

THE RISING SUN: ANALYZING POTENTIAL OF ENERGY EFFICIENT SOLAR
PHOTOVOLTAIC WATER PUMPING SYSTEMS IN INDIA

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ABSTRACT

THE RISING SUN: ANALYZING POTENTIAL OF ENERGY EFFICIENT SOLAR PHOTOVOLTAIC WATER PUMPING SYSTEMS IN INDIA

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Central and state governments have been successful in recent years in getting farmers to buy new solar photovoltaic (PV) pump systems or to replace current diesel or electric pump sets through policies involving capital subsidies that range from 30% to 90%. While the subsidy policies support installation of more solar pump systems, the policies make little or no mention in their technical criteria of the degree of energy efficiency of the pump sets.

Installation of energy efficient solar PV water pumping systems under the Indian government's "Solar Pumping Program for Irrigation and Drinking Water" scheme could result in about 600,000 MWh of additional energy savings and about 500,000 tCO_{2e} of greenhouse gas (GHG) emissions reductions during the life of the systems. These savings would be in addition to the savings from the 100,000 solar pump systems that are currently planned under the government's scheme. The additional savings would be achieved because over 30,000 additional solar pump sets could be installed within the proposed budget of \$67 million for providing subsidy to farmers if energy efficient pump sets were used.

A solar pump system that includes an efficient pump (for e.g., a Bureau of Energy Efficiency (BEE) five-star rated pump set) for water delivery would require a smaller PV array to deliver the required amount of water. Due to the reduced size and cost of the PV array, such a system is more cost effective despite the fact that highly efficient pumps are somewhat more expensive than the average electric pumps.

This research recommends reexamining the technical criteria for receiving subsidies and considering the cost and benefit of requiring a minimum efficiency equivalent to BEE's five-star level. The research shows that using five-star rated pumps reduces net costs by \$1,700 per pump and the subsidy requirement by \$1,500. Hence for the same amount of total subsidy, over 30,000 additional solar pumps can be installed, leading to both greater energy savings and greater GHG emissions reductions.

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LIST OF ACRONYMS

AC	Alternating current
BEE	Bureau of Energy Efficiency
BIS	Bureau of Indian Standards
BLDC	Brushless direct current
BREDA	Bihar Renewable Energy Development Agency
CEA	Central Electricity Authority
DC	Direct current
EESL	Energy Efficiency Services Limited
GHG	Greenhouse gas
GW	Gigawatt
HP	Horsepower
IMD	Indian Metrological Department
INR	Indian Rupee
IREDA	Indian Renewable Energy Development Agency
JNNSM	Jawaharlal Nehru National Solar Mission
kWh	Kilowatt-hour
MEPS	Minimum energy performance standards
MNES	Ministry for Non-Conventional Energy Sources
MNRE	Ministry of New and Renewable Energy
MWh	Megawatt-hour
NABARD	National Bank for Agriculture and Rural Development
NBFC	Non-banking finance companies
NISE	National Institute of Solar Energy (NISE)
NREL	National Renewable Energy Laboratory
PV	Photovoltaic
SEB	State Electricity Board
SE4All	Sustainable Energy for All
SNA	State Nodal Agencies
SPEAM	Solar Pump Economic Analysis Model
STC	Standard test conditions
S&L	Standards and labeling
TDH	Total dynamic head
UNFCCC	United Nations Framework Convention on Climate Change
USD (\$)	United States Dollar

CHAPTER 1. INTRODUCTION

India has the potential to save \$6 billion annually in diesel and power subsidies by replacing 26 million currently installed ground water pump sets, either driven by electricity or diesel, with solar water pumping systems (Pearson & Nagarajan, 2014). On July 10, 2014, during the 2014-15 union budget speech, India's Finance Minister announced a \$67 million (4 billion rupees) package for installing 100,000 solar pump systems for irrigation and water pumping (Mittal, 2014). With this recent step, India is set to attract an investment of nearly \$1.6 billion (100 billion rupees) in next five years in this sector (Pearson & Nagarajan, 2014). In a tropical climate country with half of its 1.2 billion people depending on agriculture,¹ solar pump systems for irrigation offer a promising opportunity both because they are becoming affordable and because irrigation is most needed during dry periods when the sun is shining in the sky.

