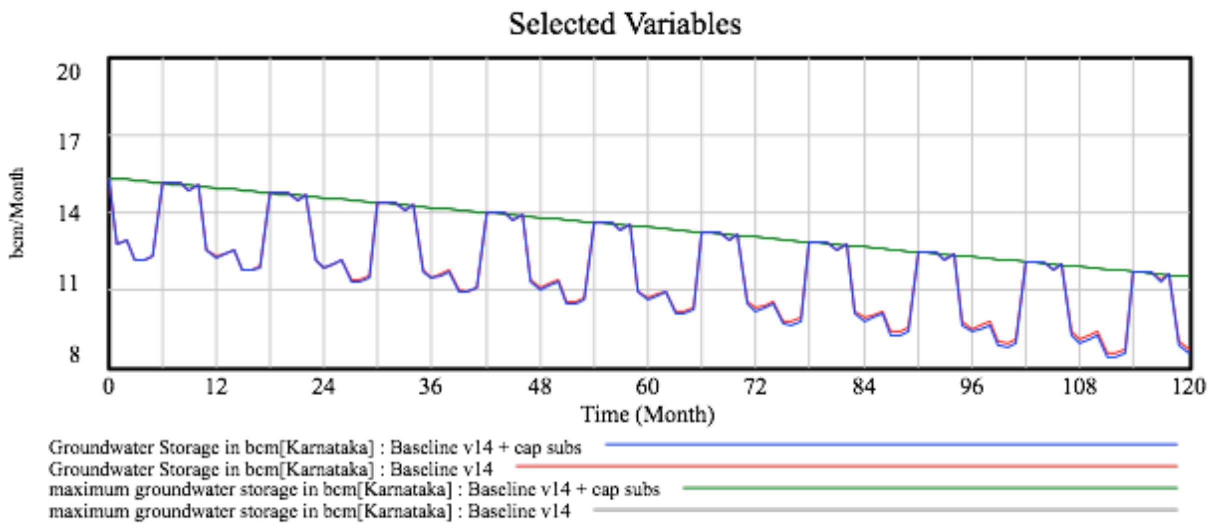
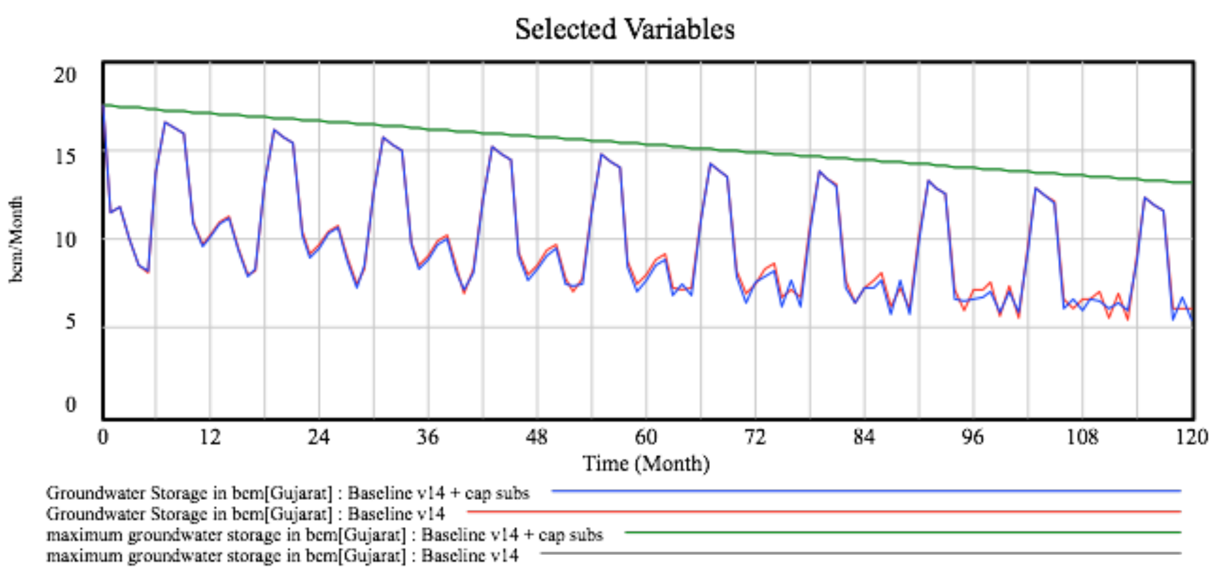
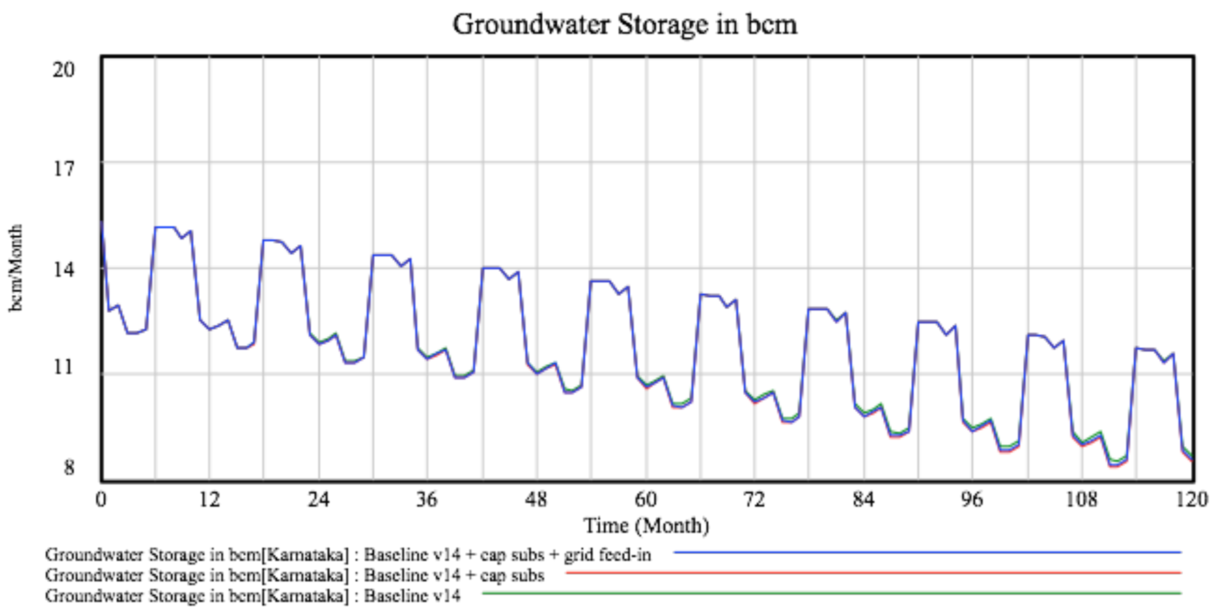


Figure 18: Introduction of Capital Subsidies in Gujarat



In order to balance this increased use of groundwater (evidenced by the reduction in groundwater storage), a policy that can be implemented in parallel is the grid feed-in tariff, where farmers get paid a per unit rate to supply electricity to the grid from their solar panels; such a policy has been approved in Karnataka and is currently being considered and piloted in Gujarat. Grid feed-in economically incentivizes farmers to conserve water by providing money (or a reduced bill) when they supply electricity back into the grid. This is only economically viable for solar water pumps, as a farmer using a diesel generator would not see a net income if it fed power into the gird. The presence of the grid feed-in scheme reduces the amount of time the solar panels are attached to the water pumps (ie. time used for water extraction) and maximizes the amount of times spent supplying power to the grid. In the SD model, the assumption was made that pumping time would be reduced by 50 percent under a grid feed-in tariff scenario. The results of such a policy, in combination with the capital subsidies, had a predicted marginal effect on the usage of groundwater, as shown in in Figure 19.

Figure 19: Introduction of Capital Subsidies and Grid Feed-in, Karnataka



However, the introduction of a feed-in tariff resulted in additional income to the farmer per month. Assuming power supply rates of 15 INR and 7.5 INR per kWh for Gujarat and Karnataka, respectively, the potential additional income per month when the grid feed-in policy is in place is shown in Table 7. The variability is due to the seasonal demand for water and seasonal sunlight hours.

Table 7: Potential Increased Income per Month with Grid Feed-in Tariffs

	Gujarat (USD)	Karnataka (USD)
0-3 HP	25 - 74	11 - 27
4-5 HP	50 - 149	22 - 53
6-8 HP	67 - 198	29 - 70
9-10 HP	100 - 297	43 - 105
< 10 HP	150 - 445	66 - 159

The final policy introduced is that of additional education around efficient irrigation. As farmers have increased access to technology for water pumping the risk increases that over-pumping will occur, specifically, the farmers will pump all day because there is no fuel cost associated with running a solar water pump. In order to combat this habit a policy was simulated that results in 90% of farmers using irrigation techniques that are over 60% efficient.

This is by far the most effective policy simulated with our SD model. Coupling the capital subsidies policy with this education-based policy has a significant effect on the groundwater storage in both Karnataka and Gujarat as shown in Figure 20 and Figure 21. This arises from the direct impact on the demand for groundwater this form of irrigation has. Additionally, it provides a short-term solution to the water shortage issue in Gujarat, delaying it by 5 years, as seen in Figure 22.

Figure 20: Effect on Groundwater Levels of Efficient Irrigation in 90 percent of Farms in Gujarat

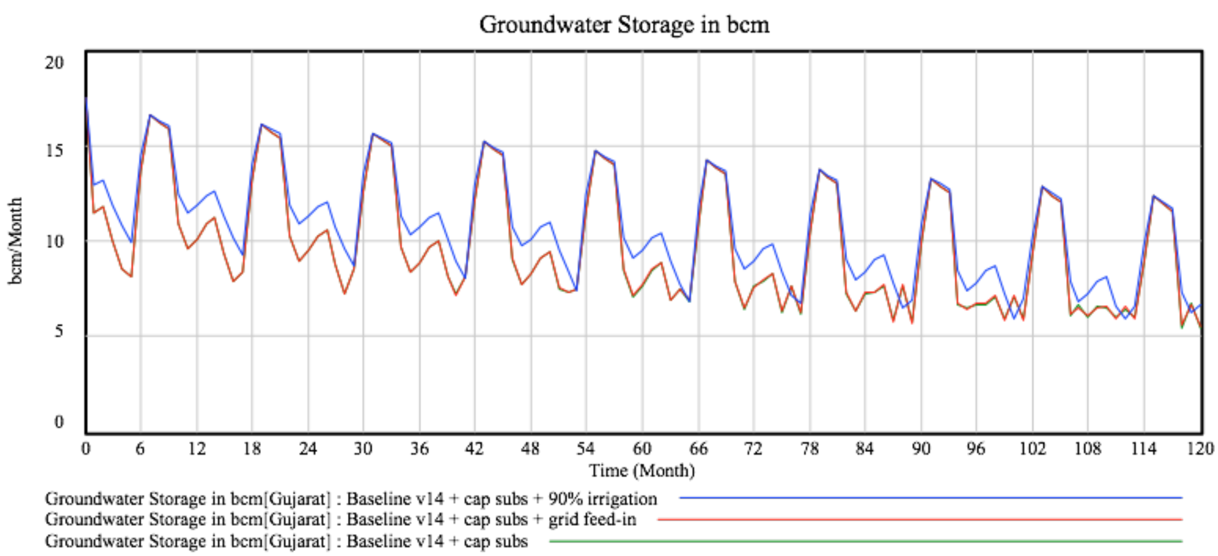


Figure 21: Effect on Groundwater Levels of Efficient Irrigation in 90 percent of Farms in Karnataka

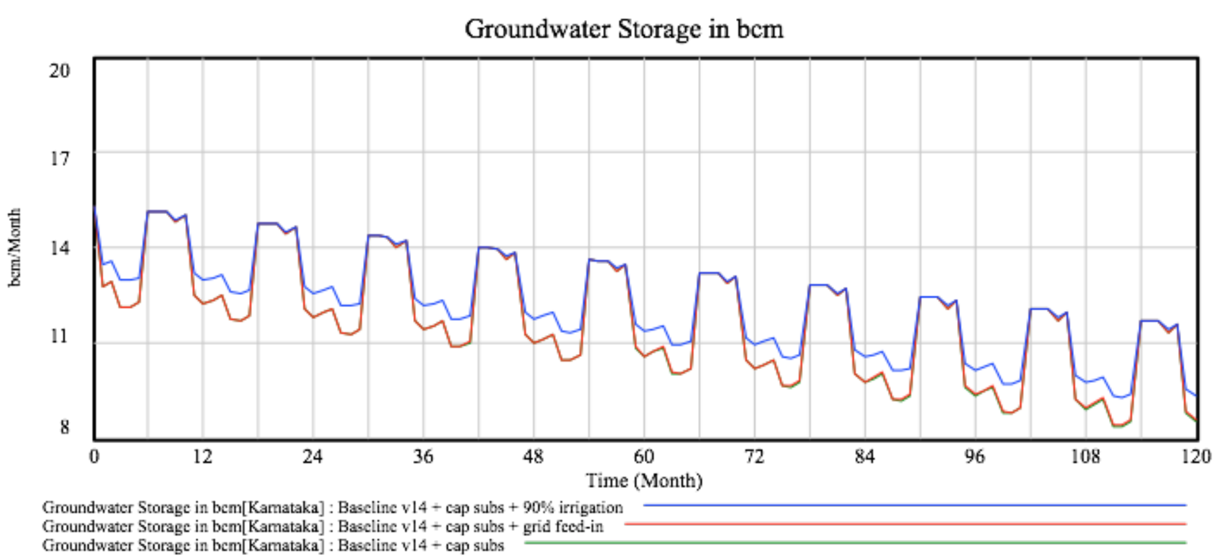
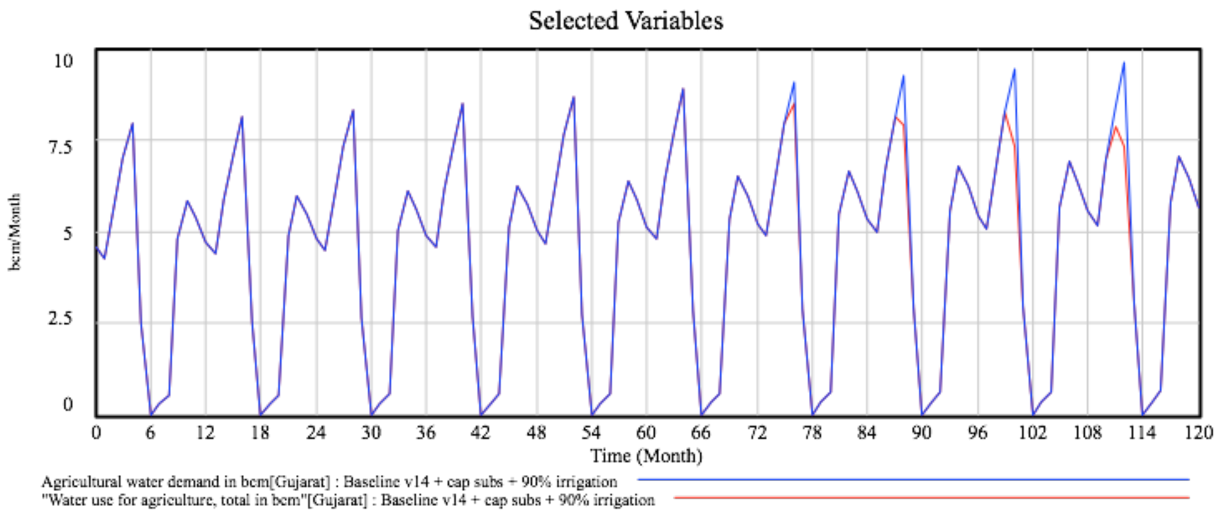


Figure 22: Effect on Water Supply versus Demand of Efficient Irrigation in 90 percent of Farms in Gujarat.



SCENARIO 3: BAN DIESEL PUMPS

As an additional investigation, an immediate policy of banning the use of Diesel pumps for irrigation was simulated. While Diesel pumps are the current norm in many places in India, due to pollution concerns the government has expressed a clear preference to using solar powered pumps, through subsidy programs etc. Our scenario takes this preference one step further by simulating the effects on the state wide agricultural water usage/demand if diesel pumps were no longer permitted in the States of Karnataka and Gujarat. In order to aid with the transition to purely solar and electric pumps, this policy was modeled alongside a capital subsidies program for solar pumps.

As expected, the simulation shows (Figure 23) that in Gujarat the actual supply of water possible from only solar and electric pumps does not meet the water demand, and worsens the problem initially as the farmers struggle to supply enough water using only these technologies. However, it does stabilize close to baseline levels after eight years. When looking at the groundwater storage levels, Figure 24, there is an immediate effect of a significant recovery; however, as the solar pumps are introduced to replace the diesel pumps the extraction rates return to pre-policy predicted levels.

Figure 23: Effect on Water Supply versus Demand of Banning Diesel Pumps in Gujarat.

