Comprehensive Initiative on Technology Evaluation

SOLAR WATER PUMPS: TECHNICAL, SYSTEMS, AND BUSINESS MODEL APPROACHES TO EVALUATION

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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 (does a product perform its intended purpose?), Scalability (can the supply chain effectively reach consumers?), and Sustainability (is a product used correctly, consistently & continuously over time?).

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. These partners have been instrumental in choosing the solar pump technology used by farmers in their communities.

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 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.

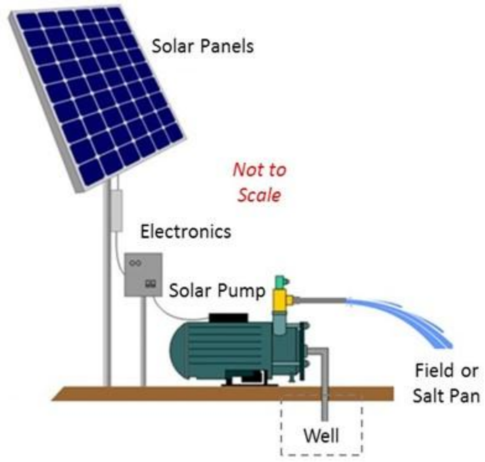
With this context in mind, the solar water pump project has the following objectives:

- 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 associated 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

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 1 shows the basic design of the solar pump systems included in this evaluation.

Figure 1: 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 2: 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 3: Solar Pump System Electronics

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 4: Solar Pump

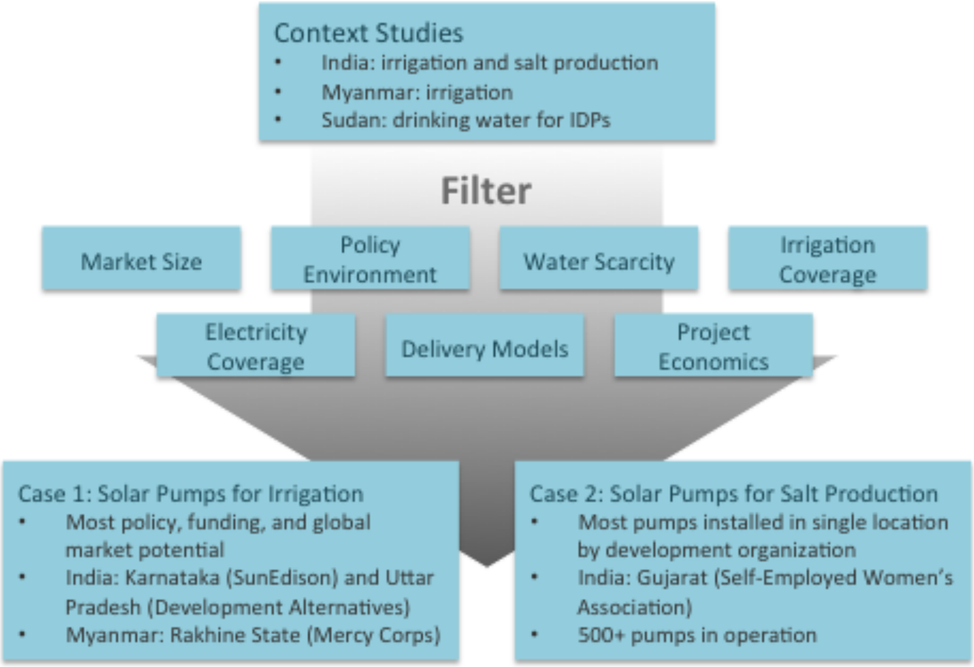
SOLAR PUMP USE CASES

In order to focus our research, the CITE team conducted a scoping study during the first several months of the project. This included field work in January and April 2016 in order to gather 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 several different use cases, including three cases in India (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), a site visit to Mercy Corps in Myanmar where the market is very nascent, and discussions with USAID and Oxfam regarding their work using solar pumps for drinking water supply to Internally Displaced Person (IDP) camps in Darfur, Sudan.

The process the team used to downselect to two Use Cases for further analysis is illustrated in Figure 5.

Figure 5: Downselect Process



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 5. 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:

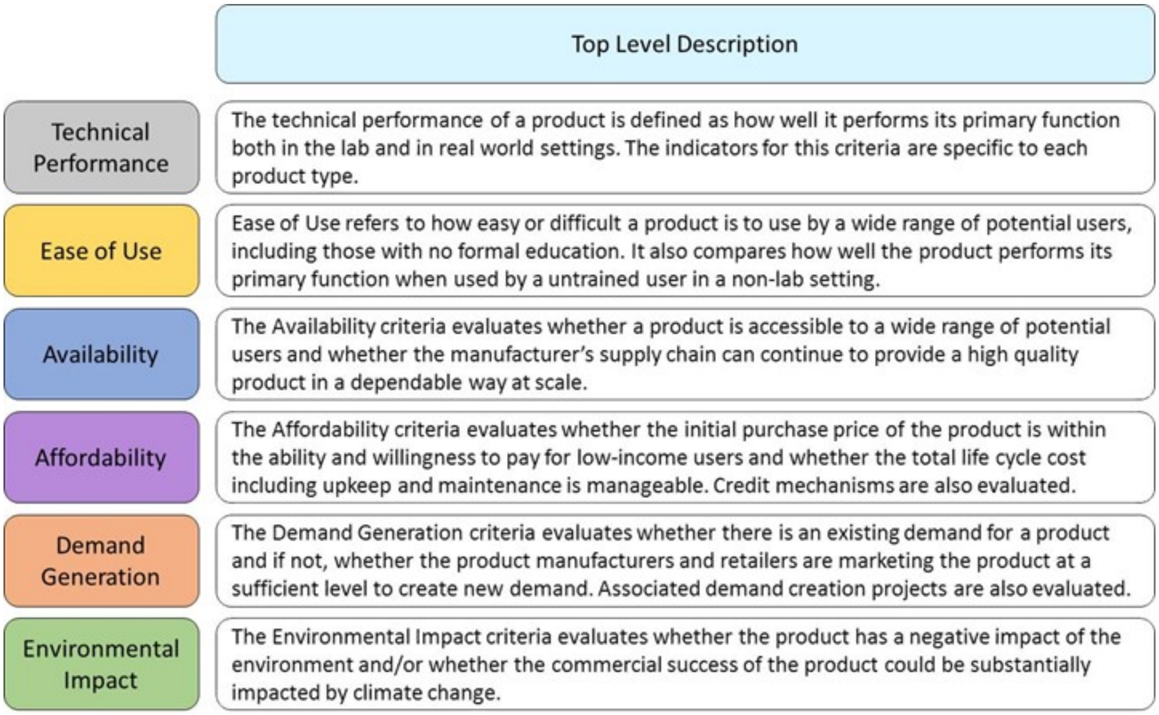
Irrigation Case

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.

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 the Self-Employed Women's Association (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.

Figure 6: 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.

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	◑	◔	◔

● OUTSTANDING ◕ VERY GOOD ◑ AVERAGE ◔ MARGINAL ○ POOR

CASE 1: SOLAR WATER PUMPS FOR IRRIGATION

Numerous programs exist in India to encourage smallholder farmers to irrigate their fields to increase self-reliance and food production. These include free or low-cost electricity in some regions and, more recently, capital subsidies for purchasing solar water pumps. In September 2014, the Government of India's Ministry of New and Renewable Energy (MNRE) set a target to deploy 1 Million solar pumps for irrigation and drinking water use in the country[1]. 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 CITE 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.

In Jhansi, the pumps we studied were part of a project implemented by Development Alternatives, and 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.

In Karnataka, the pumps 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.

Three research topics were addressed in the solar pumping for irrigation portion of this study: a) a qualitative evaluation of the CITE criteria shown in Figure 6; b) the appropriate choice of pump size and c) the impact of solar pumping on the water, energy, food nexus.

APPROACH & METHODOLOGY FOR SOLAR PUMPS FOR IRRIGATION

The irrigation use case evaluation was divided into three main activities:

- Administration of **user surveys** to gather social and economic data
- Development of a **pump sizing tool** (detailed in the "Correct Sizing for Pumps" section of this report)
- Development of a **System Dynamics model** of the effect of solar water pump implementation policies (detailed in the Water, Energy, Food Nexus section of this report)

Surveys were developed to gather data to calculate indicator and criterion scores for ease of use, availability, affordability and demand. Separate surveys were given to the end-user farmers, landowners, facilitating NGOs, system installers, and industry experts.

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[1] MNRE Directive No. 42/25/2014-15/PVSE, Dated 22nd September, 2014 http://mnre.gov.in/file-manager/UserFiles/Scheme-for-Solar-Pumping-Programme-for-Irrigation-and-Drinking-Water-under-Offgrid-and-Decentralised-Solar-applications.pdf [downloaded August 2, 2017]

For the end-user farmer surveys, a small convenience sample approach was used and a total of 25 farmers were interviewed, with the majority being in Karnataka State. An average demographic profile was developed, as shown in Table 1.

Table 1: Demographic Data of Survey Group

Average Age of Respondents	39.6
Gender of Respondents	
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 income from farming (Rps)	81,240
Average income from farming (USD)	$1,200

FINDINGS FOR THE IRRIGATION CASE: USER SURVEYS

Based on the user surveys administered to the sample group, we learned the following:

EASE OF USE

Despite the technical complexity of the solar pump systems, users overall found them overwhelmingly easy to use and maintain on a day-to-day basis, which consists primarily of cleaning the panels when they become dusty. 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. Based on these results, the importance of system-level supportability[2] becomes evident: as long as the system doesn't break, it is easy to use, but if it breaks, it may be a long time before it's fixed and could be an expensive repair depending on the warranty and/or service contract. A full supportability analysis of solar pump systems in India would be an interesting area for future research.

AFFORDABILITY

Though the cost of solar systems have come down significantly over the past decade thanks to a drop in the per unit cost of photovoltaic (PV) cells, they continue to represent a significant capital investment for smallholder farmers. As a cost of 190,000 Rps. (~$2,800), the cheapest system we saw was nearly double the average annual income from farming—approximately 105,000 Rps. (~ $1,500)—of our

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[2] "Supportability" is a systems engineering discipline that refers to the combination of Reliability (i.e., how often does it fail), Availability (percentage of time it's ready to use), Maintainability (how quickly and easily can it be fixed if it does break) and Integrated Logistics Support (i.e., if it needs a spare part, can I get it).