India has a growing economy and heavily relies on agriculture, as 15% of the country's gross domestic product (GDP) comes from this sector. Traditionally, agriculture has been a labor-intensive sector that employs 50% of country's workforce (KPMG, 2014). Irrigation, therefore, is a natural priority for economic and social system. Unreliable grid electricity supply, increasingly costly diesel, and climate change induced weather pattern fluctuations could have a huge impact both economically and socially. India currently has 26 million agricultural pump sets (KPMG, 2014). Out of these, 19

¹ India is an agrarian economy having a social system of which agriculture is the sustaining foundation.

million are grid connected pump sets and seven million are diesel pump sets (KPMG, 2014; Pearson & Nagarajan, 2014). It is estimated that the country uses approximately four billion liters of diesel and 85 million tons of coal annually to run these pumps (KPMG, 2014).

Farmers are increasingly replacing their electric and diesel engine driven pump sets with solar pump systems to reliably irrigate their land. However, the upfront costs of solar pump systems are still a major barrier. The upfront cost of a solar pump system is about 10 times the cost of an average electric pump set (KPMG, 2014). In recent years, central and state government policies have successfully provided capital subsidies to farmers for buying new solar pump sets or replacing current diesel or grid connected electric pump sets. Government programs have attracted major pump manufacturers such as Grundfos, Jain Irrigation, Shakti Pumps, and others to invest in this area, and they have also provided opportunities to new startup companies such as Claro Energy. However, the programs make little or no mention of the degree of energy efficiency of the pump system in their subsidy criteria.

An energy efficient solar pump system requires a smaller photovoltaic array to deliver the same amount of water than an inefficient pump system. If the cost reduction associated with purchasing a smaller solar array is larger than the added cost of buying a high efficiency pump, as is often the case, then the use of an efficient system results in cost savings. Currently, any solar pump set that meets a minimum set of criteria specified by the Ministry of New and Renewable Energy (MNRE) receives the same amount of

subsidy, irrespective of its energy efficiency. Also, in government tender and policy documents, the size of the photovoltaic (PV) array is frequently specified along with the other critical parameters such as water output per day (MNRE, 2014a). As a result, solar pump system providers do not have an economic incentive to use high efficiency pumps. Rather, their incentive is to use the least costly pump that can be powered by the specified solar array while meeting the water flow rate requirement. Government subsidy programs that are designed to incentivize high efficiency, cost effective solar pump systems can enable the installation of a greater number of systems from a fixed government budget. Such an approach can extend the benefit of solar pumping to a greater number of farmers.

In this research, the number of additional solar PV pumps that can be installed because of reduction in subsidy required for each system under “Solar Pumping Program for Irrigation and Drinking Water” is estimated. Associated energy savings and greenhouse gas (GHG) emissions reductions are also analyzed assuming that the additional solar pumps will replace grid connected electric pump sets in the field. The research thesis has structured in six chapters. The introduction chapter, Chapter 1, provides an overview of the research and highlights the problem that exists in the present government subsidy policy for solar PV water pumping systems. Following this introduction, Chapter 2 offers background and literature review that covers the current status of solar water pump system market, relevant government policies, availability of the solar resource, and solar pump set technology. Chapter 3 describes the methodology

used to analyze the performance data of solar pump systems that are currently receiving subsidy under the governments' scheme. This includes estimation of baseline and benchmark wire-to-water-efficiency values and steps involved in conducting an economic analysis using the Solar Pump Economic Analysis Model (SPEAM). Results of the economic analysis are provided in Chapter 4, while in Chapter 5, a discussion on the results is presented. Finally, the conclusions of the study are presented in Chapter 6 of the thesis.

CHAPTER 2. BACKGROUND AND LITERATURE REVIEW

Reliable irrigation is essential for social and economic development of farmers, as it is linked with their cash income from the crops and, therefore, it is often promoted as a tool for poverty alleviation (Polak & Yoder, 2006; Burney & Naylor, 2012). Studies from South Asia, especially India and Bangladesh, have suggested that there is a positive correlation between the rapid increase of small privately owned irrigation equipment such as electric and diesel engine driven pump sets and an increase in agricultural production, cash income, and food security (Hossain, 2009; Hossain et al., 2006). However, scarcity of electricity coupled with the increasing unreliability of monsoon rains and costly diesel pumping systems pose an economic risk to small and marginal farmers in India (Gopal et al., 2013). A complex set of factors including global warming, competitive land use, and lack of basic infrastructure is creating new challenges for India's vast agrarian population (Manjunatha et al., 2012; Gopal et al., 2013). The ever-increasing mismatch between demand and supply of energy, and electricity in particular, is posing challenges especially to farmers in remote areas. This coupled with the increasing unreliability of monsoon rains is forcing farmers to look at alternate fuels such as diesel for running irrigation pump sets.