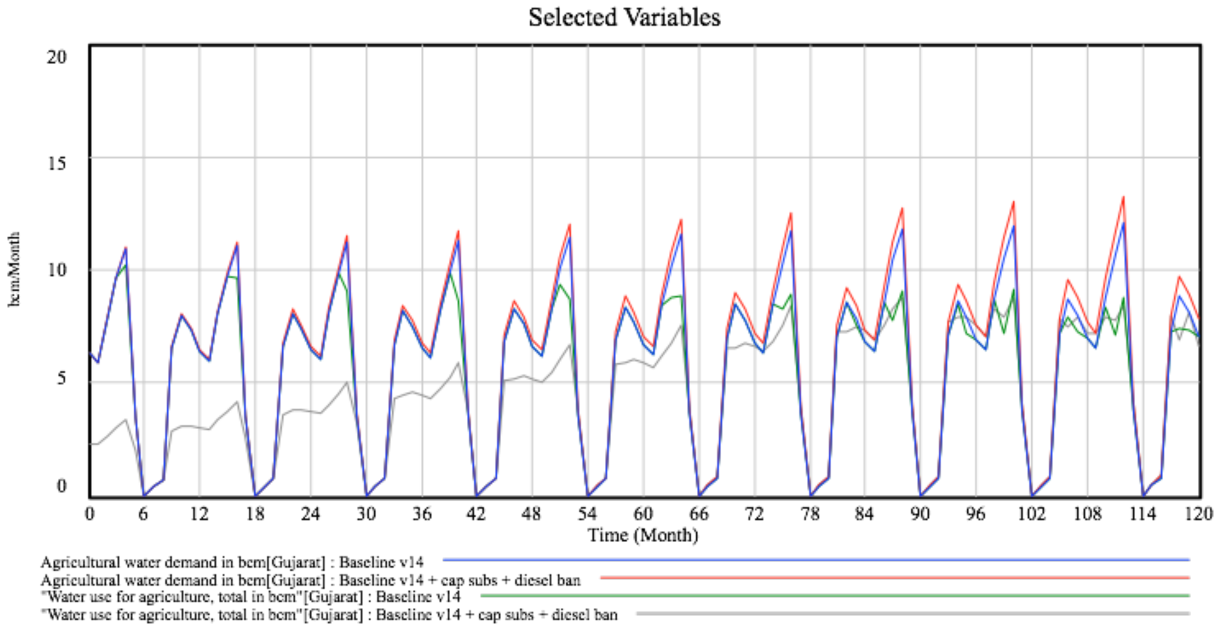
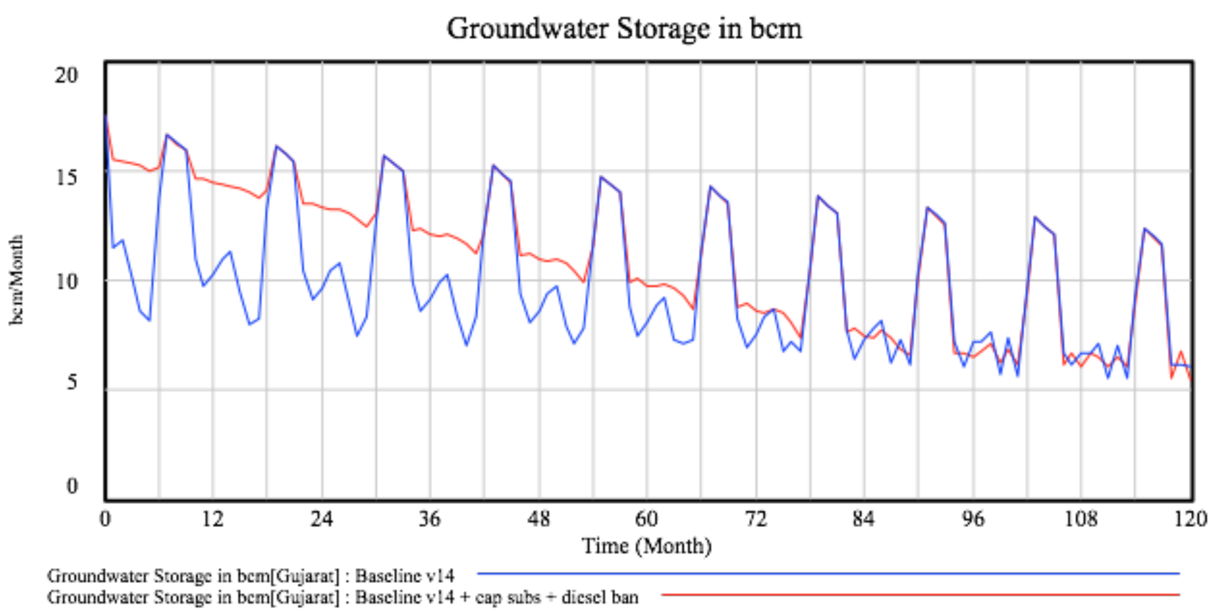
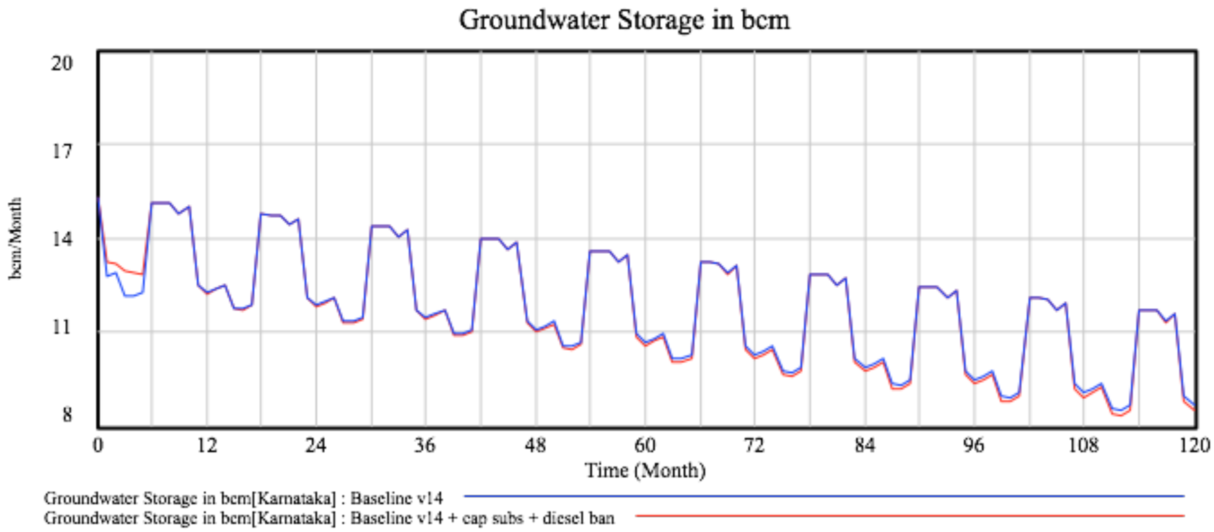


Figure 24 Effect on Groundwater Storage of Banning Diesel Pumps in Gujarat



In contrast, the introduction of a diesel ban in Karnataka has a marginal effect on the groundwater storage in the first year, Figure 25, but the capital subsidies have a stronger effect in the long term, as before. This is due to two factors. First, Karnataka has a sufficient water supply to meet demand from existing pumping systems and can increase the use of current solar and electric systems to compensate for the ban on diesel pumps. Second, 49 percent of Karnataka's water for irrigation comes from surface water via canals etc., versus 15 percent in Gujarat, meaning the effect is less pronounced when the diesel pumps for groundwater extraction are removed.

Figure 25: Effect on Groundwater Storage of Banning Diesel Pumps in Karnataka.



Combined Scenarios

Combining the policies of a diesel ban, capital subsidies and the increased use of efficient irrigation practices has the same initial effect on groundwater storage in Gujarat as the diesel ban but in the long term it increases the groundwater storage (Figure 26). However, the introduction of the efficient-irrigation training scheme alone has the best long-term effect on the groundwater level, while also alleviating the supply-demand deficit for 7 years (Figure 27). Similarly, the groundwater storage levels in Karnataka are most improved by the increase in efficient irrigation techniques (Figure 28).

Figure 26: Effect on Groundwater Storage in Gujarat due to Combining Scenarios

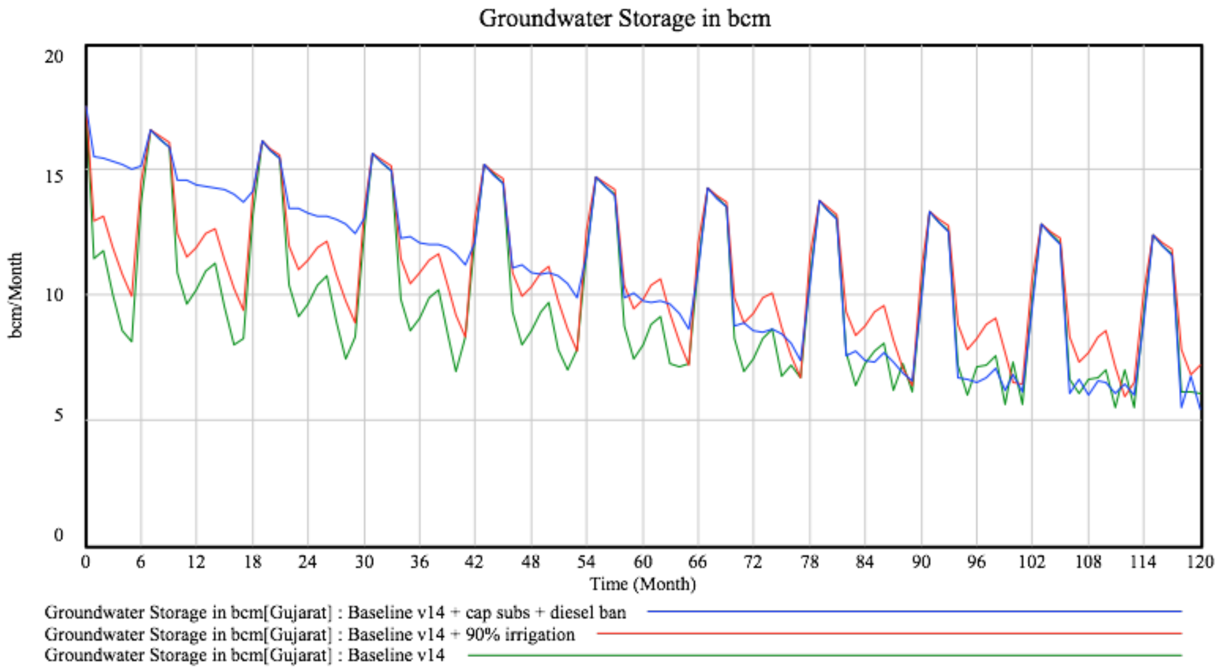


Figure 27: Effect on Supply and Demand in Gujarat due to Combining Scenarios

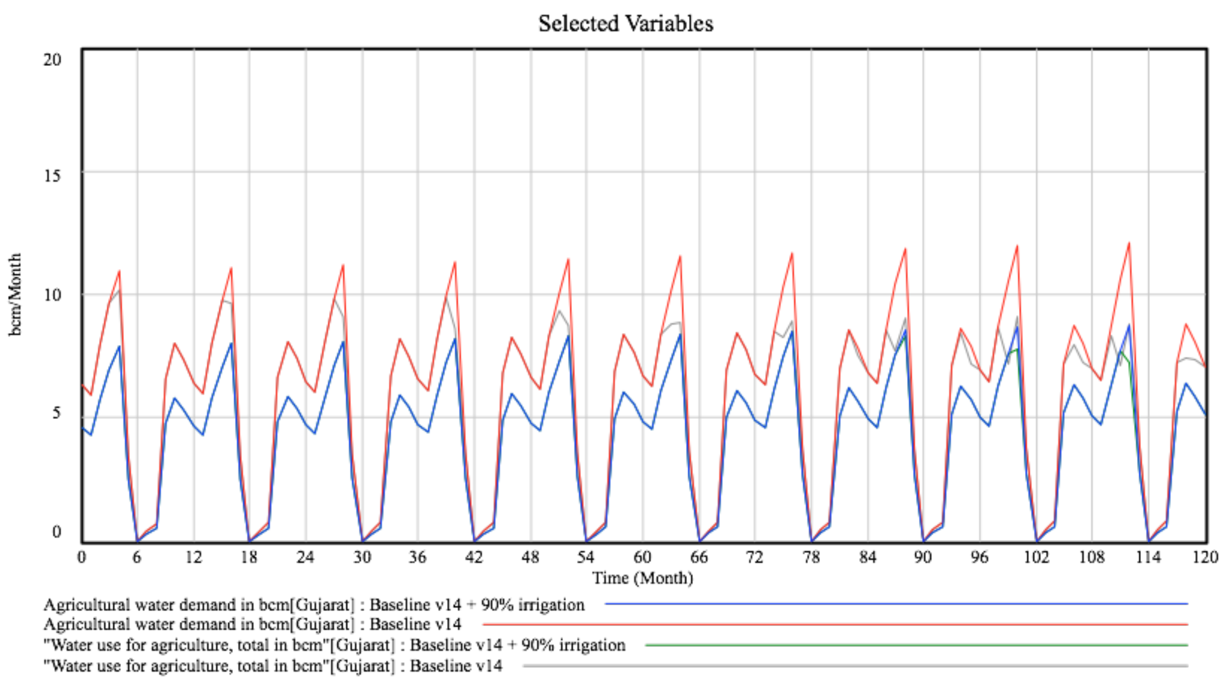
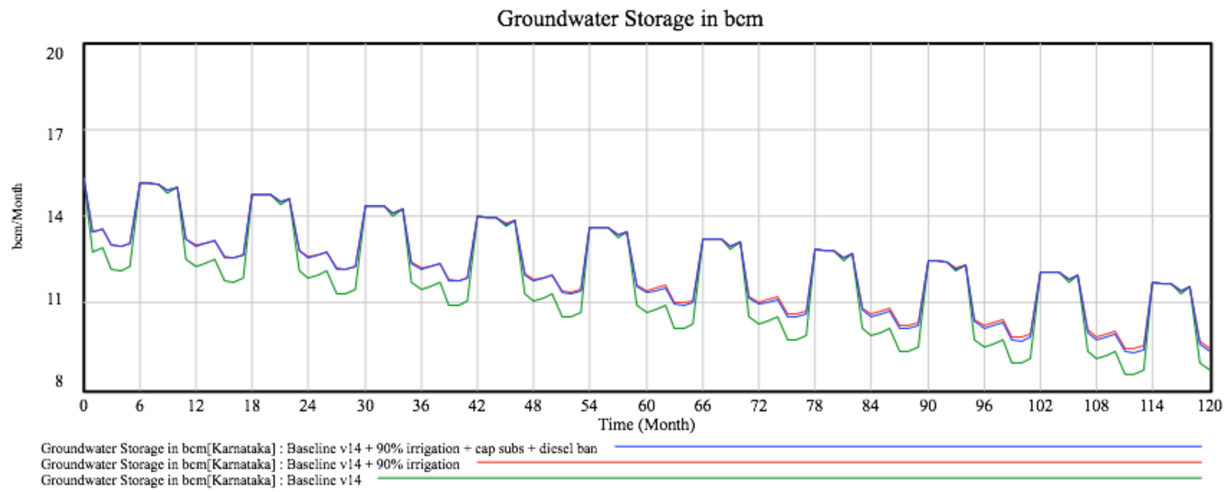


Figure 28: Effect on Groundwater Storage in Karnataka due to Combining Scenarios



CONCLUSION

When considering only the reduced impact on groundwater levels, a policy of more efficient irrigation yields the best results for both Karnataka and Gujarat, in the long-term. While initially the groundwater levels in Gujarat benefit from policies such as a diesel pump ban, over the course of 10 years the effect is negated by the adoption of alternative pumping technologies. Additionally, the reduction in groundwater usage in years 1-6 has a detrimental effect on the agricultural industry as they struggle to supply enough water to maintain the current food production levels.

The introduction of the other two policies, the capital subsidies and the grid feed-in tariffs, while assumed to reduce the pumping hours of solar systems by half, only has a minor effect on groundwater storage. However, these policies have the added benefit of eliminating fuel costs and providing an additional income source to farmers and reducing their dependence on fossil fuels. Similarly, there are a number of additional factors driving the irrigation policies in these states, including:

- The cost of diesel to the farmers;
- The cost of generating electricity to drive electric pumps; and
- Reduced CO_2 emissions from the use of solar versus diesel.

Through our model, we have sought to demonstrate the interconnectedness between agricultural technologies in the form of solar-powered pumps and their impact on the natural system—namely, on water use and more specifically on groundwater extraction. The role of policy in shaping farmers' actions and behaviors proves powerful. Importantly, the dissemination of pumping technologies alone seems to exacerbate unsustainable water usage: it augments farmers' access to supply without incentivizing demand-side restrictions. In this sense, capital subsidies alone to get solar pumps into the hands of farmers may not be the most enlightened policy. Coupling such a policy with technological and economic incentives, however, reduces the use of groundwater.

Taking current water consumption for non-agricultural uses and levels of food production into consideration, even the coupling of these interventions only takes the states of Gujarat and Karnataka halfway towards complete sustainable groundwater extraction. Several possible extensions to this model exist. Chief among them are the cost of the technology and the impact on adoption, which would require willingness to pay (WTP) data. Further, coordination issues between implementation agencies warrants further scrutiny, though such an investigation may lend itself to case studies as opposed to SD scenario modeling. Regardless, institutional fragmentation and overlap[8] remains a challenge in developing a meaningful model of the WEF nexus. As our model seeks to demonstrate, the benefits of such a holistic approach are considerable, especially for the sustainable use of water resources.

[8] For instance, the Ministry of New and Renewable Energy (MNRE) is responsible for the national solar mission scheme that provides capital subsidies for the solar pump systems, but the Central Groundwater Board (CGWB) and the Ministry of Water Resources (MOWR) are responsible for water resource management. Moreover, the Ministry of Agriculture and Farmer Cooperation (MAFC) is responsible for agricultural policy. Beyond national ministry policies and programs, state and private sector schemes complicate the institutional landscape even further.