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. This is in keeping with development literature that suggests, given the high risks and uncertainties associated with poverty, the time value of money (net present value, or NPV) is highly skewed toward the present with less regard for long-term financial considerations.

AVAILABILITY

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 critical as solar pump systems scale in a region, and would become 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 pump systems may scale and yet may underperform or fall into disrepair, misuse, or disuse. Unfortunately, this is a common theme with the introduction of technically complex products in remote, impoverished areas. The required skills and credentials to repair the solar pump systems without jeopardizing manufacturer warranties can only be obtained in larger urban areas, and once fully trained, technicians may be unwilling or unable to relocate to rural areas where the market is much smaller.

DEMAND

While there exists strong interest in solar systems for use in agriculture and beyond (household lighting, for example) 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 “soft” issues such as social norms and ingrained perceptions in the promotion of technologies.

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 solar pump systems are safer than both diesel- and electric-powered pumps.

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.

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.

More information on the user surveys and findings can be found in the Full Report at cite.mit.edu.

FINDINGS FOR THE IRRIGATION CASE: WATER ENERGY FOOD NEXUS

In order to expand the understanding of future trends in the adoption of solar pump systems in India, the team developed a System Dynamics model. 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, fertilizer and sunshine—public policies that determine their access to 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 abundant: 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.

To ensure the SD model is as accurate as possible, data was incorporated from several sources, including: primary data for CITE’s fieldwork in Karnataka and Gujarat in India; 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.

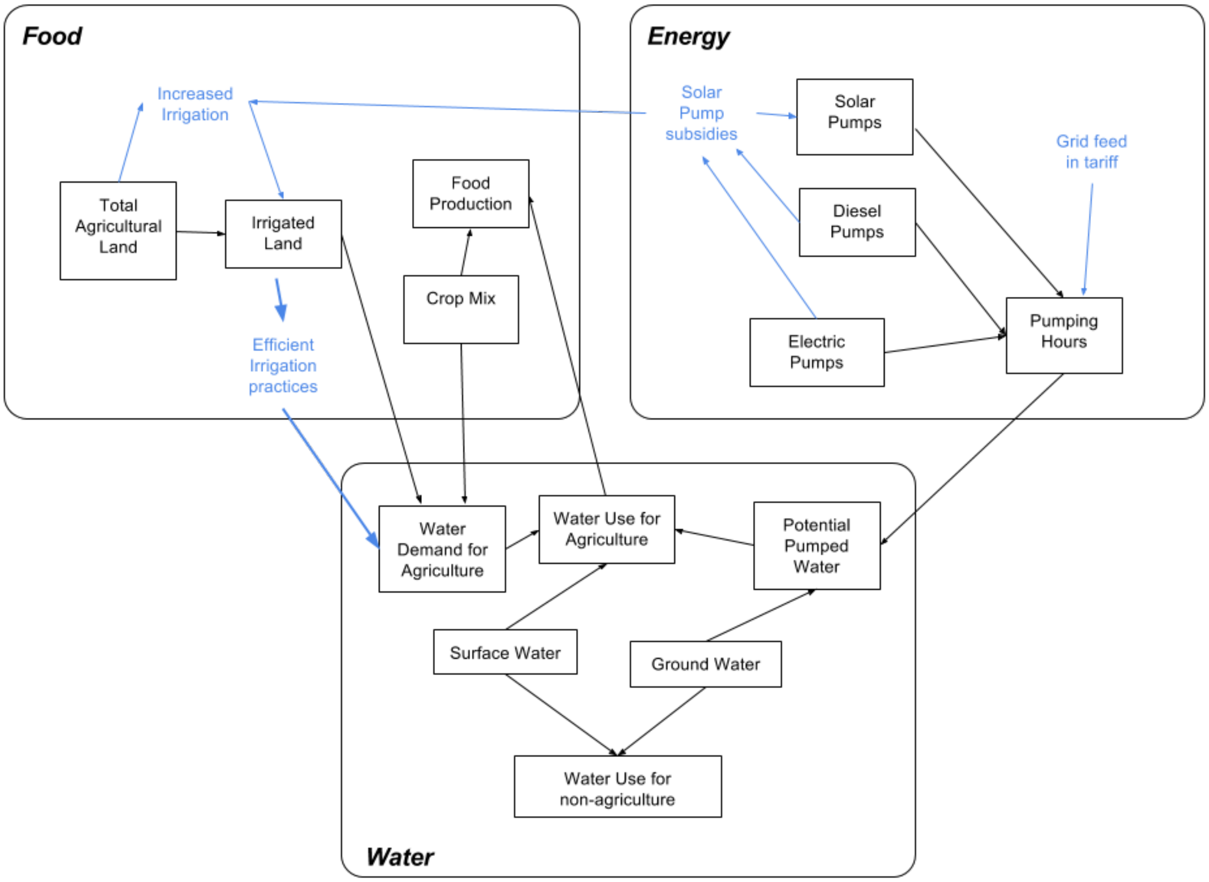
MODEL STRUCTURE

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 7shows 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 7: Schematic of SD model structure (blue: policy interventions)