In India, as in many other countries, water is an extremely important natural resource and its relative scarcity due to the limited accessibility and availability is a major

constraint for economic development of farmers. In many rural areas, water sources are spread over many miles of land and power lines are scarce. Installation of new transformers and transmission lines to these locations will be very expensive. For this reason, technology to pump groundwater in ways that are economic and environmentally friendly would be beneficial for the livelihoods of people living in rural areas (Purohit, 2007; Gopal et al., 2013; Kala et al., 2007).

Solar PV water pump systems offer a clean and simple alternative to fuel-burning engines and generators for domestic water, livestock, and irrigation. These systems are most effective during dry and sunny seasons as solar panels receive more solar radiation during this period of the year. Usually, water demand also increases during the summer when solar radiation is at its peak. Therefore, these systems match with irrigation requirements and constitute an alternative to grid electricity or diesel fuel dependent irrigation pump sets.

Powering of water pumping systems with PV generators has been an applied technology in many countries since 1977 (Daud & Mahmoud, 2004). PV cells are made of semiconducting materials that can convert sunlight directly to electricity. When sunlight falls on the solar panel, it liberates electrons within the semiconductor material, which then move to produce a direct electrical current (DC) (Sinton et al., 2001).

Conventional stand-alone type diesel water-pumping systems, which are commonly used by people in rural areas for irrigation, have an integrated internal combustion engine. These stand-alone systems are portable and easy to install. However,

they have some major disadvantages such as: high operational cost, variable water production, frequent refueling, and costly maintenance (Khan, 2012). Furthermore, diesel fuel is often expensive and not readily available in rural areas of many part of the country. Farmers have to travel to nearby towns and cities to buy diesel in bulk and store it in big tanks. Sometimes, these tanks are stored in residential premises to avoid theft. The storage of a large amount of diesel fuel inside home or residential premises always has a potential to lead to dangerous situations.

The consumption of fossil fuels, diesel in the case of diesel pump sets and coal in the case of electric pump sets, has a negative environmental impact, in particular the release of carbon dioxide (CO₂) emissions into the atmosphere. Carbon dioxide emissions can be greatly reduced through the application of renewable energy technologies, which are already cost competitive with fossil fuels in many situations. Therefore, water pumping for irrigation through solar pump systems, especially in remote areas, is not only economical and sustainable to the farmers but also clean and environmentally friendly (Kala et al., 2007). A typical solar PV water pumping system operating in the farm in a village is shown in Figure 1, below.



Figure 1: Surface pump powered by a 1,800 peak watt photovoltaic array in Landra village, Punjab. Image Credit: Thomas Pullenkav (Indo-German Energy Program).

Renewable energy sources have an important role in water pumping for irrigation and for other purposes in India (UNDP, 1987; Kandpal & Garg, 2003; MNES, 2006).

Renewable energy options for water pumping include solar PV pumps, windmill pumps and dual-fuel engine pumps with biogas/producer gas as a partial substitute for diesel (Purohit, 2007). The PV water pumping systems are expected to offer an appropriate solution for supplying water to meet drinking and irrigation requirement in remote areas. Therefore, efforts are being made in India as well as in other South Asian countries, to irrigate crops and provide drinking water by solar PV pump systems.

Until 2014, the solar pump market in India was small and concentrated in four states: Haryana, Punjab, Rajasthan, and Bihar (KPMG, 2014). As of 2014, a total of 12,000 to 13,000 solar PV water-pumping systems for irrigation were installed in India

(KPMG, 2014). The number is much smaller compared to the number of conventional grid connected or diesel engine based pumps used by the farmers. In India, the solar pump systems market is mainly driven by governments' subsidy policies and related programs/ schemes. The higher upfront cost of the solar pump systems is the biggest barrier for individual farmers to buy it in the absence of government's subsidy support. A solar pump typically costs ten times the cost of a similar conventional electric pump set and more than four times the cost of a similar size diesel engine driven pump set (KPMG, 2014).