CORRECT SIZING OF PUMPS

In order to allow users to select an appropriate pump size, the CITE team developed a software tool to automate the process. These types of tools are routinely used by pump system manufacturers and integrators to recommend pumps to potential customers; however, each company has a proprietary tool that is not available to the general public and therefore the user must rely solely on the manufacturer or integrator's advice. While this is generally fine, we believe having an independent tool to cross check the recommendations is helpful both in terms of ensuring a proper match between pump size and the user's specific conditions, as well as enabling the user to be a more informed buyer. The tool is available for download on the CITE website at http://cite.mit.edu/.[9]

INTRODUCTION

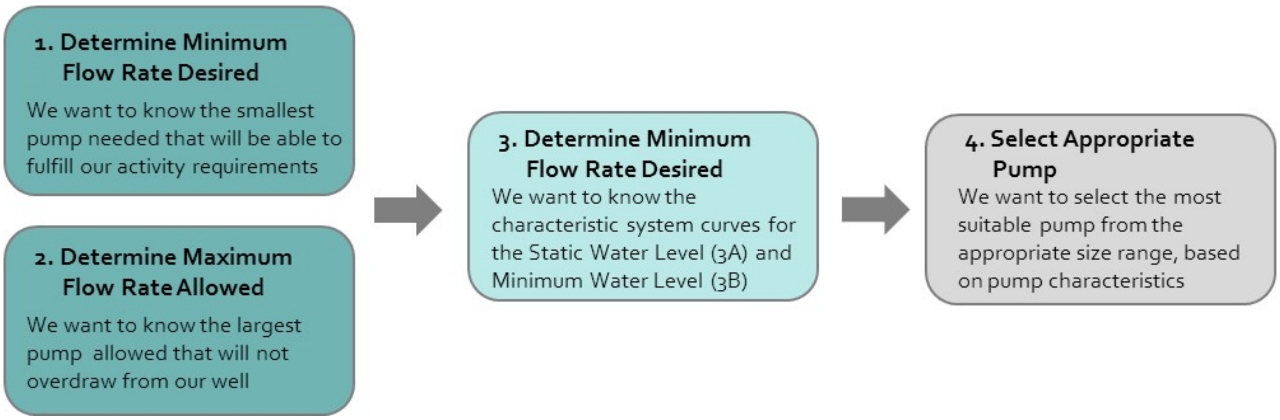
Revisiting the case in Uttar Pradesh – the irrigation systems had previously run on diesel-powered pumps. To switch over to powering these irrigation systems via solar power, a single solar pump was installed at each site, along with other necessary equipment to operate it (solar panels, inverter, etc.), replacing the diesel pump previously at the site. The method used to determine which size pumps to purchase and install was to size the pumps according to the average depth of the water table for the region. To our knowledge, there was no on-site pump testing completed prior the installation and subsequent use of the solar pumps at these irrigation sites. Prior to installation, the selected pump was purchased and tested in a facility along with other system components. However, groundwater hydrology and well limitations from the field were not considered when selecting the size of the pumps to be installed. We hypothesized that because the pump selection method was insufficient, the pumps installed on these sites were improperly sized for the irrigation systems. Thus, we explored the pump selection process specifically for shallow well irrigation systems such as the ones in Uttar Pradesh, and extrapolated our method for broader application, i.e., for in use in salt farming, keeping in mind that proper pump selection is essential to both the financial and environmental sustainability of a project.

PUMP SELECTION THEORY

We outlined the major steps of our pump selection method for shallow well water systems in Figure 29 In the following text, each major step is covered in detail.

[9] Please note that this tool is provided as a guideline only and neither MIT nor USAID guarantee the results in any way.

Figure 29: Overview of the Pump Selection Process

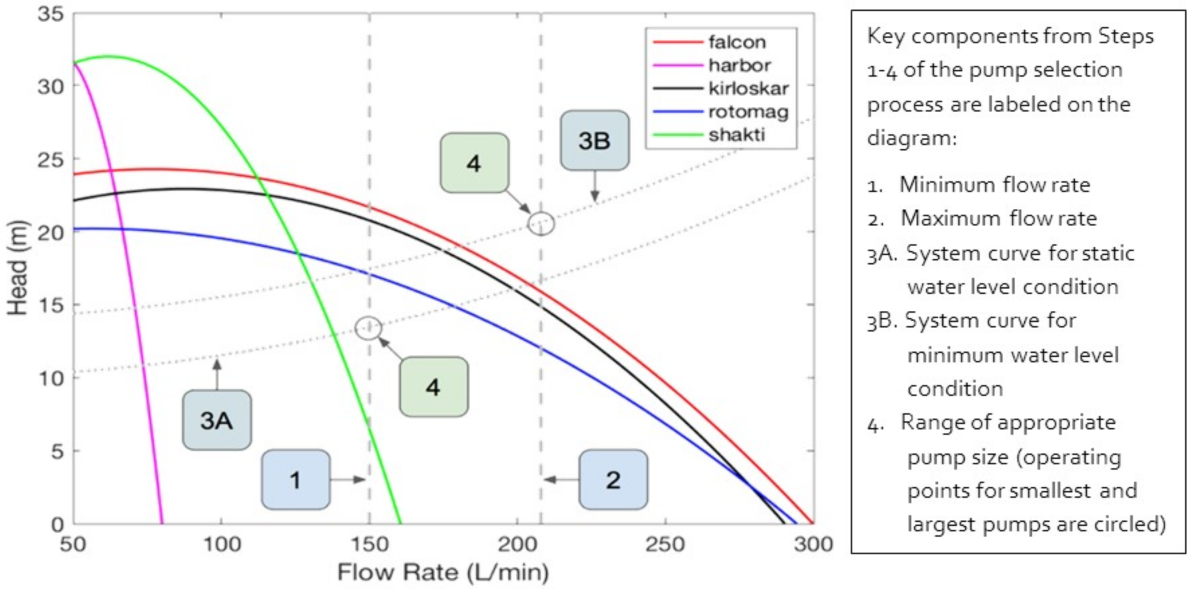


Step 1. Determine Minimum Flow Rate Desired

A main area of focus in our pump selection process is to determine the appropriate size – in terms of horsepower – of a pump for a shallow well water system. To save on cost, we aim to install the smallest pump that we can in the system, that will still be able to fulfill our water demands, whether this is for irrigation or salt farming. As part of the process to determine the smallest pump needed, we need to first determine the minimum flow rate at which we desire to operate the system. For irrigation, this minimum flow rate is determined by the irrigation water demand, which is determined by factors such as amount of rainfall, crop type, crop development stage, climatic zone, etc. Both are beyond the scope of this solar pump evaluation, and are not covered in detail our pump selection method. Additionally, for both applications, this flow rate also depends on the number of hours of available sunlight in a day.

In Figure 30, the minimum flow rate is represented by the vertical dashed line in grey on the left.

Figure 30: Head versus Flow Rate



Step 2. Determine Maximum Flow Rate Allowed

On the other end, we also want to determine the largest pump that we can install in the shallow well water system. This is related to the maximum flow rate allowed for the shallow well water system, or in other words, the maximum flow rate at which we can remove water from the well. The well itself imposes limitations to how much water we can pump out of it in a certain amount of time. As water is removed from a well, each well also has a unique rate at which water flows back into it via groundwater recharge processes that are dependent on geologic formation and construction of the well. By conducting aquifer tests which are beyond the scope of this evaluation, we can find the maximum safe pumping rate of a particular well. This maximum safe pumping rate determines the maximum flow rate allowed. In Figure 30, this is represented by the vertical dashed lined in grey on the right.

Step 3. Determine Head vs Flow Rate Relationship for a System

Now that we have determined the lower and upper bounds for the flow rate of our desired operating point, we need to determine the operating heads that correspond to these two flow rates.

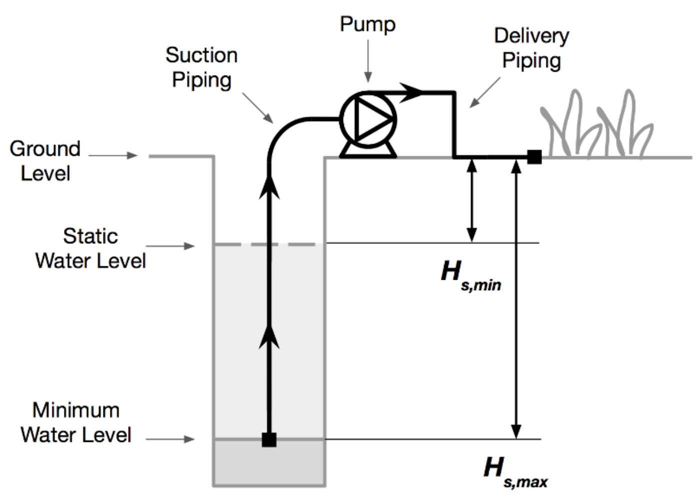
In general, the purpose of a pump is to move fluid – in our case, water – through a system at a desired flow rate. The desired flow rate is determined by the specific application – irrigation or salt farming – of the shallow well water system. The pump needs to provide enough head to overcome the operating head of the system in which it is installed. One can think of the operating head of the system as the amount of resistance which prevents water from traveling from the well and through the piping all the way to the pipe outlet where the crops or salt pans are located. The operating head depends on (1) the flow of the water through the system and (2) the arrangement of the system. The arrangement of the system involves piping specifics (e.g. length, valves, fittings, joints) as well as the change in elevation from the starting point from where we are pumping the water, to the point where the water is discharged from the piping to the irrigation field or salt pan.

To determine the operating heads which correspond to the two flow rates which we found in Steps 1 and 2, we need to determine the characteristic relationship between (total) head and flow rate for our shallow well water system. For a pumping system, the total head of a system, H_{total}, is comprised of the static head, H_s, and the dynamic head, H_d:

$$H_{total} = H_s + H_d$$

The units of head are meters. The static head is purely determined by the elevation that the water must travel, from the level of the surface of the water in the well, to the level where the water is discharged into the irrigation field or salt pan. Since the water level in a shallow well drops significantly during pumping, we need to consider two different conditions of the water level in the well determining static head. As depicted in Figure 31, we need to consider (1) the static water level and (2) the minimum water level. The static water level of the well is the “normal” water level in the well when the well is full and before any pumping occurs. The minimum water level in the well is the safety level at which we want to stop pumping. When the well is about to run dry, the pump will begin to intake air along with water, which can erode parts of the pump due to hammering. Therefore, we set a minimum water level in the well for purposes of preventing damage to the pump itself. Thus, we will actually end up with a minimum value for static head, $H_{s,min}$, as well as a maximum value for static head, $H_{s,max}$.

Figure 31: : Schematic of a Shallow Well Water System with a Non-Submersible Centrifugal Pump



The dynamic head is determined by the flow of the water through the system, as well as piping specifics. As water flows through the system, there will be head losses, which can be categorized into major head loss (from viscous forces along the pipe) and minor head loss (from components in the piping system such as valves, fittings, and joints.) The dynamic head can be determined by the following equation:

$$H_d = \sum f \frac{L}{D} \frac{v^2}{2g} + \sum K \frac{v^2}{2g}$$

where,

$\sum f \frac{L}{D} \frac{v^2}{2g}$ = Major head loss (m)
$\sum K \frac{v^2}{2g}$ = Minor head loss (m)
f = Darcy-Weisbach friction factor (unitless)
K = Minor loss coefficient (unitless)
L = Length of piping (m)
D = Diameter of piping (m)
v = Average velocity of water in piping (m/s)
g = Standard acceleration due to gravity (m/s^2)

To find the average velocity of the water in the pipe, v, which remains constant in incompressible flow if the cross-sectional area of the pipe is constant, we can use the following equation:

$$v = Q/A$$

where,
Q = Flow rate through piping (m^3/s)
A = Cross sectional area of piping (m^2)

We use the Haaland equation to solve directly for the Darcy-Weisbach friction factor f for a turbulent flow through a circular pipe:

$$f = \left[1.8\, log\left(\frac{6.9}{Re} + \frac{\varepsilon/D}{3.7}^{1.11}\right)\right]^{-2}$$

where,
ε = Absolute roughness of piping (m)
Re = Reynolds number (unitless)

For the absolute roughness of the piping ε, which depends on piping material, we can look up tabulated values. We use the following to calculate the Reynolds number Re for this flow:

$$Re = \frac{\rho v D}{\mu}$$

where,
ρ = Density of the water (kg/m^3)
μ = Dynamic viscosity of the water (kg/m^3)

The values for both density ρ and dynamic viscosity μ will differ between fresh water and salt water.

To find the minor loss coefficient K, we can look up tabulated values associated with different piping components and sum these together.

Once we have determined $H_{s,min}$, $H_{s,max}$, and H_d, we can find a minimum total head, $H_{total,min}$, and maximum total head, $H_{total,max}$, for the shallow well irrigation system:

$$H_{total,min} = H_{s,min} + H_d$$

$$H_{total,max} = H_{s,max} + H_d$$

For both conditions of the water level of the well, we now know the associated total head for any given flow rate. Plotting total head versus flow rate for both conditions, we obtain two system curves – one associated with the static water level condition in the well, and the other associated with the minimum water level condition in the well. In Figure 30, these are shown as the dotted curves in grey.

Step 4. Select the appropriate pump

From intersection of the two curves generated in Step 3 with the lower and upper bounds for the flow rate of our desired operating point determined in Steps 1 and 2, we can find the operating heads that correspond to these two flow rates. In Figure 30, the operating points corresponding to the smallest sized pump and the largest sized pump are circled.

To determine the range of nominal pump sizes from which we are to select from our system, we need to know the horsepower that corresponds to each of the two operating points. The hydraulic horsepower, WHp, which is the power associated with the water at the discharge point of the system, is related to the total head of the system by the following equation:

$$WHp = \rho g Q H_{total}$$

To determine the brake horsepower, BHp, which is the power input into the pump, that is associated with each of the hydraulic horsepower values that we have determined, we can use the following relation:

$$BHp = \eta * WHp$$

where, η = Pump efficiency (unitless). The pump efficiency can be found from manufacturing specifications, or by testing the pump in an appropriate testing facility.

Now that we have range of acceptable brake horsepower, we can select a suitable pump for the shallow well water system from among pumps with nominal horsepower that fall within this range. The details of this selection will be covered in a practical example later in the text.

Using the CITE Pump Sizing Tool

The CITE Pump Sizing Tool was created in Matlab™ and modified to run in Microsoft Excel to aid with selecting a suitable pump for a shallow well water system. The user provides inputs about (1) water requirements for the intended activity (eg. irrigation or salt farming), (2) well characteristics, and (3) the piping system through which water is delivered, and the Pump sizing Tool outputs a range of recommended pump sizes for the specific shallow well water system. The user interface of the tool is shown in Figure 32, with inputs highlighted in yellow and outputs highlighted in blue. While the user interface was designed to be as simple as possible, the tool uses the formulas and calculations mentioned in the previous section on pump selection theory and in the Excel version, this "backend" can be found locked on additional sheets in the same document.

Figure 32: Pump Sizing Tool User Interface

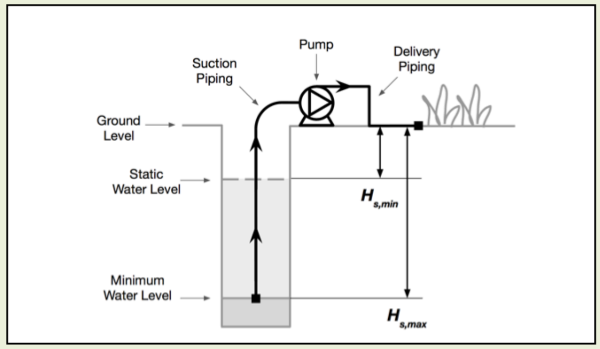
Pump Sizing Tool

Solar Water Pumps Evaluation from the Comprehensive Inititative for Technology Evaluation at MIT
Last Updated: April 25, 2017

Introduction

This tool was created to aid with selecting a suitable pump for a shallow well water system. From inputs about (1) water requirements for the intended activity (eg. irrigation or salt farming), (2) groundwater/well characteristics, and (3) the piping system through which water is delivered, the tool will output a range of recommended pump size for the shallow well water system.

Inputs = Cells highlighted in yellow
Outputs = Cells highlighted in blue



(1) Water Requirements

Total amount of water required per day	72000 [L]
Total pump operating time per day (*Max = 8 hours of available sunlight*)	8 [hr]

(2) Groundwater/Well Characteristics

Type of water	Freshwater
Maximum safe pumping rate	208 [L] *per* 1 [min]

(3) Piping System Characteristics

Hs,min *(refer to diagram)*	10 [m]
Hs,max *(refer to diagram)*	14 [m]
Pipe diameter	4 [in]
Total pipe length	52 [m]
Pipe material	Polyvinyl chloride (PVC)
Minor loss coefficient	5.1 [--]

(4) Recommended Pump Size Range

Pump Efficiency	60 [%]
Minimum Pump Size *(BHp)*	0.70806 [hp]
Maximum Pump Size *(BHp)*	1.527127 [hp]

A Practical Example of Pump Sizing Tool Usage

For the purposes of this example, assume a pump installer wants to know which size pump to install on a specific farm for crop irrigation. The farm already has an irrigation system in place, which consists of a well in an unconfined aquifer, a diesel-powered pump, and a piping system through which water is delivered from the well to the crops. The pump installer's goal is to replace the diesel-powered pump, which was not properly sized, with a new solar-powered, non-submersible centrifugal pump. The following steps take us through the pump sizing process.

Step 1. Determine Minimum Flow Rate Desired

First, we need to determine the minimum flow rate that the pump needs to be able to provide for crop irrigation. We determine that at peak demand, the crops on the farm need to be irrigated with 72,000 L of water each day. During this season, we know that there are eight hours of available sunlight each day - taking full advantage of this, we can operate the pump for a maximum of eight hours each day. To fulfill our irrigation requirements, the pump must be large enough to deliver water at an average flow rate of 150 L/min during the eight hours of operation, since:

$$72000\ L \div 8\ Hr = 150\ L/min$$

Thus, this is the minimum flow rate that the pump needs to be able to provide. In *Figure 30*, this is represented by the vertical dashed line in grey on the left.