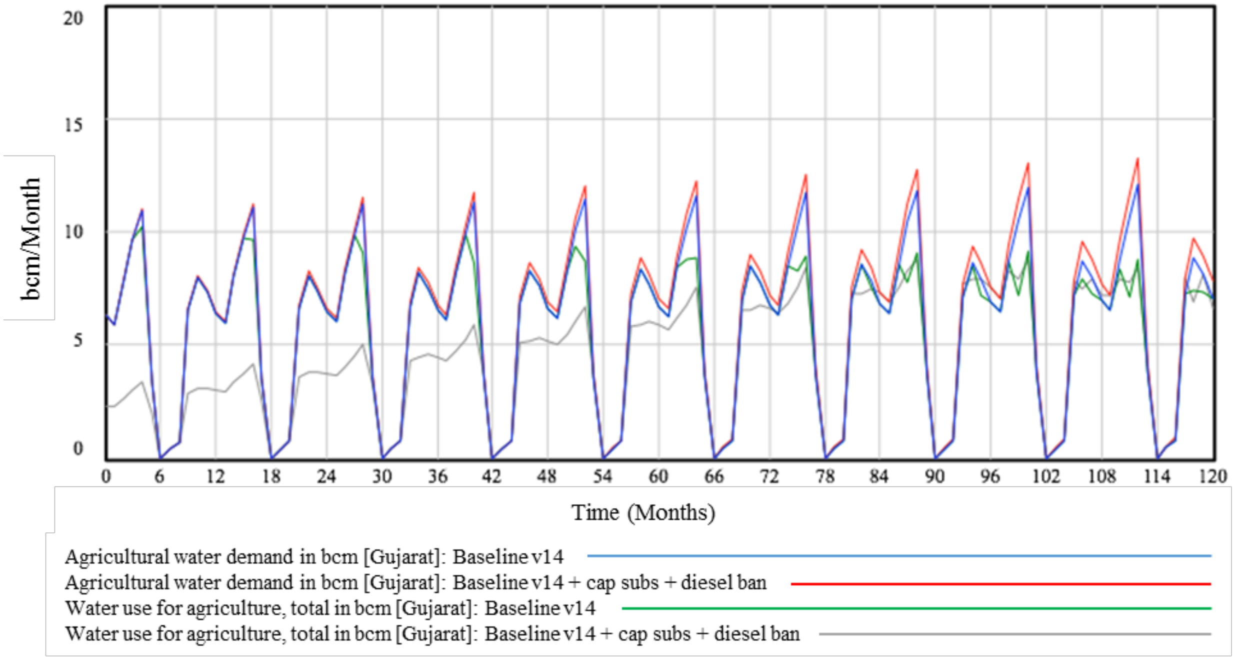
APPROACH

The CITE team developed a series of Scenarios to understand the impact of different policy initiatives and technology decisions over time. These include: a Baseline Scenario, which reflects the current situation in Karnataka and Gujarat and projects ground water depletion over time; a Policy Intervention Scenario, including examination of possible capital subsidies, mechanisms to feed into the electrical grid, and varying levels of irrigation efficiency; a Ban Diesel Pumps Scenario, which eliminates diesel pumps while adding subsidies for electrical pump purchase; and a Combined Scenarios study which looks at interactions of the other scenarios at different levels of implementation.

SELECTED FINDINGS

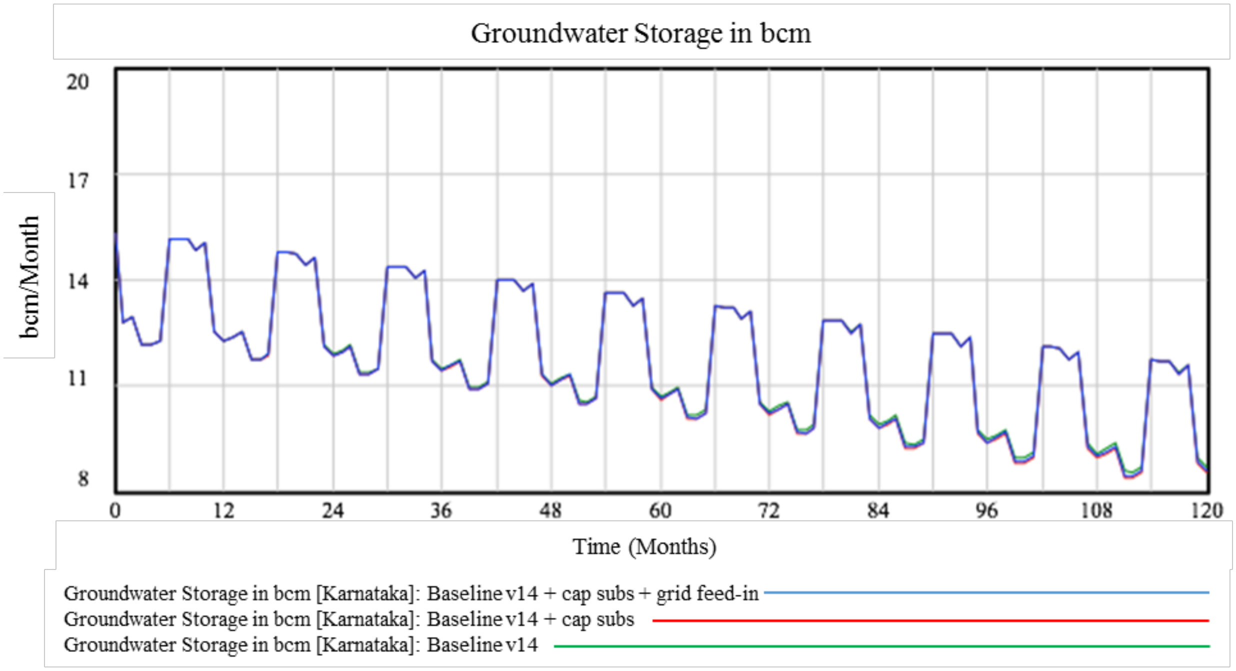
While initially the groundwater levels in Gujarat benefit from policies such as a diesel pump ban (Figure 8), over the course of 10 years the effect is negated by the adoption of alternative pumping technologies. Additionally, the reduction in groundwater usage in years 1-6 has a detrimental effect on the agricultural industry as they struggle to supply enough water to maintain the current food production levels.