Solar pump systems have been installed largely by state renewable development agencies with capital subsidy assistance from the Ministry of New & Renewable Energy (MNRE). MNRE provides a 30% capital subsidy assistance that is coupled with state subsidy assistance that has historically ranged between 50-60% to offer subsidized pumps to farmers at 15%-20% of their total initial cost (Maity et al., 2014; Joy et al., 2015). There is a small market for non-subsidized pumps that witnesses demand from non-government organizations (NGOs) and institutions. However, this is currently a small market.

There are two types of solar pump systems. Alternating current (AC) based standalone solar water pumping systems in general consist of a PV array, an inverter with centralized maximum power point tracker, and a pump set (pump and motor). While direct current (DC) solar water pumping systems are very similar, they use a DC pump and therefore do not require an inverter to convert DC current coming out from solar

panel to AC current (Joy et al., 2015). DC solar systems are typically more efficient than AC solar systems because there are no losses in the inverter and associated electronics. However, DC systems are not preferred in rural areas (Pullenkav, 2013) due to the lack of locally available spare parts and technicians who can repair DC solar pump sets (Pullenkav, 2013).

As per the KPMG report, farmers provided mixed feedback on already installed solar pump systems (KPMG, 2014). While some of the systems are working well and have access to quality servicing, some of the installed base has not been working because of various reasons. In certain cases, lack of spare parts for DC pumps (typically brushes) have rendered them non-functional, while in certain other cases the quality of the solar panels was not up to the mark and output has diminished significantly or stopped altogether (KPMG, 2014). There is also an issue of secondary market of solar PV modules that creates a challenge for subsidized solar pumps provided through government schemes. It has been observed that the high value solar panels have been sold off, thereby making profits on the subsidized panels that came along with the pump, while the farmers returned to their regular fuels for irrigation (KPMG, 2014).

While the existing numbers of solar pump systems are small, the Ministry of New & Renewable Energy (MNRE) has embraced the potential of solar pumps and has enacted an ambitious program to provide subsidy for 100,000 pumps in the year 2015 (MNRE, 2014a). The ministry expects installation of one million solar pumps by the year 2020-21. MNRE has made a provision to provide subsidy at 30% of the capital cost and

allocated \$67 million for first phase of 50,000 pumps (MNRE, 2014a; MNRE 2014b).

Additional subsidy is provided by the state governments to encourage farmers to buy solar pump sets. The state subsidy component varies from 30% to 60% across the various states (Pullenkav, 2013; Joy et al., 2015). For example, the Bihar Renewable Energy Development Agency (BREDA) of Bihar state provides 60% additional subsidy on the cost of a solar pump system (Pullenkav, 2013). Therefore, a farmer in Bihar can avail 90% capital subsidy (30% by MNRE and 60% by BREDA) and purchase a solar pump system by just paying 10% of its initial cost. A summary of central and state government subsidy components for the solar water pumping sets is provided in the Table 1, below.

Table 1: Central and state government subsidies for solar water pump systems in India (Pullenkav, 2013; Goyal, 2013; Haryana, 2014).

State	Central government subsidy component through MNRE scheme	State government subsidy component	Total subsidy on the overall cost of the pump sets
Bihar	30%	60%	90%
Rajasthan	30%	56%	86%
Punjab	30%	40%	70%
Haryana	30%	30%	60%

2.1. Status of Solar Water Pumping in India and Summary of Key Federal and State Government Programs

The use of solar PV for water pumping in India started in 1993-94 (Purohit, 2007; Kapoor et al., 2014). The Ministry of New and Renewable Energy Sources (MNRE), then called the Ministry for Non-Conventional Energy Sources (MNES), signaled that solar

PV water pumping is a technically proven product and could be suitable for replacing diesel powered pumps at un-electrified locations. The central ministry took initial steps to develop a system for the delivery of solar pump systems. MNRE initiated a program for the deployment of 50,000 solar PV water-pumping systems for irrigation and drinking water across the country (Purohit, 2007; Pullenkav, 2013). One of the main objectives of the program was commercialization of solar PV water-pumping systems over a five-year period across 29 states. They accomplished this objective by strengthening the production base and creating the required institutional infrastructure for marketing and after sales support (Planning Commission, 1992; Pullenkav, 2013).