PUMP SIZING TOOL: Enter the numbers 72000 and 8 into the Water Requirements section, and select the correct units from the dropdown menus.

Step 2. Determine Maximum Flow Rate Allowed

Next, we conduct aquifer tests at the irrigation site and from the results; we find that the maximum safe pumping rate of the well is 208 L/min. In Figure 30, this is represented by the vertical dashed line in grey on the right.

PUMP SIZING TOOL: First select "Freshwater" from the dropdown menu for type of water. Enter 208 into the Groundwater/Well Characteristics section of the Pump Sizing Tool, and select the correct units from the dropdown menus.

Step 3. Determine Head vs Flow Rate Relationship for a System

Using a rope or other measuring device, we measure that the static water level of the well before pumping is ten meters below ground level. The minimum level of water that we must maintain in the well to avoid damage to the pump is 14 meters below ground level. Thus, we know that:

$$H_{s,min} = 10\ m$$

$$H_{s,max} = 14\ m$$

Additionally, we measure that the piping is four inches in (inner) diameter, and the total length of piping used in the system which includes the suction piping and the delivery piping, is 52 meters. We determine that the material of the piping is polyvinyl chloride, or PVC.

PUMP SIZING TOOL: Under the section named piping system characteristics, enter in the values 10, 14, 4, and 52, for $H_{s,min}$, $H_{s,max}$, pipe diameter, and total pipe length, respectively. Select the correct units from the dropdown menus. For pipe material, select "polyvinyl chloride (PVC)" from the dropdown menu.

We also find that there are the following additional components in the piping system which contribute to head losses and need to be accounted for: one sharp entrance, four 90 degree elbows (threaded, regular), 12 pipe joints. Looking up values from published minor loss coefficient tables, we find that this corresponds to a total minor loss coefficient value of 5.1.

$$K_{total} = K_{entrance,sharp} + 4K_{elbow,90deg} + 12K_{joint}$$
$$= 0.5 + 4 * 1.0 + 12 * 0.05 = 5.1$$

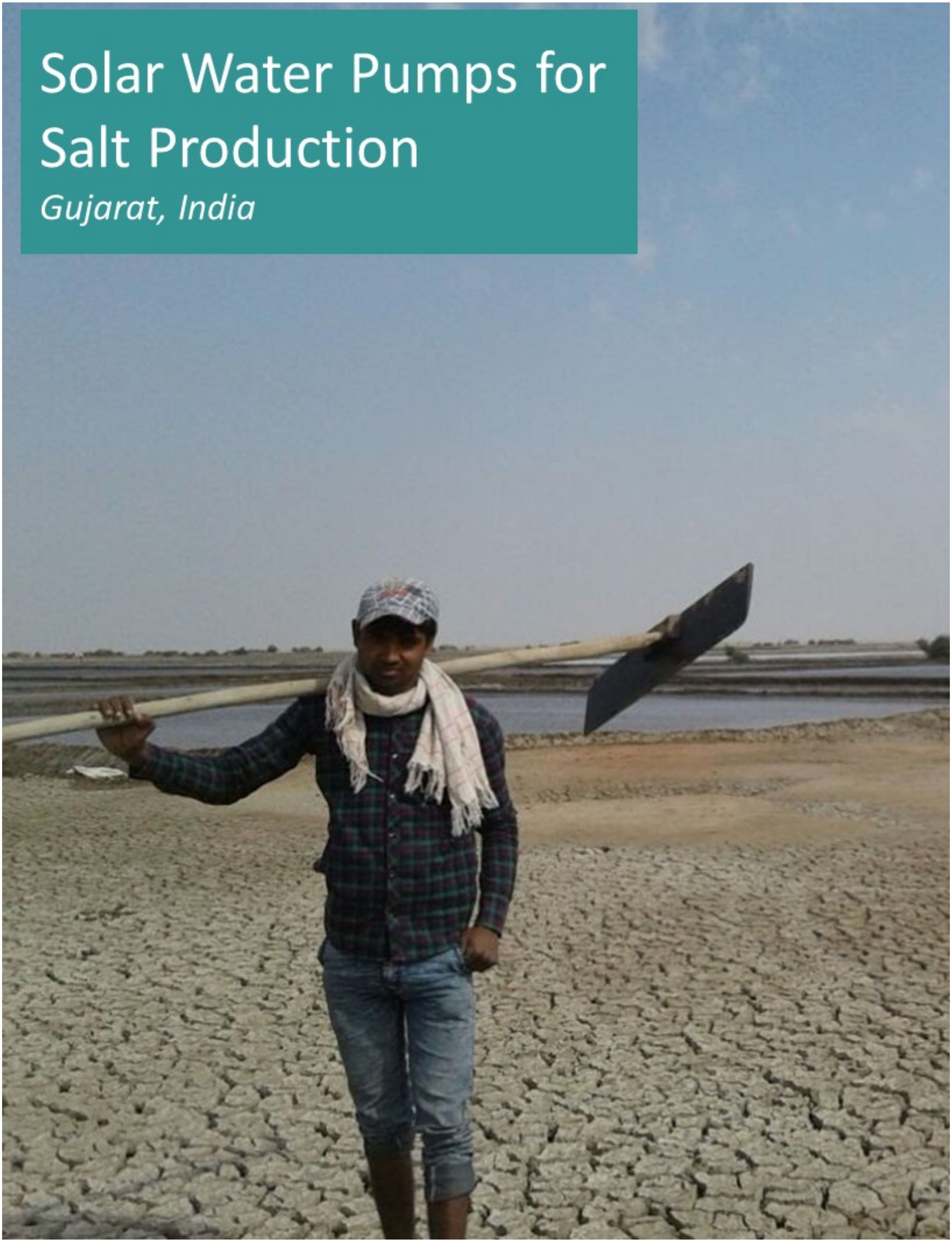
PUMP SIZING TOOL: Under the same section as before, enter the value 5.1 for Minor loss coefficient.

Step 4. Select the Appropriate Pump

PUMP SIZING TOOL: Under the section “Recommended Pump Size Range”, enter a value for pump efficiency value under the section. Typical values are 30-60 percent. The boxes highlighted in light blue will then display the values for minimum pump size and maximum pump size. These values determine the recommended pump size range.

Solar Water Pumps for Salt Production

Gujarat, India



Solar Water Pumps for Salt Production

Findings at a Glance

- **Technical performance:** Of the five pumps tested, Falcon and Kirloskar brands offered the best performance at a price affordable for the farmers who were using them
- **Ease of use:** Based on sensor data, the salt farmers appear to run their systems all day, every day (on both solar and diesel).
- **Affordability:** Before loan payback, profit margins are similar to diesel systems, but after the loan is repaid, farmers can realize significantly increased profits from the same quantity of production compared to diesel pumps

Introduction

During the months from October to May, 40,000 farmers enter the Little Rann in Kutch, Gujarat (see Figure 33) to practice an age-old industry, the production of salt. They use the same wells each year, hand dug down to 23 feet and reinforced with bamboo to prevent cave ins, and then bored out the rest of the way down to the water level which varies between 40 to 69 feet. Every several thousand feet on the Little Rann, there is another well, another pump, and a surprising number of solar arrays powering them.

Figure 33: Map of Gujarat

In addition to the agricultural irrigation cases presented in the previous section, the CITE team also worked with the Self Employed Women's Association (SEWA) in Gujarat, India to evaluate the 1- 1.5 horsepower solar water pumps that are currently being used by seasonal salt farmers.

We chose to evaluate these smaller scale solar water pump systems for the following reasons:

- SEWA has an extensive solar pump program;
- the harsh environmental conditions in the Little Rann are something of a "worst case" scenario for the technical performance of the pumps;
- the small scale pumps are much more affordable and the results of the evaluation could be used as a guide for individual farmers or other organizations interested in using solar water pumps for irrigation of small farms
- the larger solar pump systems identified in the previous section (3 to 7 HP) were too expensive to allow purchase of 5-10 pumps for lab testing at MIT

The Self-Employed Women's Association (SEWA), an organization whose membership consists of informal workers and whose mission is to ensure their rights, is the driving force behind the solar pump project for the salt farmers in the Little Rann of Kutch. They have secured loans for the salt farmers and negotiated the purchasing of the solar water pumping systems. Additionally, SEWA has taken an active role to date in relation to maintenance and after sales support. This is motivated by a desire to continue the project and encourage more farmers to adopt the technology.

SEWA first started installing the solar pumps four years ago. As of our first visit in 2016, 250 of the 286 solar pumps installed on the Rann were installed by SEWA.

Approach and Methodology for Salt Production Case

The methodology for evaluation of solar pumps for salt production use case was divided into several activities:

- **User surveys** for social and economic factors, including perceived technical performance (April 2016)
- **Farmer interviews** for seasonal cash flows of both solar and diesel pump systems (February 2017)
- **Technical performance** measurement in the field, both in-person and through sensors (April 2016 onward)
- **Lab testing** of the pumps used in the solar pump systems (October 2016 onward)

User Surveys for Salt Production

In April 2016, the CITE research team traveled to Gujarat and conducted 25 interviews of salt farmers in the Little Rann of Kutch, as shown in Figure 34 and Figure 35. The demographic characteristics of the farmers surveyed are as follows:

Table 8: Demographic Data

Demographic Data of Surveyed Salt Farmers	
Average Age of Respondent	39.6
Male	12
Female	13
Average Household Size	6.6
Education Level	
No school or Illiterate	15
Primary, Middle, or Secondary	9
Higher Secondary	1
Average Annual Income from Farming (Rs)	81,240
Average Annual Income from Farming (USD)	1,200

Figure 34: Interview Locations

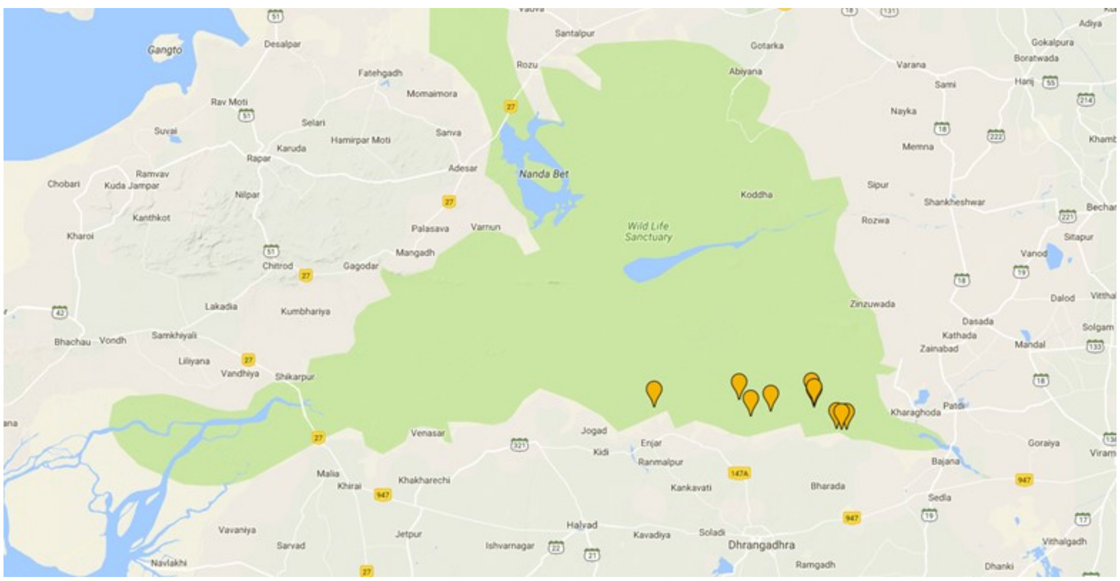


Figure 35: Interviewing Salt Farmers in the Little Rann

In addition to these preliminary surveys, a further 108 farmers were surveyed with a focus on their cash flows, in order to carry out the cost-benefit analysis and comparison of solar pumps to diesel pumps in a subsequent section of this report.

EVALUATION CRITERIA FOR SALT PRODUCTION

For the pump evaluation, the CITE team addressed the following variables:

Table 9: Evaluation Metrics

Indicator	Description
Ease of Use	Ease of use refers to the ability of the end-user to operate the system as it was intended, as well as the system's ability to meet the farmer's pumping needs. Maintenance, convenience, user satisfaction, and required training were taken into account to evaluate ease of use for each pump.
Technical Performance (Perceived)	Perceived technical performance was evaluated based on farmer satisfaction with the solar pumps vis a vis their previous pumping method (either grid electricity or diesel). Technical performance was taken as a perceived measure gathered from survey data rather than actual technical data taken in the field, due to a small sample size and high variability in field-collected data.
Affordability	Affordability is measured both as the farmers' perception of system cost, as well as actual cost relative to income. We also gathered information on the financial model of each case study and the ability of the NGO and/or financing agency to pay for the system up front and over time.
Availability	The availability criterion includes access to trained personnel and physical parts. Technical support proves very important for systems as complex as these, while ease of repair also necessitates easy access to replacement parts in local markets.
Demand	Demand generation was calculated by evaluating the extent to which farmers endorse the systems they have been using, as well as the diffusion of knowledge about the systems throughout the greater community. While these systems are generally part of specific projects, and therefore not a "consumer" good in the sense that it can be readily purchased by individuals in local markets, awareness of their existence and of their value proposition is important in driving scale.
Safety	Safety was evaluated based on the availability of an automatic shut off valve. Overall perceived safety of the system to the user vis a vis their grid electric or diesel alternatives was also noted as well as actual reports of injury from either solar or alternate pumping systems.
Environmental Impact	Though solar pumps have a positive effect on energy balance, they can have a negative impact on groundwater resources. Rather than evaluating the environmental impact of specific systems, we chose to develop a System Dynamics model to evaluate the effect of different policies on the water-energy-food nexus. This is presented as a separate section in the document (The Water-Energy-Food (WEF) Nexus).

User Survey Findings for Salt Production

Ease of Use

Despite the technical complexity of the solar systems, users overall found them overwhelmingly easy to use on a day-to-day basis, which consists primarily of cleaning the panels when they become dusty. One respondent demonstrated how easy the system was to operate by having his infant daughter toggle the on/off switch.

While day-to-day use proved easy, some respondents noted a desire to learn how to troubleshoot more complex problems, expressing concern that they were exclusively reliant on having to call technical staff to come inspect and fix the problems. Since pumping is not possible during more serious technical problems, having to wait for technical staff translates to lost income. On the other hand, several respondents also expressed hesitation at fixing any major issues by themselves and preferred that trained technicians handle problems as they arose.

User Satisfaction with the Technology: A significant perception of solar pumping systems as an improved technology was observed. In Gujarat, users of the system with higher solar capacity were very likely to recommend the solar pump to others, whereas the users of the reduced capacity were only somewhat likely to recommend on average. This was due to their awareness of the ability of the alternative system to run more than one pump at one time. When directly questioned about the payback-time and full cost of the systems, the majority of end-users were unaware of both and unable to estimate with any degree of confidence. All but one respondent indicated that they would not have purchased the systems if their corresponding program did not exist.

Usability: Because the solar pump systems are quite technologically complex, we were surprised to find that all users considered the solar systems very easy to use. Respondents reported that compared to diesel pumps, which can be difficult to start and require the procurement of fuel from sometimes remote locations, the solar pumps are turned on and off with a simple flick of a switch. Some farmers had their children operate the pumps. This demonstrates, that in addition to the financial benefits of solar pumps, the solar systems provide additional benefits in terms of increased safety, ease of use, and comfort.

Affordability

Despite the long-term commitment to make payments to own the solar pump systems, farmers who used a diesel-powered generator prior to purchasing a solar system in our sample realized fairly immediate savings. A sample of 23 farmers shows average diesel expense savings of more than Rs 26,000 (about USD 400) in a single season, as illustrated in Table 10. In contrast, three households consumed a greater amount of diesel after installation of the solar system—hence the negative minimum values in Table 10. Instead of decreasing their diesel use and replacing it with solar, these farmers added the solar pump and in addition, increased their diesel consumption, which significantly increased their overall salt production.

Table 10: Diesel Savings per Season Post-Switch to Solar Pump System, by Volume and Cost

	Volume savings (Liters per season)	**Cost savings (Rs per season, 67 Rs = 1 USD)**
Average	498	26,217
Minimum	-650	-39,000
Maximum	1,400	72,000
Standard deviation	517	28,419

AVAILABILITY

Systems are provided to program participants, or those residents within the jurisdiction of an implementer's project, and so availability on products on the market is not an issue per se. However, a key dimension of availability that emerged during interviews with implementing partners was the importance of skilled technicians at the local level. This would be required as solar systems scale in a region, and would become more and more important as the systems age and require greater maintenance and increase in their likelihood of needing repairs. In the absence of a skilled, local workforce, solar systems may scale and yet may underperform or fall into disrepair, misuse or disuse.

Technical Capacity and Local Servicing: The knowledge, ability, and capability of farmers to interact with and operate their systems beyond simply flipping a switch varied greatly from location to location. In Gujarat, the representatives from SEWA understood the operation of the pumps in detail and were on hand for repairs and maintenance on a weekly basis.

FARMER INTERVIEWS: CASH FLOWS FOR SOLAR VS DIESEL

INTRODUCTION

The focus on solar pumps for salt production in the Little Rann of Kutch in 2017 builds on CITE's previous work in 2015-16 by focusing on the financial implications to the farmer of incorporating a solar pump into their salt production. Unlike agricultural farmers who only use pumps for several hours a day for irrigation, salt farmers often pump around the clock, leading to much higher diesel expenses. It follows that the scope for savings from either switching some of their pumping from diesel to solar, or increasing production by adding a solar pumping system is relatively greater for salt farmers than for agricultural farmers.

Though the cost of solar systems has come down significantly over the past decade thanks to a drop in the per-unit cost of photovoltaic (PV) cells, it continues to represent a significant capital investment for smallholder farmers.