Figure 8: Effect on Water Supply versus Demand of Banning Diesel Pumps in Gujarat.



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. 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 pump systems by half because farmers are incented to maximize the amount of energy they can feed back into the grid, only has a minor effect on groundwater storage, as shown Figure 9. However, these interventions do have an impact on other criteria, such as farmer income.

Figure 9: Introduction of Capital Subsidies and Grid Feed-in, Karnataka



An extensive discussion of the scenarios and model results can be found in the full report at cite.mit.edu.

SUMMARY

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, such as banning diesel pumps and providing mechanisms to feed electricity back into the grid, 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[3] remains a challenge in

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[3] 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

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.

More information on the SD model and findings (and a downloadable Vensim file) can be found in the Full Report at cite.mit.edu.

FINDINGS FOR THE IRRIGATION CASE: PUMP SIZING TOOL

In order to allow users to select an appropriate pump size, the CITE team developed a software tool to automate the process. As previously mentioned, the proper pump selection is essential to both the financial and environmental sustainability of a project. These types of sizing 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. 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 Excel-based tool is available for download on the CITE website at cite.mit.edu and a Matlab version is also available upon request. It should be noted that these tools are still in development and the results cannot be guaranteed by USAID or MIT. We welcome discussion and improvements to the tools.

As an example of how the pump sizing tool can be used to make purchase decisions, we revisited the case in Uttar Pradesh where Development Alternatives has replaced a few diesel-powered pump systems with solar pump systems. Based on the field research and interviews, we know the following:

- 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 to 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.
- Groundwater hydrology and well limitations from the field were not considered when selecting the size of the pumps to be installed.

In order to test the pump sizing tool, 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. This process is shown in Figure 10.

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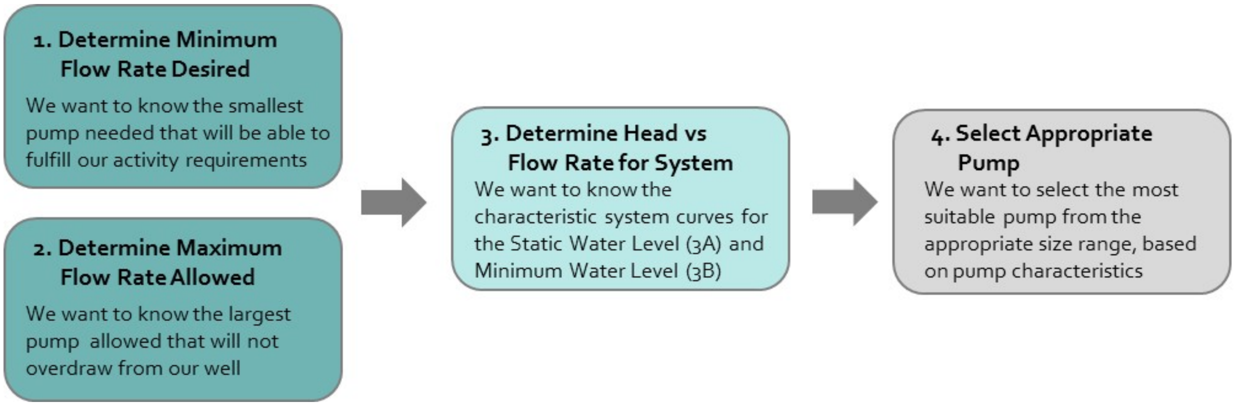
of Agriculture and Farmer Cooperation (MAFC) is responsible for agricultural policy. Beyond national ministry policies and programs, state and private sector schemes complicate the institutional landscape even further.

Figure 10: Overview of the Pump Selection Process



1. Determine Minimum Flow Rate Desired

We want to know the smallest pump needed that will be able to fulfill our activity requirements