The MNRE scheme to promote solar pump systems was started by assuming that economies of scale and technology improvements in coming years would drive down the costs of solar water pumping systems, making the system economically viable on its own. The Indian Renewable Energy Development Agency (IREDA) and state renewable energy development agencies, often called State Nodal Agencies (SNAs), were designated to implement the program (Planning Commission, 1992; Purohit, 2007; Pullenkav, 2013). MNRE subsidized the capital cost of the solar pump and the interest costs. Besides channeling this financial assistance to the end user, IREDA provided financing for the unsubsidized portion of the system costs from its own funds. In cases where SNAs were channeling MNRE's financial assistance, the IREDA financing was not available to the end user (Radulovic, 2005; Pullenkav, 2013).

Between 1993 and 2000, the program was implemented mainly by IREDA using the non-banking finance companies (NBFC) as intermediaries (Radulovic, 2005; Pullenkav, 2013). The NBFCs took advantage of the availability of capital subsidies, low cost financing and 100% depreciation in Year 1 in order to provide the end users the system at a concessional rate (Pullenkav, 2013). However, after the year 2000 the program was mainly implemented through the SNAs (Purohit & Michaelow, 2008; Purohit, 2007; Pullenkav, 2013). The SNAs were able to bring in a component of subsidy from the respective state governments. The subsidy component received through SNAs was reduced after the initial stage from Rs. 135/Wp to Rs. 100/Wp (Purohit & Michaelowa, 2008; Purohit, 2007; Pullenkav, 2013). A summary of financial assistance that was available under the scheme is provided in the Table 2, below (Purohit, 2007; Purohit & Michaelowa, 2008; Pullenkav, 2013; MNES, 1994).

Table 2: Financial Assistance for the MNRE Solar PV Water Pumping Program (Purohit, 2007; Purohit & Michaelowa, 2008; Pullenkav, 2013; MNES, 1994).

Financial Year(s)	Subsidy Applicable	Other facilities
1993-94 to 2000-01	INR 170/Wp, subject to a maximum of 70% of the system cost.	Soft loan for unsubsidized system cost from IREDA at an interest of 2.5% p.a. with 10-year repayment period and 1 year moratorium.
2001-02 to 2002-03	INR 110/Wp, subject to a maximum of Rs. 0.25 million or 90% of the system cost.	Soft loan at an interest of 5% per annum.
2003-04 to 2004-05	INR 75/Wp, subject to a maximum of Rs. 0.2 million.	Soft loan at an interest of 5% per annum.
2005-06	INR 30/Wp, subject to a maximum of Rs. 0.05 million.	Soft loan at an interest of 5% per annum.

In the first year, the program was considered as a demonstration program with a target of 1,000 Solar PV pumping systems. However, less than 500 solar PV water - pumping systems were installed during the first year of the program (Pullenkav, 2013). From 2004 the program was modified: it became applicable only for community drinking water projects. Solar PV water pumping for irrigation was no longer applicable under the program. As of March 2012, 7,771 solar PV water-pumping systems had been installed against the targeted 50,000 systems (MNRE, 2012; Pullenkav, 2013).

2.1.1. Jawaharlal Nehru National Solar Mission (JNNSM) – 2010 – 2017

With the launch of the Jawaharlal Nehru National Solar Mission (JNNSM) in 2010, the solar water-pumping program of the MNRE was clubbed with the off-grid and decentralized component of the JNNSM. Under the JNNSM, solar PV water pumping systems are eligible for a financial support from MNRE through a capital subsidy of 30%. Currently, the financial assistance available is 30% subsidy subject to a benchmark price of INR 190 per peak watt (Wp) (MNRE, 2014a; MNRE, 2014b).

The farmers are free to procure systems from any of the empanelled manufacturers that agreed to supply the pumps as per the rate approved by the program. Some of the empanelled manufacturers include Topsun Energy Ltd.; Waaree Energies Pvt. Ltd.; Jain Irrigation Systems Ltd.; and Rajasthan Electronics and Instruments Ltd. Several states have taken up initiatives to implement solar PV water-pumping programs using the financial assistance available under JNNSM and funds from the respective state government budgets. The states of Gujarat, Chhattisgarh, Uttar Pradesh, Maharashtra,

Tamil Nadu and Bihar have programs in their pipelines that encourage farmers by offering subsidies from the states' budgets. Subsidy components that are currently available in key states are summarized in the Table 1, above.