With such an expensive product, it is perhaps not surprising that payback period length was not a consideration that drove purchasing decisions—either between buying or not buying, or between one system and another. This is in keeping with development literature that suggests that given the significant risks and uncertainties associated with poverty, some studies have found that the time value of money (net present value, or NPV) is skewed toward the present with less regard for long-term financial considerations among lower-income individuals.[10]

APPROACH & METHODOLOGY

METHODOLOGY

To better understand the affordability of solar pumps, it was necessary to examine the farmers' cash flow beyond the savings in diesel pre- and post- solar pump installation. In order to get a complete financial picture of the farmers' salt production, we conducted interviews that focused on the costs and revenues associated with salt production.

SEWA has 10,000 members active in salt production in the Little Rann of Kutch, of which about 600 have installed solar pumps. For the purposes of the research, we interviewed a total of 98 solar pump owners, of which 10 used only the solar pump systems and 88 used a combination of solar pumps and diesel pumps. We also interviewed 10 farmers who used only diesel pumps. Because of the variation in salt production from farmer to farmer, as well as variation in the price they were paid, it was important to get a large sample size. Once the survey had been piloted, these cash flow surveys could also be done much more quickly than previous interviews which collected more qualitative data on a broader range questions.

Our first step was to conduct detailed interviews with the farmers who had agreed to have sensors installed on their solar pump systems, in order to evaluate their technical performance. These farmers already had a relationship with our researchers and were able to give us about an hour of their time. These longer interviews allowed us to understand the vocabulary, timing, and units they used to talk about their cash flows, while also providing more detailed information about how and when they are paid by the merchants, and how fuel is transported to the salt pans. Of the 20 farmers who had sensors installed, 16 were available to be surveyed. We these interviews over the course of three days.

From these longer interviews, we were able to construct a much more concise interview that could obtain almost all of the same information in a much shorter period. Over the course of three more days of interviews, we were able to conduct 92 more interviews including 72 with farmers that used both diesel and solar pump systems, ten who used only diesel systems, and ten who used only solar pump systems.

The interviews collected a variety of information on the farmers' cash flows, such that a simple financial statement could be constructed for each farmer, showing total revenue from their solar pumps, diesel if

[10] Nielsen U. 2001. "Poverty and attitudes towards time and risk – experimental evidence from Madagascar." Working paper, Royal Veterinary and Agricultural University of Denmark

they have them, and the percentage of that revenue each year that goes toward maintenance, loan repayment, equipment, fuel, and what remains as profit.

METRICS

Operational Costs: Maintenance and Fuel Costs: Operational costs indicate the cost of operating the pump system throughout the season including maintenance and fuel costs. For the diesel system, this includes the cost of rehabbing the system at the beginning of the season[11], as well as other maintenance through the pumping season. However, the largest portion of these operational costs is the cost of fuel – either diesel or other fuel. The operational costs for the solar pump system include only the maintenance performed on the pumps or other system components throughout the season.

Solar pump systems required much lower maintenance costs. None of the farmers interviewed needed any maintenance on the panels or electronics, so pumps were the only system component that required maintenance.

Table 11: Operational Cost Comparison: Average Across Short Surveys

	Average Annual Maintenance Cost (Rs)	Average Annual Fuel Cost (Rs)	Average Total Variable Cost (Rs)
Solar Pump System	2,023	0	2,023
Diesel Pump System	6,255	58,134	64,389

The biggest difference in the variable costs between solar pump systems and diesel systems is the fuel cost. On average, the farmers used 6.0 barrels of diesel (200 liters per barrel) throughout the season, and spent an average of Rs 58,134 per season on fuel.

Average Cost of Equipment: The payments made for the equipment are different for the diesel and solar pump systems. The diesel equipment is made up of the diesel engine, pump(s), and sometimes, a generator. This equipment is paid for upfront by the farmer, and is used for a defined period of time, until it is no longer operational, and is then sold for scrap. To understand the total cost per season of the equipment, we asked the farmers to tell us not only the original cost of the equipment, but also the length of time they expect it to last. While the costs are often paid in large amounts all at once, to understand the average cash flows of the farmer and for the purposes of the indicator calculation, the total cost of an individual piece of equipment has been divided by the number of years of its useful life, as provided by the farmer.

For solar pump systems, the cost of the equipment is already smoothed through the loans provided to the farmers through SEWA. These payments are non-standard, and based on the farmer's self-judged ability to pay. For the purpose of calculating this indicator, we have averaged the last three years' payments to get an average annual payment, or in the case of newly installed systems, we have taken the farmer's self-reported planned payments for the first full season.

[11] Routine maintenance to restore the pump to working order after having been stored, often buried underground, during the monsoon.

However, the most important aspect of the cost of equipment indicator is the fact that while diesel equipment costs can be depreciated across the life of the equipment, the loan for the solar pump system is designed to be repaid long before the useful life of the equipment has been completed. This means that after the loan repayment, the annual expenses associated with the equipment drops to zero.

The largest annual cost to the farmer for the solar pump system is the payback of the loan. Some loans have been administered through Grassroots Trading Network (GTN), a SEWA offshoot that provides energy products to SEWA members, while other loans have been administered directly through SEWA Bank, SEWA's microfinance arm. The loan is made for the full price of the solar pump[12], currently Rs 151,000, and farmers repay the loan monthly during the season. SEWA has given full flexibility on loan repayment to the farmer.

Table 12: Average Loan Repayment: Across Short Surveys

	To date 2016-17	2015-16	2014-15	Low	High
Average Total Payments per Season (Rs)	19,413	23,097	20,881	30,000	5,000
Payback Period if Average Payment Remains the Same (years)	7.8	6.5	7.2	5.0	30.2

For the diesel systems, the number and cost of equipment components – pumps, engines, and generators (if used) – was collected, as well the number of years the farmer predicted that each element of the system would last.

Table 13: Profile of Equipment – Average Across Short Surveys

	Average number	Average Cost (Rs)	Average Life (years)
Pumps	1.7	6,492	3.0
Engines	1.0	30,766	8.0
Generators	0.4	31,537	10.8

In line with standard practices for depreciation, to calculate an average cost of equipment per year, the number of each piece of equipment was multiplied by the cost and divided by the expected life. No end value was assumed because farmers told the interviewers that the equipment was sold to metal scrappers for a minimal amount at the end of its life. For the sample farmer below, his total equipment cost was Rs.16,933.

Table 14: Profile of Sample Farmer – Survey Number 1-030

	Number	Cost (Rs)	Expected Life (years)	Average Cost per Year (Rs)

[12] Although there are government subsidies available in theory, the bureaucracy involved creates too high a hurdle for individual farmers and NGOs. Most government subsidies for solar pumps are lumped into much larger projects and tendered to project developers.

Pumps	3	5,000	2	7,500
Engines	1	31,000	5	6,200
Generators	1	26,000	15	1,733
Total				**15,433**

Variability of Expenses: This indicator takes into account the range of variability and predictability of expenses for the farmer from year to year. While diesel system expenses can vary greatly from one season to the next, due to (but not limited to) replacing expensive equipment, variability in fuel costs, and highly variable maintenance expenses from year to year, solar expenses are much more predictable. Maintenance costs are generally much lower, fuel costs are non-existent, and the loan repayments are of a standard suggested amount and ultimately decided on by the farmer.

Findings/Results

The following table shows the average costs and profit margins associated with the production of one metric ton of salt, from farmers solar-only or diesel-only systems, not both. In general, the farmers with diesel-only pumps produced much more salt than those with solar-only systems, due to higher efficiency of diesel pumps, the longer run time, and a higher incidence of multiple pumps (sometimes up to four). The figures are presented in Rs/MT to adjust for differences in production and income levels.

Table 15: Diesel-Only and Solar-Only Comparison

<table>
<tr><th colspan="5">Farmers with Diesel-only and Solar-only Pump Systems</th></tr>
<tr><th></th><th>Operational Costs / MT</th><th colspan="2">Average Cost of Equipment / MT</th><th>Profit Margin</th></tr>
<tr><td>Diesel Powered Pump System</td><td>Rs. 76</td><td colspan="2">Rs. 12</td><td>46 percent</td></tr>
<tr><td rowspan="2">Solar Powered Pump System</td><td rowspan="2">Rs. 1</td><td>Pre-Payback</td><td>Post-Payback</td><td rowspan="2">65 percent</td></tr>
<tr><td>Rs. 49</td><td>Rs. 0</td></tr>
</table>

Model 1: Diesel-Powered Pump System

Of the 108 farmers surveyed, ten were using diesel-only pumping systems. A typical farmer's diesel-only pumping business produces just over 1500MT of salt in a season, and gets paid an average of Rs.161 (USD 2.40)/MT.

Table 16: Average Cash Flows for a Farmer Using Diesel-Powered Pumps per Season

	Average	High	Low
Production (MT)	1515	2400	900
Price (Rs/MT)	161	186	135
Revenue (Rs)	243,915	446,400	121,500
Operating Expenses: Fuel and Maintenance (Rs)	115,450	223,500	55,000

Cost of Equipment: Annual depreciation over useful life (Rs)	17,848	27,483	8,639
Diesel Pumping System Profit	111,332	242,783	28,961
Diesel Pumping System Profit Margin	46 percent	67 percent	19 percent

Model 2: Solar-Powered Pump System

Of the same 108 farmers interviewed, ten were using solar-only systems. Their production was generally much lower than the diesel-only counterparts.

Table 17: Average Cash Flows for a Farmer Using Solar-Powered Pumps

	Average	**High**	**Low**
Production (MT)	530	800	400
Price (Rs)	142	140	160
Revenue (Rs)	75,260	112,000	64,000
Operating Expenses: Maintenance (Rs)	681	1,980	0
Cost of Equipment: Loan repayment (Rs)	25,755	36,000	9,692
Cost of Equipment: Pump depreciation over useful life (Rs)	4,204	4,946	2,473
Loan Payback (Straight-line)	6.9 years	4.2 years	19.6 years
Profit (Pre-payback)	44,360	74,185	25,825
Profit Margin (Pre-payback)	59 percent	66 percent	46 percent
Profit (Post-payback)	70,115	106,954	50,754
Profit Margin (Post-payback)	93 percent	95 percent	91 percent

The most important conclusion to be drawn from this comparison is that while the farmers using solar-only systems had a higher profit margin overall, it was after the payback period that their income increased substantially. And while farmers using diesel pumps in addition to solar pumps are still collecting more revenue in an absolute sense, it is only because they are able to produce more salt overall. With the increased availability of solar pumps over time, diesel pumps will increasingly be used only during non-daylight hours, reducing the overall percentage of salt produced by diesel vs solar, but keeping the total production constant.

For the sake of simplicity, because the farmers repay at varying intervals and amounts, the payback has been calculated without interest. Without the cost of fuel or the cost of the loan repayment, the solar pumps have very low operating costs and farmers will see significantly improved incomes, all else equal.

The challenge for SEWA is to educate farmers about the benefits of repaying as early as possible. Although some farmers understood that the long-term benefits of early repayment include not only reduced interest payments but also realizing the benefit of having neither loan nor diesel expenses, many were making payments far behind the suggested schedule.

Model 3: Farmers Using Both Diesel and Solar Powered Pump System

For the farmers who used both solar and diesel pumps, the challenge was to determine how much of their total annual production (and therefore income) came from solar pumping and how much came from diesel pumping. During the long-interview format, the farmers estimated that the relative productivity of the diesel pumps compared to solar pumps was about 150 percent. This figure was used in conjunction with the number of solar and diesel pumps, as well as the number of hours per day each one is used, and the number of months out of the year in which each system type was operational.

Of the 108 farmers interviewed, 88 used a combination of solar and diesel systems. Five of those interviews have been removed from the dataset because of incomplete data, leaving 83 farmers with the combined system.

The proportion between solar and diesel is determined by the number of hours per day each systems is run, the months during which each system is active, and the relative productivity of solar pumps vs diesel pumps as provided by the farmer.

To analyze the cash flows of the farmers with the combined systems, the costs, revenues, and profit figures are analyzed per metric ton. The average price per ton that the farmers received was Rs.159 (USD 2.37). The margin analysis below shows how Rs.159 is split between the different types of expenses, and farmer's profit margin. Again, as with the solar-only farmers, the most important take-away is that while the solar and diesel elements of the farmer's income both gave very similar profit margins (of 33 percent and 34 percent respectively), once the loan was repaid, the profit margin for the solar production increased dramatically.

Although the ultimate test for improved livelihoods for salt farmers is an increase in absolute income, because of the large variation in total production, the figures have been broken down into a margin analysis in order to better show how a farmer's total revenue in a single year is broken up into expenses, loan repayments, cost of equipment, and profit for the season.

Table 18: Division of Income for Farmers with Both Solar and Diesel Pumping Systems

	Total	**Solar**	**Diesel**
Price (Rs/MT	159	159	159
Production (MT)	1,217	383	834
Total Revenue (Rs)*	196,936	60,655	136,281

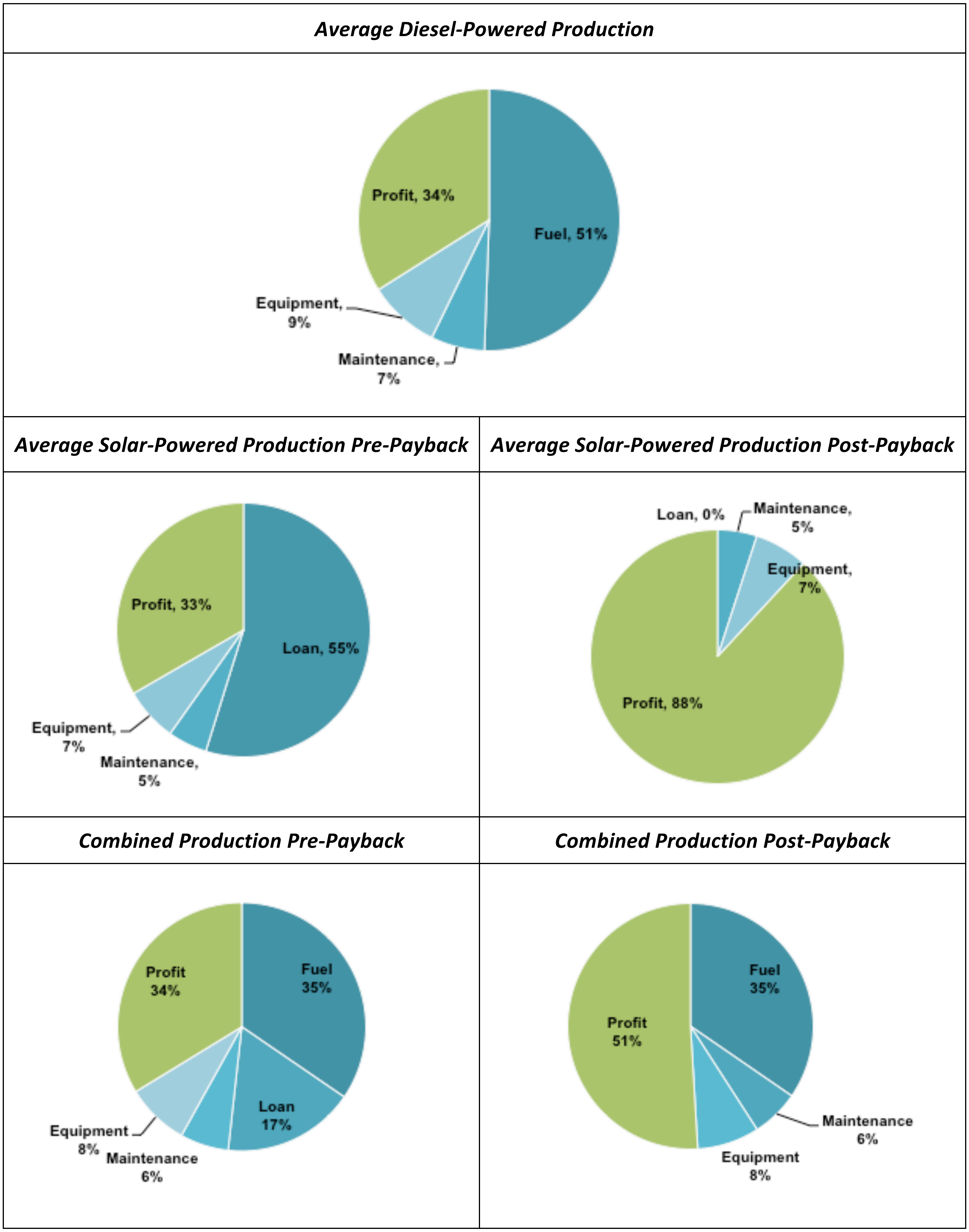
Table 19: Margin Analysis: Rs/MT Salt Produced – Solar and Diesel Separated

	Solar		**Diesel**	
	Rs/MT	*Margin of Revenue*	*Rs/MT*	*Margin of Revenue*
Fuel Expense	0	0 percent	80	51 percent
Maintenance Expense	8	5 percent	11	7 percent
Loan Repayment	87	55 percent	0	0 percent
Average Cost of Equipment	11	7 percent	14	9 percent
Total Expenses (Pre-payback)	106	67 percent	105	66 percent
Total Expenses (Post-payback)	19	12 percent	105	66 percent
Profit (Pre-payback)	53	33 percent	54	34 percent
Profit (Post-payback)	140	88 percent	54	34 percent

Table 20: Margin Analysis: Rs/MT Salt Produced – Solar and Diesel Combined

	Rs/MT	***Margin of Revenue***
Fuel Expense	55	35 percent
Maintenance	10	6 percent
Loan Repayment	27	17 percent
Average Cost of Equipment	13	8 percent
Total Expenses (Pre-payback)	105	66 percent
Total Expenses (Post-payback)	78	49 percent
Profit (Pre-payback)	54	34 percent
Profit (Post-payback)	81	51 percent

Figure 36: Visualizing the Margin Analysis



QUALITATIVE METRICS

Finally, the business model includes more than just the cash flows to the farmer. There are also inherent benefits, drawbacks, and risks associated with both models.