2. Determine Maximum Flow Rate Allowed

We want to know the largest pump allowed that will not overdraw from our well

3. Determine Head vs Flow Rate for System

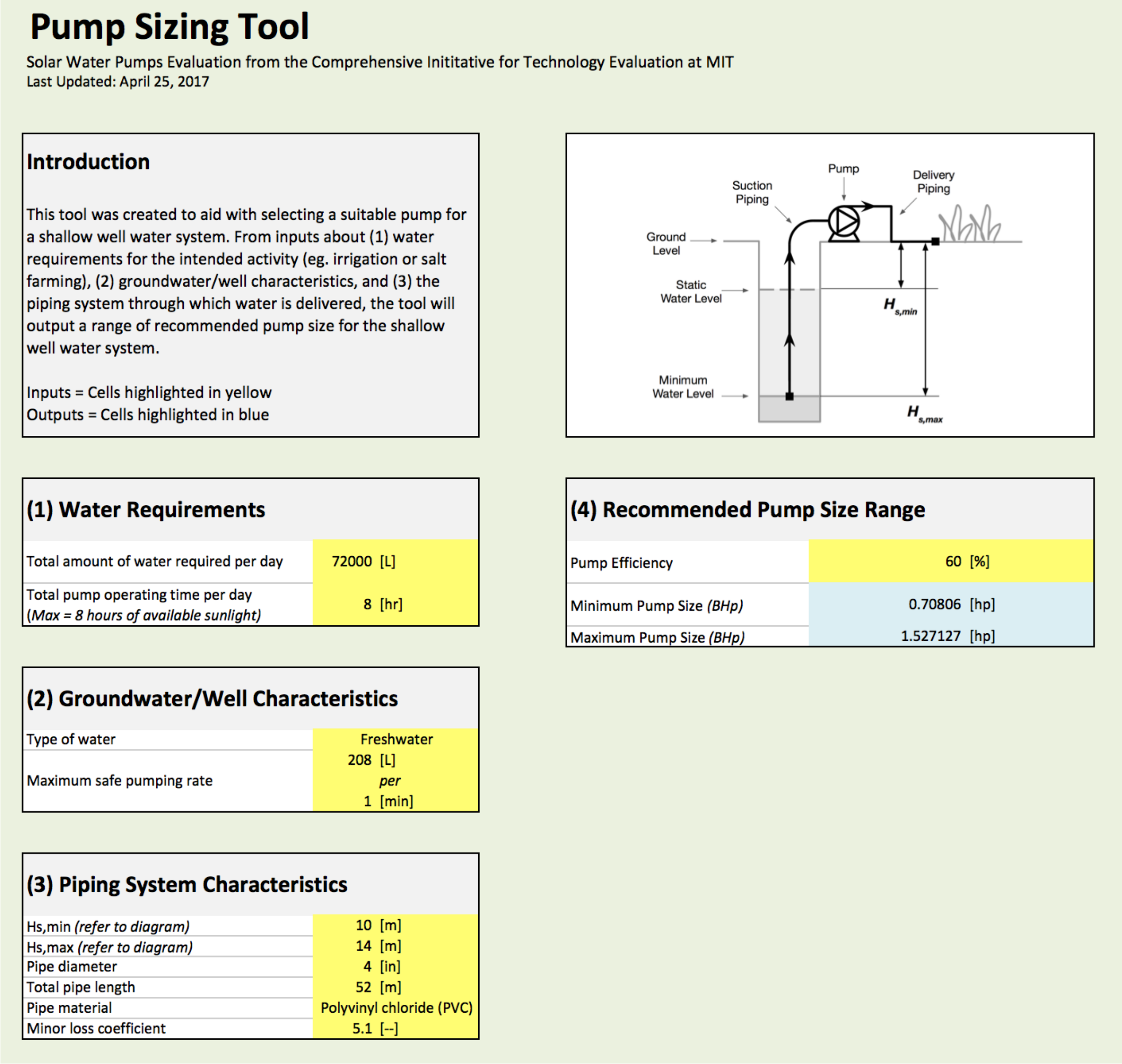
We want to know the characteristic system curves for the Static Water Level (3A) and Minimum Water Level (3B)

4. Select Appropriate Pump

We want to select the most suitable pump from the appropriate size range, based on pump characteristics

The calculations for this particular case are shown in Figure 11. The recommended pump size range shown in (#4) on the user interface varies between 0.7 and 1.5 hP, which is significantly less than the current 3 horsepower (HP) AC submersible water pump that is being used at the Development Alternatives site.

Figure 11: 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]

CASE 2: SOLAR WATER PUMPS FOR SALT PRODUCTION

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, Gujarat, India are something of a "challenge 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 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 & 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
- **Farmer interviews** for seasonal cash flows of both solar and diesel pump systems
- **Technical performance** measurement in the field, both in-person and through sensors
- **Lab testing** of the pumps used in the solar pump systems

USER SURVEYS AND FARMER INTERVIEWS

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. The selection of farmers was based on a convenience sample and also considered the geographic distribution of the farmers.

Our first step was to conduct fairly 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. We conducted 16 of 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.

TECHNICAL PERFORMANCE IN THE FIELD

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.

For the 28 systems measured (owned by 25 farmers), we were able to gather flow data for 7 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.).

Following the field work, we developed specialized remote-sensing prototypes to characterize the output and usage of the systems. The prototype data-loggers were built using the Particle Electron platform and 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 controller and the output to the motors. The data was uploaded to a cloud-based server using cellular networks every 12 hours. Figure 12 shows the installation of the sensors in one of the 17 locations in the Little Rann of Kutch in January and designed to measure output of the systems until May-June.

Figure 12: Researchers Éadaoin Ilten (left), Amit Gandhi (middle) and Przemyslaw Pasich (right) testing performance and installing sensors

TECHNICAL 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. The pumps were mounted to the test rig, shown in Figure 13 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.