The cost structure or financing of the two models is very different. While the diesel pump equipment is required to be paid for upfront in cash, unless a loan can be secured privately, SEWA offers very flexible financing options for the solar pump, including very little cash as a down payment and payments not in excess of the savings provided by the switch from diesel to solar. While they suggest the farmers try to repay the loan within three years, in reality, most are on track to repay in 7 or 8 years, which is still well within the 20 year useful life of the panels and electronics.

Variability of expenses is also a factor for the farmers choosing between a diesel and solar pump. Diesel pump systems are expensive and time consuming to maintain, and their repair and replacement can come at unexpected times. They also include three components: the pump itself, the engine, and in some cases, the generator. Solar maintenance, by contrast, is relatively easy and much less expensive, because only the pump itself would need to be repaired and replaced.

Flexibility of pumping time highly favors the diesel pump, because it can be run 24 hours a day if the farmer chooses, and is not bound by daylight hours.

Technology risk to the farmer is higher for solar than for diesel. Diesel pumps have been used for decades in the production of salt, the farmers understand the technology intimately, and they have knowledge and understanding of diesel systems. The solar pumps present a new technology for the farmers, and they would require technical assistance from a SEWA staff member if any adjustments needed to be made to the electronics or panels. In addition, placing solar panels and electronics in such a harsh environment has not been extensively tested, and if they technology fails, the farmer, as owner of the panels, would still be responsible for repaying the loan.

Lastly, farmer autonomy increases throughout the use of solar pumps, because they lessen the farmer's reliance on the advances given by the salt merchant, which would usually be required to purchase fuel. The farmers are already at the mercy of the merchants for setting the price of salt, and the freedom from diesel expenses throughout the season gives them flexibility in their cash flows. Unfortunately, the merchants have recognized that the farmers are able to produce salt at a lower cost, and have forced salt prices lower as a result. SEWA staff are working with members to unionize in order to demand a better price for their produce and more favorable terms.

Table 21: Business Model Comparative Evaluation

	Diesel-Powered System	**Solar-Powered System**
Cost Structure/Financing	Paid upfront	Flexible financing
Variability of Expenses	High/Unpredictable	Low/Flexible
Flexibility of Pumping Time	Can operate at any time	Can only operate during daylight hours
Technology Risk to Farmer	Low	Med-High
Farmer Autonomy	Low-Med	Med

Technical Performance of SEWA Solar Pumps

Technical testing of pump performance was performed both in the field and in the lab.

Pump Performance in the Field

Introduction

In April 2016, the CITE team traveled to India and visited numerous sites and partners, including SEWA in Gujarat. During the visit, Solar Water Pump users were surveyed on their reactions and opinions of the systems. In parallel to gathering survey responses, the team collected instantaneous technical data for 28 of the systems, in order to inform the subsequent design of sensors.

Figure 37: CITE/TEL Researcher Eadaoin Ilten Measuring Water Flow

Figure 38: Typical Pipe Used in the Salt Farmer Boreholes

Recorded Data for SEWA Pumps

The information collected ranged from distances between the water sources, pumps and outlets to instantaneous electrical and flow rate measurements, as shown in Table 22.

Table 22: Raw Data from User Surveys (left) and Calculated Indicators (right)

Recorded Data	Calculated Data
Flow rate (L/min)	*Total Head (m)*
Pump rating (HP)	*Frictional Head Suction pipe (ft)*
Well depth from surface (ft)	*Frictional Head discharge pipe (ft)*
Water level from pump (ft)	*Discharge Head (ft)*
Distance to outlet (ft)	*Suction Head (ft)*
Suction Pipe diameter (")	*Pump Power out (HP)*
Discharge Pipe diameter (")	*Panel Array Power (W)*
Panel voltage (V)	*Pump Power In (W)*
Panel current (A)	*Pump Power In (HP)*
Pump voltage (V)	*Pump Efficiency*
Pump current (A)	*Controller Efficiency*

For the 28 systems measured (owned by 25 farmers), we were able to gather flow data for seven pumps, due primarily to the fact that we had two teams conducting surveys in parallel, but only one flow meter. Also some of the farmers did not want us to check the rate as it would interfere with their pumping. The solar panel voltage and current data was gathered for some almost all of the systems, but we were unable to gather all of the pump voltage and current numbers due to various reasons (e.g., no open wires to take measurements, etc.). Table 23 shows the data gathered in the field in April 2016.

Figure 39: Histogram of Flow Rates of Falcon 1 HP Seen in the Field. Mean 120 L/min (s = 48 L/min)

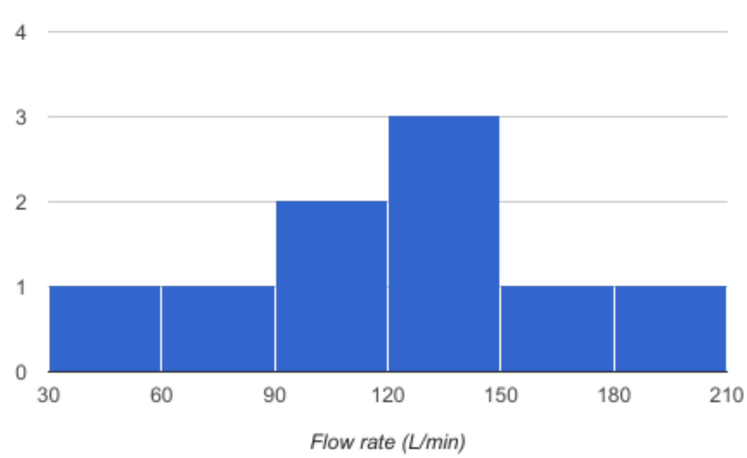


Table 23: Field Measurements from April 2016

Survey #	Type	Flow rate (l/min)	Pump rating (Hp)	Panel voltage (V)	Panel current (A)	Pump voltage (V)	Pump current (A)
1103	Sun Edison SEWA			220			0.8
1118	Sun Edison SEWA		1	364	3.4	258.4	2.7
1131	Sun Edison SEWA		1.5	364	5.28	208	1.71
1133	Sun Edison SEWA			360			2.2
1135	Sun Edison SEWA		1.5	362.8	3.59	256	3.4
1146	Sun Edison SEWA		1	262.8	1.38	259.1	2.43
1161	Sun Edison SEWA			360			0.9
1177	Sun Edison SEWA			362			
1205	Sun Edison SEWA	52	1	360	4		1.4
1230	Sun Edison SEWA		1.5	262	3.58		3.2
1241	Zynergy		1	227.1	5.7	122.1	
1247	Sun Edison SEWA		1.5	363.3	3.48	256.7	2.8
1256	Sun Edison SEWA		1.5	363.7	3.4		3.02
1258	Sun Edison SEWA	160		362	2.4	195	0.7
1288	Sun Edison SEWA			360	3.2	390	3
1293	Zynergy		1	200.9	6.5	154.6	6.2
1307	Zynergy	22	1	201	4.6	317	5.6
1312	Sun Edison SEWA			361	2.5		2
1334	Sun Edison SEWA			402	3.4		3.1
1347	Sun Edison SEWA		1.5	49.6	3.4	70.7	3.65
1352	Sun Edison SEWA	38	1	362	2.3	184	1.7
1385	Sun Edison SEWA		1	0.787	3.41	50.5	2.4
1399	Sun Edison SEWA		1.5	401	3.64		2.6
1216-B1	Sun Edison SEWA	25	1.5	361	2.5	190	1.5
1216-D1	Sun Edison SEWA	8	1	203	4.5	140	5.2
1216-E1	Sun Edison SEWA	32	1	208	4.7	141	5.4
1363-A2	Sun Edison SEWA		1	249.5	6	59	5.92
1363-B2	Sun Edison SEWA		1.5		3.38		2.91

Notes:

1363-A2: Pump voltage: pump wasn't on when reading was taken

1363-B2: Panel voltage: wide fluctuations in reading

1347: Panel voltage: wide fluctuations in reading

1385: Technician not sure why voltage readings are so low

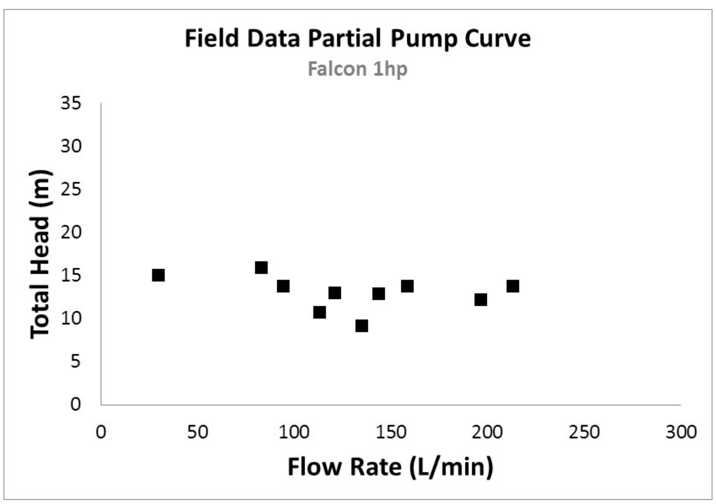
Findings from Field Testing

This preliminary field data allowed us to create a pump curve for the Falcon 1 HP pumps seen in the field. Figure 40 shows the recorded instantaneous flow rate versus the corresponding calculated total head for each system. As with the laboratory data, the total head and flow rate do not exceed 24.3m and 300 L/min, respectively. As expected, the performance of the pumps in the field is significantly reduced when compared to the lab data, this is assumed to be due to general usage and exposure to the high levels of salinity (total dissolved solids (TDS) = 13,000-17,000 mg/L). The average efficiency was 35 percent (s = 16 percent), again this low efficiency is attributed to the harsh nature of the environment. On average, the salt farmers reported the expected pump lifetime to be 3.2 years before needing replacement due to rust, as seen in Figure 41.

From the electrical measurements, current and voltage of both the pumps and panels, the mean AC power into the pumps was calculated as 0.91 HP (+/- 0.59) for the 1.5 HP pumps, and 0.53 HP (+/- 0.28) for the 1 HP pumps, showing that they were not being powered at optimal levels. The panels generated a mean of 1.54 HP and 1.34 HP for the 1.5 HP and 1 HP pumps systems, respectively, showing a loss of 40 percent and 60 percent respectively when converting from DC to AC.[13]

To reiterate, these values were instantaneous and not tested in a laboratory setting, each solar pumping system was located at a different location with differing water levels and exposure rates to the environment.

Figure 40: Field Recorded Pump Curve Data for the Falcon 1 HP Pumps Found in the Field.



[13] Electrical power is reported here in horsepower to better conceptualize the values for pumping.

Figure 41: Rusted Pump Seen in the Little Rann of Kutch

PUMP PERFORMANCE IN THE LAB

To measure the technical performance of pumps, several test pumps were used that corresponded to both pumps that were being used at the field-testing site and other similarly sized commercially available pumps that were available in India. While some overlap exists in the two sets of pumps, pump availability, cost, and functionality constraints narrowed the lab test pump list to those described below. In particular, several of the pumps used in the areas where fieldwork was conducted were large (e.g., 5 or more HP) and a comparison between these and 1 HP pumps would prove imbalanced. A harbor freight pump purchased in the US was added as a baseline.

The following pump-sets were tested in lab:

Table 24: Pumps Tested in the MIT/CITE Lab

Manufacturer	Model	Size	Voltage	Type
Falcon	FCM 115	1 HP	110V	3-phase AC
Futurepump	SF1 v1.5	1 HP	30V	DC
Harbor Freight (baseline)	Pacific Hydrostar	1 HP	120V	1-phase AC
Kirloskar Brothers	SKDS 116++	1 HP	110V	3-phase AC
KSB Group	Monosub-R 1.0 H.P.	1 HP	220V	1-phase AC
Lubi	MDH 313	1 HP	415V	3-phase AC
Rotomag	MBP30	1 HP	30V	DC
Shakti	SMP 1200-20-30	1 HP	120V	3-phase AC

TEST RIG

The experimental setup is shown in Figure 42. The test rig consisted of a 330 gallon IBC tank to serve as the primary water tank and a 50 gallon drum to serve as a secondary collection tank and a flange with a valve was installed to allow drainage from the secondary tank to the primary tank. To mount the pumps rigidly, we built a test stage on top of the primary tank. The inlet plumbing for the pumps was made using 1.5” PVC piping with a one-way check valve attached at the bottom to allow for pump priming. To be able to measure the performance of the pump, the outlet of the pump was connected to the secondary tank using 1.5” PVC and included an Omega FTB794 flow rate sensor and an Omega PX309 pressure transducer. The system also included a Valwox 565262 electric ball valve between the two sensors to generate backpressure to simulate additional head.

Figure 42: Pump Testing Experimental Setup at MIT

POWERING PUMPS FOR TESTING

To power the pumps for lab testing, different power sources had to be used to generate the appropriate power. Table 25 summarizes the power sources for each pump that was tested.

Table 25: Power Sources

Manufacturer	Model	Type	Power Source
Falcon	FCM 115	3-phase AC	VFD
Futurepump	SF1 v1.5	DC	DC
Harbor Freight	Pacific Hydrostar 1 HP	1-phase AC	120V AC
Kirloskar	SKDS 116++	3-phase AC	VFD
KSB Group	Monosub-R 1.0 H.P.	1-phase AC	220V AC
Lubi	MDH 313	3-phase AC	415V AC
Rotomag	MBP30	DC	XANTREX
Shakti	SMP 1200-20-30	3-phase AC	VFD

The power supply to the 110-120V 3-phase pump sets was a Jalverter 1.6 VFD manufactured by Kirloskar Brothers that operated with a DC input or an AC input and outputted 3-phase power at the desired voltage. For the input power to the VFD, we used both a 1200W DC power supply (Ametek DCS-3000 power supply) configured to output up to 300V at 4A. The pumps using the VFD were tested both with AC and DC power and the VFD was set at the voltage rating for the pump at 50Hz.

The power supply to the DC pumps was a Xantrex DC power supply rated to output 40V at 30A. The power supply was set to the operational voltage for the pump.

The power supply to the single-phase AC pumps were powered directly from wall outlets (120V single phase or 220V single phase) and were frequency from 60Hz to 50Hz AC when necessary using a VFD output.

Testing Procedure

The pumps were mounted to the test rigs and attached to the plumbing with flow and pressure sensors. After priming the pumps, we turned them on and slowly ramped up power to full power, as defined in the power pumps section. If the pump was not primed properly and we noticed the water hammer effect, power was immediately disconnected and the pump was disconnected from the plumbing and primed. This was process was repeated until the pump was able to achieve steady-state flow and performance.

The pump curve for each pump was generated by collecting 3-5 characterization runs on each pump. For each run, the pump was allowed to operate unrestricted for at least 5 minutes to ensure that it had reached steady state. Steady state flow was verified by checking the pressure and flow-rate sensors to make sure there was no variation in readings. After the initial phase of operation, the pressure valve was incrementally closed to simulate head by increasing the resistance to flow. After the flow stabilized, values for flow rate and pressure were recorded. The valve was progressively closed until the pump could no longer pump water, at which point the pumps were switched off. Power input to the system was recorded at various points.

The data from the various runs was aggregated for each pump set. To generate a pump curve, a polynomial of degree 2 was fitted to data using MATLAB.

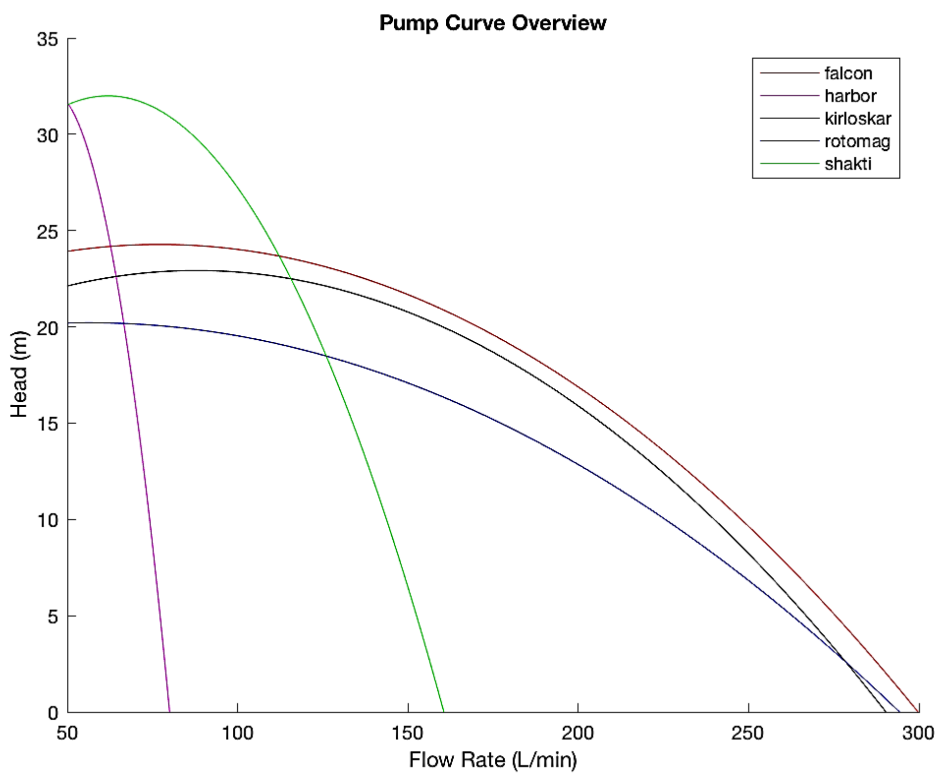
Pump Lab Testing Results

Max Power Pump Curves

Pump curves demonstrate a pump's performance characteristics, plotting the flow rate outputted by the pump (x-axis) against gravitational head the pump must overcome (y-axis). Generally, pump manufacturers provide pump curves to demonstrate how their pumps are likely to perform under different scenarios. Pump performance varies based on available power, but for this evaluation we evaluated pumps at their maximum power draw (as per the pump rating).

Figure 43 below demonstrates a plot of the pump curves for the various pump sets that were tested.

Figure 43: Pump Curves of Tested Pumps



The pump curve at maximum power captures the maximum head that the pump can pump to and the highest flow rate that the pump can produce. This data is summarized in Table 26 below.

Table 26: Pump Max Head and Max Flow Rate

Pump	Max Head (m)	Max Flow Rate (LPM)
Falcon	24.3	300
Harbor Freight	32.2	81
Kirloskar	22.9	291
Rotomag	20.2	295
Shakti	32.0	162

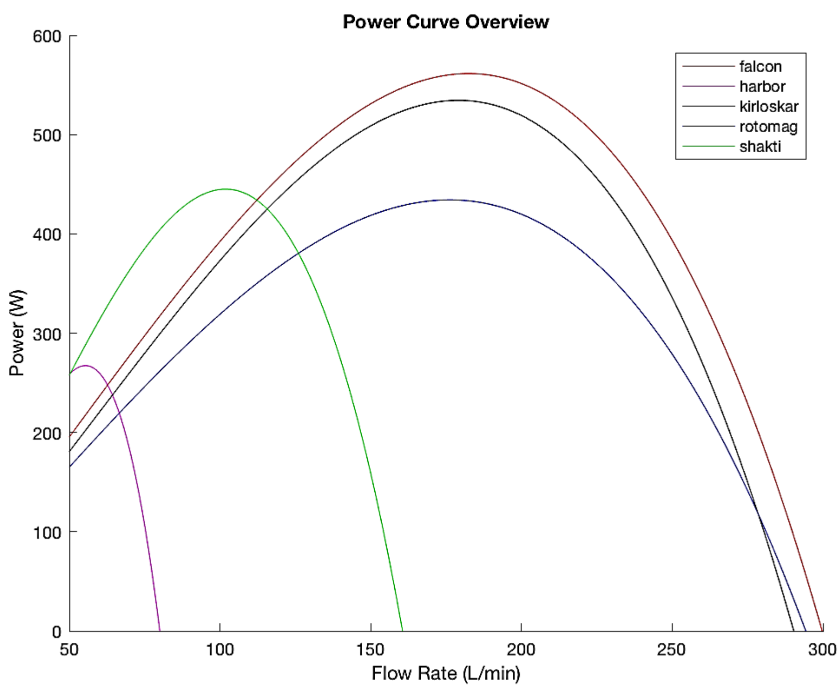
To characterize the overall performance of the pump, we can measure the hydraulic power output, which measures the amount of work done by the pump when it moves water. This power output varies based on where along the pump curve we are operating the pump and is defined as:

$$P_{hydraulic} = q\ \rho\ g\ h$$

where q = flow rate, ρ = density of fluid, g = gravitational acceleration, h = head

Figure 44 provides a summary of the hydraulic power curves for each of the pumps that were tested in lab. We can see that each pump operates most efficiently at a different flow rate.

Figure 44: Summary of Hydraulic Power Curves



PUMP EFFICIENCY

Using the hydraulic power and the electrical power input, we can further calculate system efficiency. The instantaneous efficiency of the pumping systems vary depending on where on the curve the pump is operating, but we can calculate peak efficiency by selecting the maximum power output and measure efficiency using the following equation:

$$\eta = \frac{P_{hydraulic}}{P_{input}}$$

Table 27 summarizes the power inputs, hydraulic power outputs, and peak efficiencies for each tested pump.

Table 27: Power Input/Output and Peak Efficiencies

Pump	Electric Power Input (W)	Hydraulic Power Output (W)	Peak Efficiency (percent)
Falcon	1200	561	46.75 percent
Harbor Freight	750	267	35.60 percent
Kirloskar	1200	534	44.50 percent
Rotomag	750	434	57.87 percent
Shakti	1400	445	31.79 percent

Daily Output

The ministry of new and renewable energy (MNRE) in India benchmarks the output of solar pumping systems for shallow/surface water by amount of water pumped at a head of 10m. In our testing, the solar pumps were run at steady state at a pressure corresponding to 10m head to measure flow rates. Maximum daily output was calculated by assuming 8 hours of daily solar availability to run the pump.

Table 28: Pump Maximum Daily Output

Pump	Flowrate at 10m (LPM)	Daily max output (L)
Falcon	215	103,200
Harbor Freight	21	10,080
Kirloskar	207	99,360
Rotomag	178	85,440
Shakti	134	64,320

Pump Priming

All of the pumps tested required priming. While many pump manufacturers are starting to make self-priming pumps, our field research team did not encounter any of them in use. Pump priming contributes to the ease of use of the product and is determined by the physical geometry of the housing and rotor. The primary cause for pumps to not start properly is that air gets captured within the pump housing and the pump cannot pull suction properly as a result and good pump design reduces this effect. Pump priming contributes to the ease of use of the system and smaller pump sets that are designed to be moved may require routine priming.

Figure 45: Salt Farmer Priming His Pump in the Little Rann

To generate a metric for ease of priming, each pump was connected to the test rig, primed by filling water through the outlet, and turned on. We repeated this process and measured the rate of successful priming, disconnecting the pump completely between each test.

Table 29 below summarizes the ease of priming results.

Table 29: Ease of Priming Results

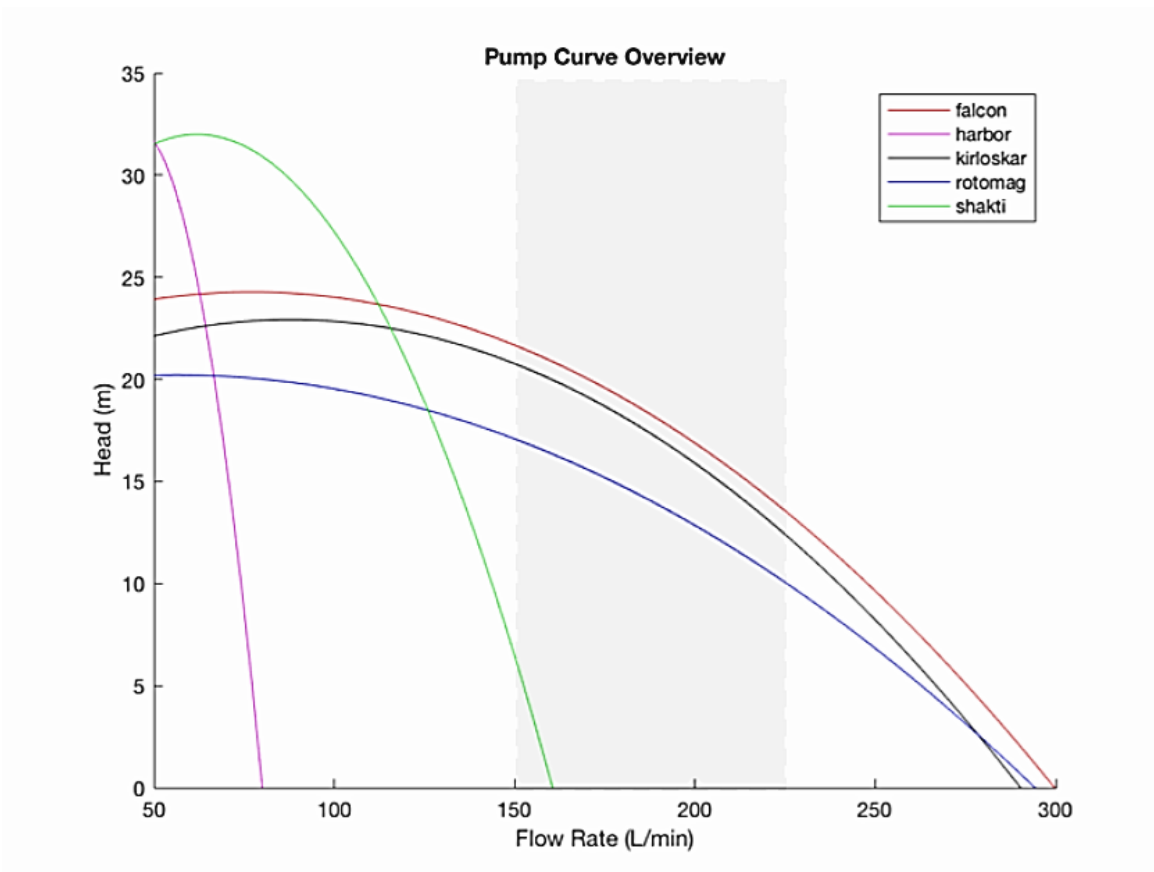
Pump	Priming Score
Falcon	4 ★★★★☆
Harbor Freight	5 ★★★★★
Kirloskar	3 ★★★☆☆
Rotomag	4 ★★★★☆
Shakti	2 ★★☆☆☆

INTERPRETING THE PUMP TESTING RESULTS

Pump sizing and selection is a complex process and users need be able to select the appropriate range of pumps to be considered for a specific application. However, as seen in our technical testing, pumps within the same horsepower rating have varying output. Below, we show an example of how a farmer might use the pump curve results to select a pump.

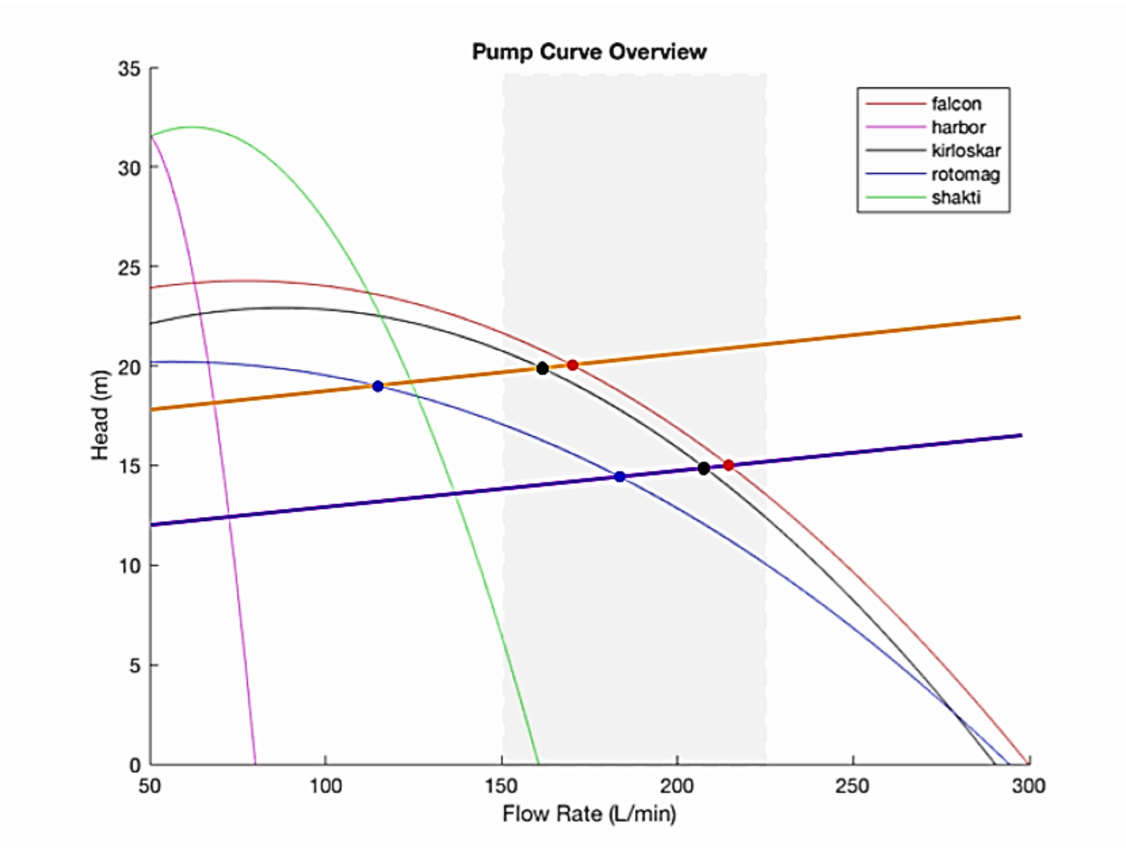
Consider a farmer who requires at a minimum continuous flow rate of 150 L/min for his crops. The water source for the farm is a shallow well with a recharge rate of 225 L/min. We can start by overlaying the operational region required by the farmer's flow rate requirements on the pump curves shown in Figure 46.

Figure 46: Farmer's Operational Region



We now need to consider the farmer's head requirements: we can plot a sample system curve for the farmer on graph. Wells typically have some degree of variability in their static head, so we have to plot both the maximum (orange) and minimum (purple) system curves on our plot as shown in Figure 47.

Figure 47: Maximum and Minimum System Curves



Based on our curves, we can see that the Falcon, Kirloskar, and Rotomag pumps provide sufficient flow when the well is full (the intersection of the pump curves and the purple system curve are within our shaded region). However, at times when the well level is at its lowest, the Rotomag pump is insufficient to meet our needs and only the Kirloskar and Rotomag pumps provide sufficient flow (the intersection of only two pump curves and the orange system curve are within our shaded region). As a result, our farmer is left to choose between the Falcon and Kirloskar pumps.

To determine which of the pumps to use, we would further consider the pump efficiencies within the operating region as well as the cost of the pumps. From our results, we see that the Falcon FCM 115 is slightly more efficient than the Kirloskar SKDS 116++ pump, but the difference in minimal. We can also further consider the ease of use of the pumps – the Falcon pump received a higher score in the priming category so installation and maintenance of the pump is better than the Kirloskar. Cost irrespective, we would recommend the Falcon FCM 115 for this use case.

Comparing Solar Pumps Based on Lab Testing Results

The comparative results of the lab testing are shown in Figure 48 (metric units top, SI units bottom). While the CITE team decided not to rank the pumps due to the strong dependence on the specific use case (i.e., one size does not fit all), several conclusions can be drawn from the data. First, the Falcon and Kirloskar pumps have similar performance and a similar price, so either one would be a good choice for small scale farming.

Figure 48: Pump Comparison Chart

product Information			product attributes				
make/model	Unit cost USD (incl. shipping)	type	max head (m)	max flow (LPM)	daily max at 10m	priming ease	efficiency
Falcon FCM 115	$260 ($455)	3 Phase AC 120V	24.3	300	●	◕	◕
Harbor Freight (baseline)	$128	1 Phase AC 120V	32.2	81	○	●	◔
Kirloskar SKDS116++	$236 ($486)	3 Phase AC 120V	22.9	291	●	◑	◕
Rotomag MBP30	$535 ($730)	DC 30V	20.2	295	◕	◕	●
Shakti SMP1200-20-30	$1835 ($2018)	3 Phase AC 120V	32.0	162	◑	◔	◔

product Information			product attributes				
make/model	Unit cost USD (incl. shipping)	type	max head (ft)	max flow (GPH)	daily max at 33 ft	priming ease	efficiency
Falcon FCM 115	$260 ($455)	3 Phase AC 120V	79.7	4755	●	◕	◕
Harbor Freight (baseline)	$128	1 Phase AC 120V	105.6	1284	○	●	◔
Kirloskar SKDS116++	$236 ($486)	3 Phase AC 120V	75.1	4612	●	◑	◕
Rotomag MBP30	$535 ($730)	DC 30V	66.3	4676	◕	◕	●
Shakti SMP1200-20-30	$1835 ($2018)	3 Phase AC 120V	105.0	2568	◑	◔	◔

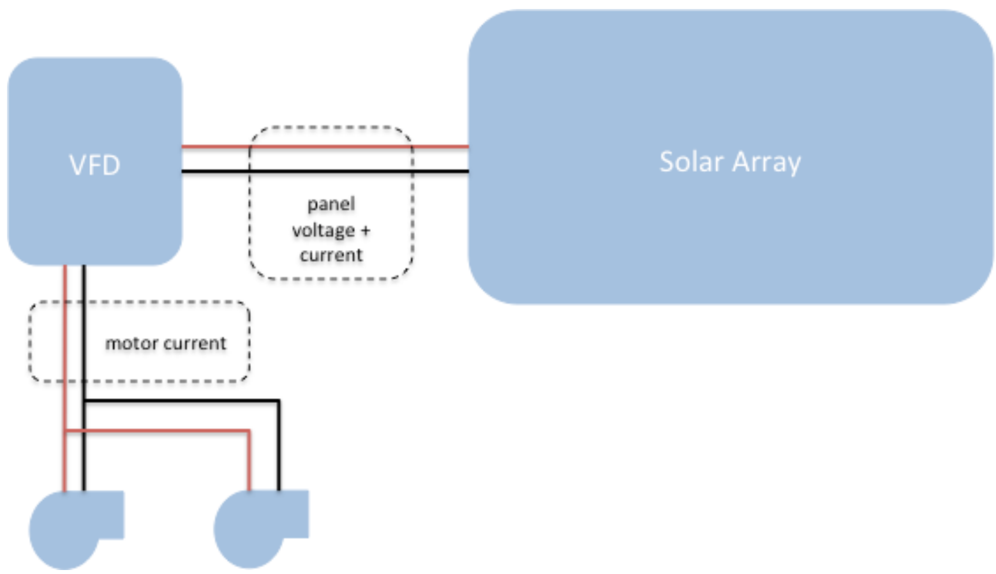
Remote Monitoring of Pump Usage Using Sensors

Solar pump usage and performance varies significantly depending on user-behavior and localized environmental conditions. In prior work conducted by CITE, we found significant discrepancies between self-reported product usage and actual product usage. To determine the appropriate scoping and deployment of the solar pumping systems for use the SEWA salt farming pilot, we developed specialized remote-sensing prototypes to characterize the output and usage of the systems.