Figure 13: Pump Testing Experimental Setup at MIT

FINDINGS FOR THE SALT PRODUCTION CASE

USER SURVEYS AND INTERVIEWS

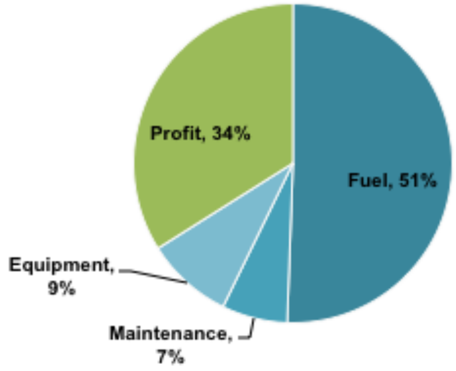
The focus on solar pumps for salt production in the Little Rann of Kutch in 2017 builds on CITE's previous work in 2015-16 by considering the financial implications to the farmer of incorporating a solar pump into their salt production. Unlike agricultural farmers who only use pumps for several hours 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.

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.

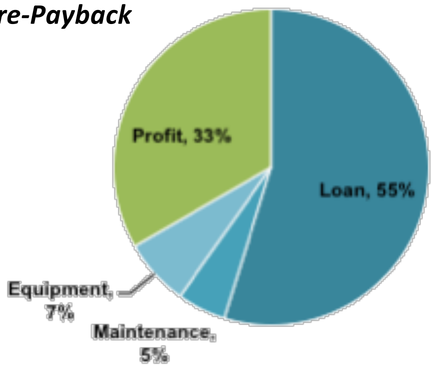
To analyze the cash flows of the farmers with the combined systems, the costs, revenues, and profit figures are analyzed per metric ton. The average price per ton that the farmers received was Rps.159 (USD 2.37). The margin analysis illustrated in Table 2 shows how this Rps.159 is split between the different types of expenses, and the 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) during the pay-back period, once the loan was repaid, the profit margin for the solar production increased dramatically.

Table 2: Visualizing the Margin Analysis

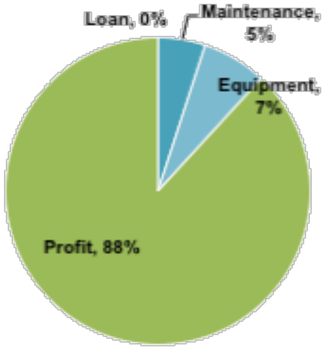
Average Diesel-Powered Production



Average Solar-Powered Production Pre-Payback



Average Solar-Powered Production Post-Payback



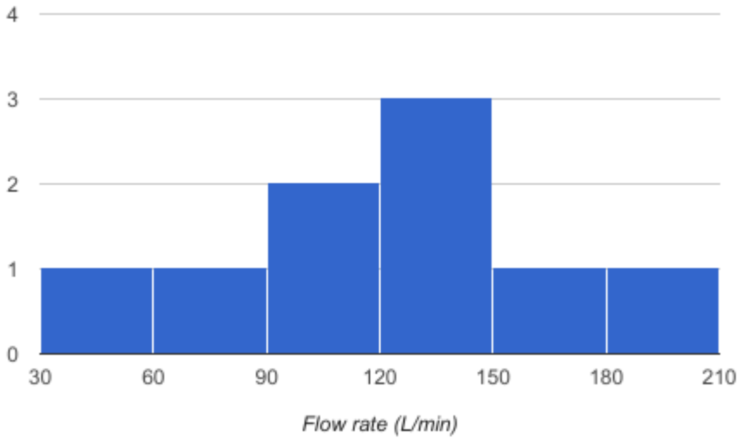
TECHNICAL PERFORMANCE IN THE FIELD – MEASURED DATA

The CITE team attempted to gather data on as many pumps as possible in the field, resulting in a sample size of 28 pumps, owned by 25 farmers. The measured data included Flow rate (L/min), Pump rating (Hp), Well depth from surface (ft), Water level from pump (ft), Distance to outlet (ft), Suction Pipe diameter ("), Discharge Pipe diameter ("), Panel voltage (V), Panel current (A), Pump voltage (V), and Pump current (A). Unfortunately, it was not possible to record all of the parameters for all 28 pumps due to a number of reasons.

Figure 14 shows the recorded instantaneous flow rate for each Falcon 1 HP system we found in the Little Rann of Kutch. We selected this system because it was also tested in the lab. 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. Note that the lifetime of structural components in a harsh environment is extremely difficult to measure in a lab and speaks to the importance of field research. That said, with an extremely limited sample size and no available performance data on the same pumps used in different environments, these results must be taken with a grain of salt.

Figure 14: Histogram of flow rates of Falcon 1 Hp seen in the field. Mean 120 L/min (s = 48 L/min)



From the electrical measurements of the 28 pumps, 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.[4] This is considered a fairly low efficiency by industry standards, but given the cost of the systems and the harsh operating environment it was not flagged as a major issue, especially considering the limited sample size. Also note that the lab testing results contained in the next section were fairly consistent with these values.

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 and the panels and pumps were of varying size, age and maintenance level.