Data-logger design and installation

The prototype data-loggers were built using Particle Electron platform (www.particle.io). The data-loggers interfaced with a custom circuit board that allowed for localized data storage to microSD cards. The data-loggers connected to the system at the solar panel input to the VFD and the VFD output to the motors as shown in Figure 49. The data was uploaded to a cloud-based server using cellular networks every 12 hours. Devices were powered from the DC voltage output of the VFD.

Figure 49: Data-Logger Design

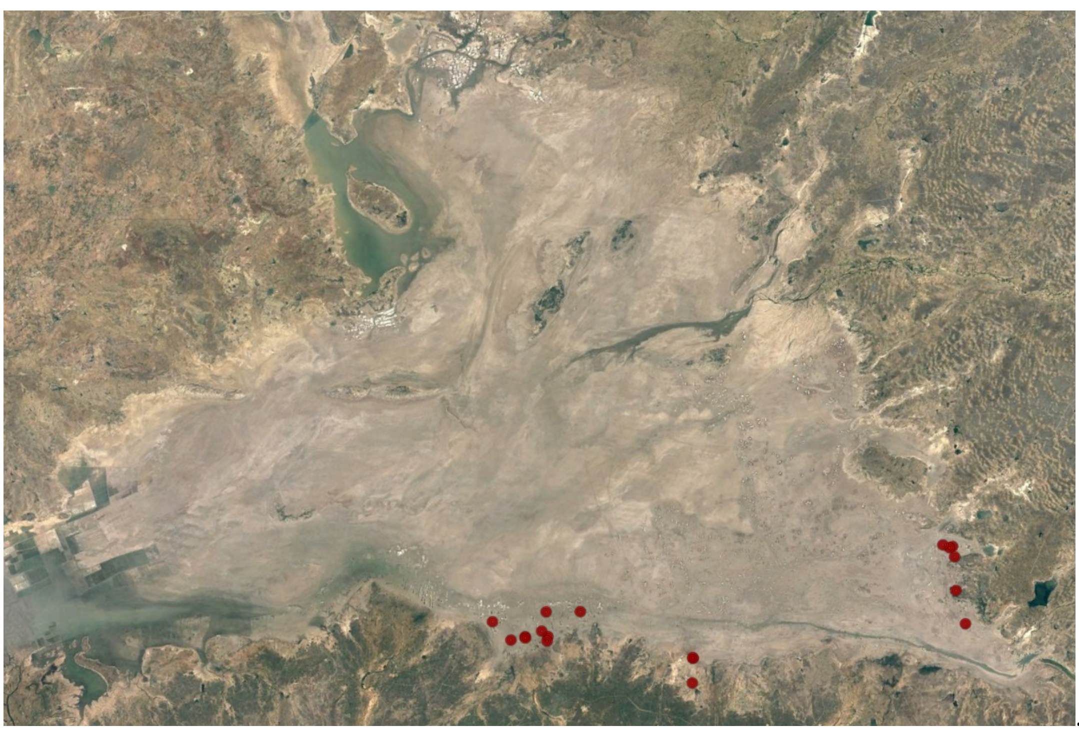


To measure the voltage output of the solar panel, we used designed a circuit using the IL300 photovoltaic output isolator to step down the voltage from 300V to 3V. To measure the current output of the solar panel and the input current to the motors, we used a HO 25-P non-contact 25A hall effect current sensor. The installed system is shown in Figure 50.

Figure 50: CITE Researchers Amit Gandhi (left) and Przemyslaw Pasich (right) Installing Sensors

The data-loggers were installed in the 17 locations in the Little Rann of Kutch in January and designed to measure output of the systems until May-June. The location of the installations is shown in Figure 51.

Figure 51: Location of Installation Sites

.

Sample data-logger output

The data from several pumps was aggregated from installation through March 31, 2017 to understand regularity of system usage and production. A sample of the output from SP020 is shown in Figure 52, Figure 53 and Figure 54. The data shows consistent usage of the pumping systems with varying levels of pump usage. The motor current variation could be attributed to salt farmers using one or two pumps in their system or because of solar array power limits. It was difficult to find locations with good cellular availability in the Little Rann of Kutch and gaps in data are likely a result of poor cell coverage. We will continue to analyze the data to determine season variability and track longer term adoption rates for the different sensor systems.

Figure 52: Plot of Motor Current

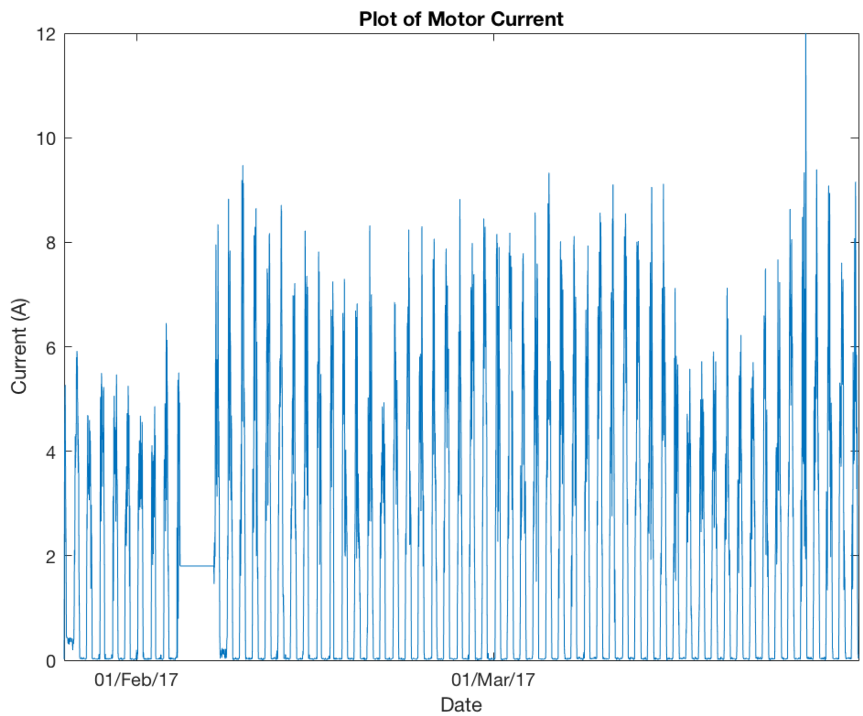


Figure 53: Plot of Solar Panel Voltage

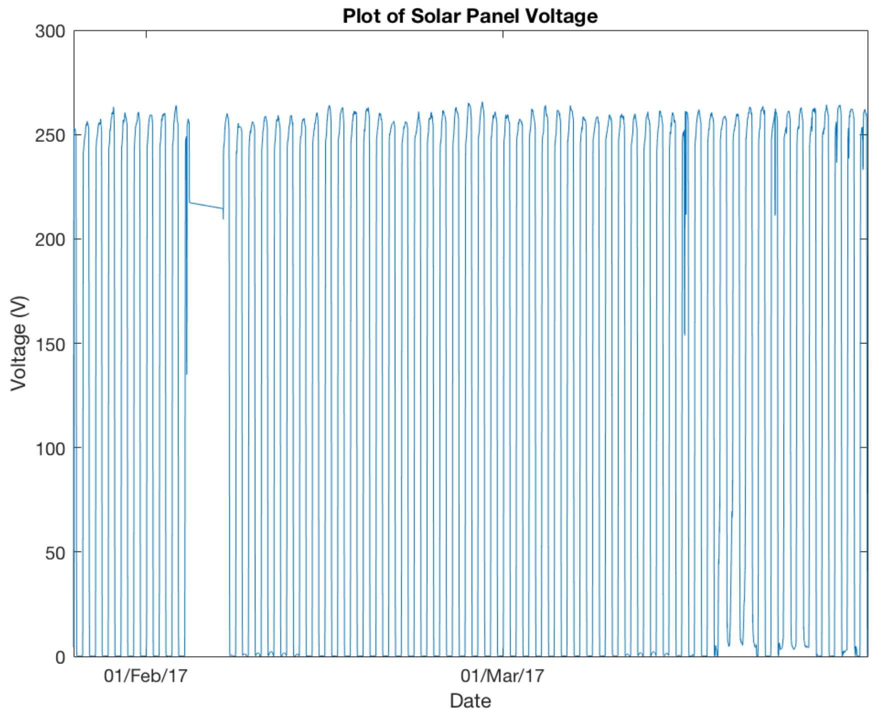
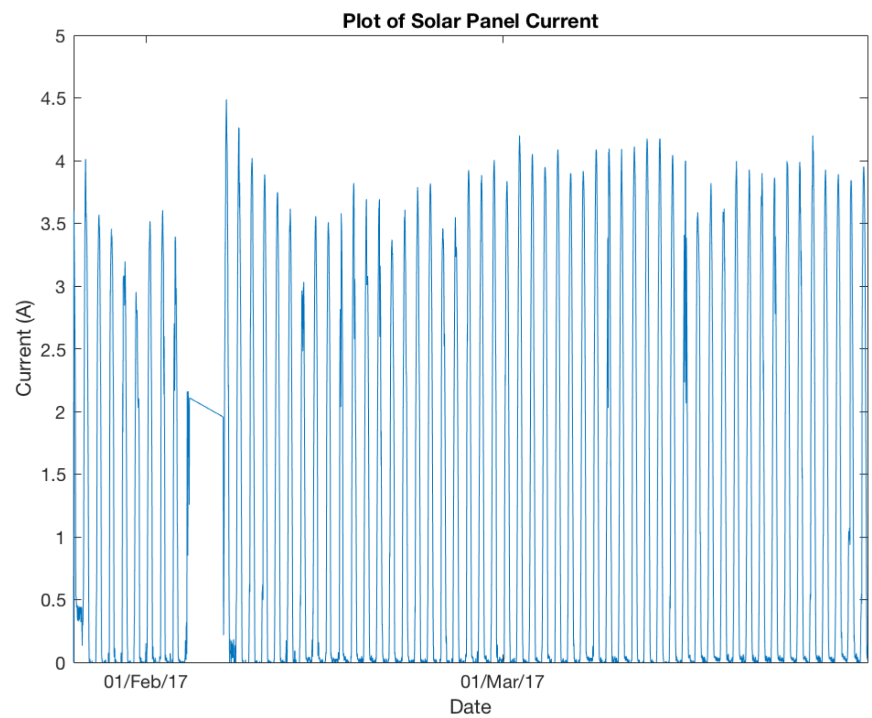


Figure 54: Plot of Solar Panel Current



Summary of Findings

As a sustainable and scalable technology, solar water pumps reside at the water-energy-food nexus. Their implementation in regions heavily reliant on fossil fuels or grid electricity (powered primarily by coal) is often hailed as a vital step in battling climate change and increasing food security.

The cases studied were approached from a programmatic standpoint and revolved around community integration. Through a research approach that included case study development, direct end-user surveys, and stakeholder interviews, five key factors to consider before implementation were identified: end-user satisfaction with the technology, system sizing, water availability, technical capacity and local servicing, and financing availability. They are listed as a formative first stage checklist when choosing to implement an agricultural-based, community-wide solar water pumping program. Though the factors listed arise specifically from the introduction of solar pumping systems, they may offer lessons germane to alternative technologies more broadly. Beyond the checklist, topics such as supply chain mapping in rural areas and alternative asset productivity uses for the solar panels, are highlighted as of interest to those procuring solar pumping systems at scale but beyond the scope of this initial investigation.

One of our findings from this research was that many partners jumped straight into solar pumping deployment without fully investigating the other elements of an integrated irrigation system, or understanding whether such a system is financially or environmentally sustainable.

Choosing the Right System

Solar pump systems are a powerful technology farmers can use to increase their crop production and augment their income. Every farmer's irrigation needs are different, and are also constrained by the local environment. Two farms that are geographically proximate and that are the same size are growing the same crops may have widely differing environmental conditions that will determine what type of solar pump system is appropriate for them, or whether one is appropriate at all.

Toward that end, it may be best to first employ more efficient irrigation measures, then plan for a solar pump. The amount of water required will be much less for efficient irrigation measures, meaning that a lower-powered pump may work just as well, requiring a smaller solar array. This will greatly reduce the cost of the project.

The other key element of technology choice is the correct sizing of the solar pump system to suit a specific farm's and farmer's needs. Solar panels are an expensive asset, so the pump size should be chosen carefully. If the system is undersized, the pump will not work well, but if the system is oversized (something that farmers often requested), the panel cost increases accordingly and the overall cost of the system may become unnecessarily costly. This is particularly important when considering that for agriculture, the capacity utilization factor (CUF)—the ratio of real output to maximum output under ideal conditions—is relatively low.

While the pump is able to operate during all daylight hours, it is rarely used more than a few hours per day and sometimes not at all. As all of the systems considered in this paper were designed to work without batteries to store energy, this means all the power the panels could produce during that time is wasted, resulting in a prolonged payback period. Similarly, such waste also translates to a longer energy payback time. Greater productive use of the asset could be addressed by using the solar panels for other applications beyond agriculture, such as home lighting or small machine operation (e.g., milling cutter), though this adds system complexity, requiring greater training and local technical support. Systems with these capabilities are currently in use around the world but were considered out of scope for this initial study.

Overall, the message is clear: proper system sizing is essential to both the financial and environmental sustainability of a project.

Water Availability

Our observations in the field suggest that efficient irrigation systems could potentially have a larger impact for a smaller cost than solar-powered irrigation systems. The current drought conditions in Uttar Pradesh underscored this point: because farmers have a limited amount of water at their disposal, efficient irrigation can help them cultivate more land with the same total amount of water.

For example, in an area we visited in Uttar Pradesh, the farmer was able to irrigate for only 20 minutes at a time because the water level in his well had dropped so low. This amount of water could only irrigate a small, 350-square-foot patch of tomatoes. With a storage tank and drip irrigation system, he may have been able to irrigate more land and see more income with the same amount of water, for a minimal cost.

When considering technology applications for irrigation, it would behoove project implementers and funders to first consider the suitability of efficient irrigation systems, then consider solar energy to power the pump. Drip irrigation systems are lower cost than solar, so as an initial investment for a farmer, the financial burden will be less of a barrier. If the farmer later chooses to purchase a solar array to power the pump, the pump will also be of the right size and the solar system overall will cost less.

Technical Capacity and Local Servicing

The knowledge, ability, and capability of farmers to interact with and operate their systems beyond simply flipping a switch varied greatly from location to location. In Gujarat, the representatives from SEWA understood the operation of the pumps in detail and were on hand for repairs and maintenance on a weekly basis. Conversely, the farmers in Uttar Pradesh and Karnataka were not only discouraged to service the solar panels and inverter, but were effectively unable to do so. At most, users were able to clean their pumps and wells of debris.

However, in places where the farmers received less training, they were also provided support from installers. Yet, in these cases it is less the lack of technical training and instead the understanding of the business model that needs to be better conveyed, especially in complicated financing arrangements like those we saw in Karnataka. This lack of understanding is unfair to the farmer, but is also a risk to the ongoing viability of the project.

User Satisfaction

Because the solar pump systems are quite technologically complex, we were surprised to find that all users considered the solar systems very easy to use. Respondents reported that compared to diesel pumps, which can be difficult to start and require the procurement of fuel from sometimes remote locations, and electric pumps, which often require nighttime operation and sometimes dangerous travel to agricultural fields away from the farmer's home, the solar pumps are turned on and off with a simple flick of a switch. Some farmers had their children operate the pumps. This demonstrates, that in addition to the financial benefits of solar pumps, the solar systems provide additional benefits in terms of increased safety, ease of use, and comfort.

Affordability

We also found that farmers have a high capacity to accept increases in monthly payments up to and maybe just slightly more than their current payments for diesel. It follows that the farmers are not at all sensitive to the total cost of the system, as long as their monthly payments are manageable. However, inasmuch as they have a choice in technology, the farmers are highly sensitive to the technology type and deployment in a particular project. The lesson learned is that involving farmers in the technology choice is an important element in the ongoing success of solar pump projects.

In 2010, the central Government of India (GoI) launched the Jawaharlal Nehru National Solar Mission (JNNSM), whose aim is to make India a global leader in the development and deployment of solar energy technologies. One scheme under JNNSM offers a capital subsidy to support the expansion of solar pumping for irrigation, at a desired rate of 30,000 systems annually. The Ministry of New and Renewable Energy (MNRE) is responsible for administering JNSSM, while the National Bank for Agriculture and Rural Development (NABARD) serves as the subsidy channelizing agency.

Despite the scheme's existence, subsidies prove difficult and time-consuming to avail of, with larger-scale, government-tendered projects (like the one in Karnataka) being the primary beneficiaries. This limits the scheme's ability to reach farmers in more remote areas, where low population densities do not warrant large-scale projects. Further, such government tenders often offer little flexibility to size systems appropriately for the context, which may lead to the financing of projects that would otherwise be unviable. Mismatches in agricultural timelines and financial regulations also present a real obstacle: farmers' incomes are seasonal, while banks often require monthly payments.

Financial mechanisms beyond capital subsidies are needed. For individual farmers, readily available low-cost debt for the purchase of solar pumps and larger-scale debt financing programs would be beneficial. Even as significant potential for agricultural loans exists in India, the solar pump system market is relatively under-developed, such that commercial banks show little interest in offering financing. Indeed, mature financial products and infusions of venture capital funds in this sector remain low.

One of the common complaints we heard during the fieldwork was that farmers only used the solar panels during a short season and then stored them until they were needed again. There is a significant interest in finding off-season applications for these investments. Finding business models that provide farmers with the service they need but that mitigates their financial risk is the primary objective. These include leasing, pay-as-you-go, secondary uses during off-season and selling excess power to the grid and/or providing small electronics charging.

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