TECHNICAL PERFORMANCE IN THE FIELD - SENSORS

The data from several pumps was aggregated from installation in late January 2017 through March 31, 2017 to understand regularity of system usage and production. A sample of the output from SP020 is shown in Figure 15. The data shows consistent usage of the pumping systems (indicated by the Solar Panel Voltage) with varying levels of pump usage (indicated by the Motor Current). The motor current

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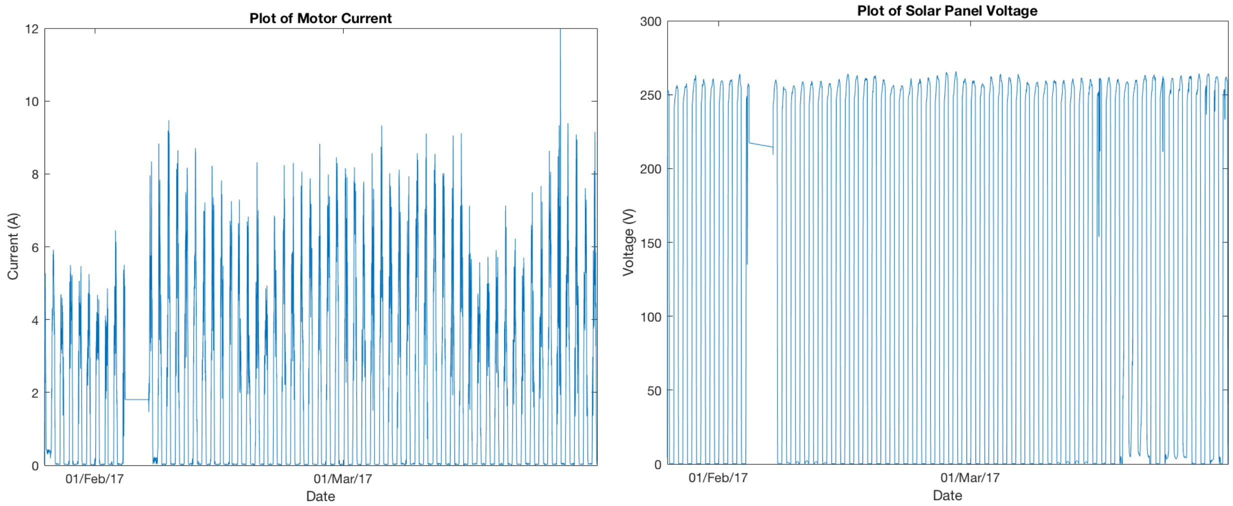
[4] Electrical power is reported here in horsepower to better conceptualize the values for pumping.

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 15: Plot of Motor Current and



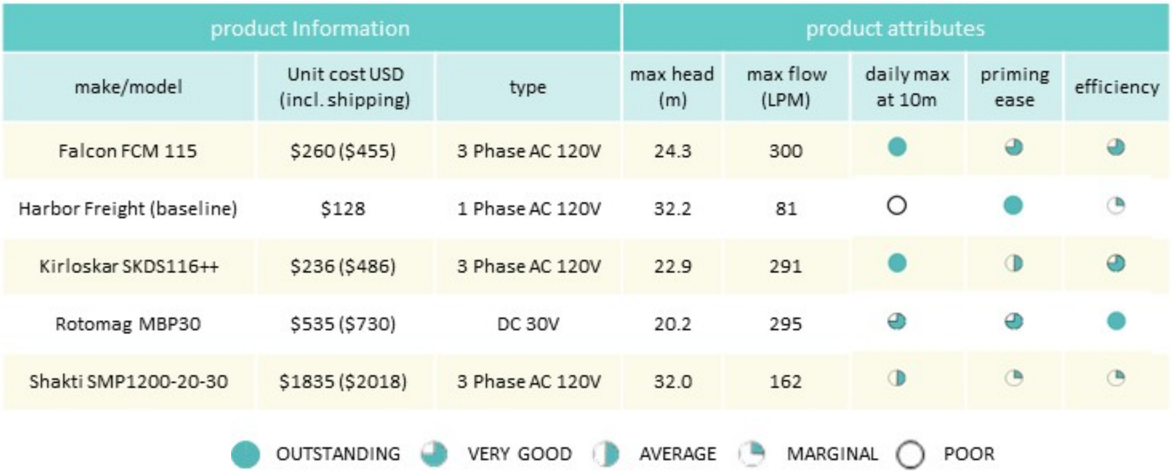
TECHNICAL PERFORMANCE IN THE LAB

The comparative test results for the 5 pumps tested in the MIT laboratory are shown in Table 3 and Figure 16. The Harbor Freight pump was purchased locally and was used primarily to test the experimental procedure and test rig; however, the results are included for reference.

Table 3: Results from Lab Testing

Pump	**Max Head (m)**	**Max Flow Rate (LPM)**	**Electric Power Input (W)**	**Hydraulic Power Output (W)**	**Peak Efficiency (%)**	**Flowrate at 10m (LPM)**	**Daily max output (L)**
Falcon	24.3	300	1200	561	46.75%	215	103,200
Harbor Freight	32.2	81	750	267	35.60%	21	10,080
Kirloskar	22.9	291	1200	534	44.50%	207	99,360
Rotomag	20.2	295	750	434	57.87%	178	85,440
Shakti	32.0	162	1400	445	31.79%	134	64,320

Figure 16: 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	◑	◔	◔

● OUTSTANDING ◕ VERY GOOD ◑ AVERAGE ◔ MARGINAL ○ POOR

Based on our results, 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.

CONCLUSIONS FOR BOTH CASES

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
- 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. 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.

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.

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.

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