2.2. Potential for Solar Irrigation in India

The utilization potential of solar PV water pumping systems for irrigation depends on several factors, such as availability of surface and ground water, availability of the solar resource, regional agricultural practices, and alternatives for powering of pump sets. For example, in the areas where grid connected electricity is easily available to the farmers for irrigation purposes, the adoption of solar pump systems is expected to be very limited or negligible (Raghavan et al., 2010). This is because grid connected electricity is available at no or very low cost to the farmers (Raghavan et al., 2010). Therefore, the total life cycle cost, that is, the initial cost and operating costs, of the grid-connected electric pumps is very low compared to the life cycle cost of the solar pump sets. Similarly, some other critical factors such as availability of ground water and solar energy are analyzed in this section.

2.2.1. Surface and ground water levels in India

India is the largest user of groundwater in the world (Meinzen et al., 2014). It uses an estimated 230 cubic kilometers of groundwater per year - over a quarter of the global total (World Bank, 2010; Meinzen et al., 2014). More than 60% of irrigated agriculture and 85% of drinking water supplies are dependent on groundwater (World Bank, 2010; Meinzen et al., 2014; MoWR, 2013.).

However, an increasing number of aquifers are reaching unsustainable levels of exploitation. If current trends continue, in 20 years about 60% of all India's aquifers will be in a critical condition according to a World Bank report, "Deep Wells and Prudence" (World Bank, 2010). This will have serious implications for the sustainability of agriculture, long-term food security, livelihoods, and economic growth. It is estimated that over a quarter of the country's harvest will be at risk (World Bank, 2010).

As per the World Bank report, farms irrigated with groundwater have twice the crop water productivity of those that rely on surface-water alone (World Bank, 2010). This is largely because the availability of water resources and pump technology allows farmers greater control over when to irrigate their fields and how much water to use each time (Purohit, 2007; Purohit & Michaelowa, 2008, World Bank, 2010). The ground water situation in India is complicated due to diverse geological formations (Pullenkav, 2013). The hydrogeological map of India and the depth of water level map are shown in Appendix A and Appendix B, respectively. The data show that Punjab, Uttar Pradesh, Bihar, and Jharkhand have the maximum potential for the use of ground water for irrigation. Most of the areas in these states have water at less than 10-meter depth, which makes these states attractive for solar PV water pumping systems.

The use of solar pump systems and the selection of pump technology depend on the depth at which the water is available. Surface water pumps are suitable for lifting and pumping water from a maximum depth of 20 meters whereas submersible water pumps can be used in areas where water is available at a greater depth and where open wells are

not available (Pullenkav, 2013). The maximum recommended depth for submersible systems is 50 meters (World Bank, 2010; Pullenkav, 2013).

2.2.2. Availability of solar resource in India

India is endowed with a rich solar energy resource. This is vital to the success of installation of renewable energy systems in India, including solar PV water pumping systems. As per the US National Renewable Energy Laboratory (NREL), solar maps of a country provide monthly average daily total solar resource information on grid cells. The insolation values represent the resource available to a flat plate collector, such as a photovoltaic module, oriented due south at an angle from horizontal equal to the latitude of the collector location. NREL, the Indian Ministry of New and Renewable Energy (MNRE), and the Indian Metrological Department (IMD) conducted a detailed study and prepared high-resolution solar resource maps and data for India. The annual average direct normal irradiance in kWh/m²/day is shown in the map in Appendix C.

As per a recent report published by MNRE, India has a solar potential of about 760 GW (MNRE, 2014d). The report was published based on a study carried out by the National Institute of Solar Energy (NISE) of India. The solar power potential was estimated by assuming that 3% of the available wasteland in each state was used for the development of solar power projects (MNRE, 2014d).

According to this study, the states of Rajasthan and Jammu & Kashmir have the highest solar power potential in the country. Rajasthan has a solar potential of about 142 GW because of solar radiation and availability of vast tracts of wasteland in the form of

the Thar Desert. The state of Jammu & Kashmir (J&K) in the North receives the highest amount of solar radiation. A large wasteland area of Ladakh is also a part of the state of J&K. Overall, J&K has an estimated potential of 111 GW as per the study conducted by NISE (MNRE, 2014d).

The states of Madhya Pradesh (M.P.) and Maharashtra both have more than 60 GW of solar power potential (MNRE, 2014d). Maharashtra and M.P. are among the largest of the Indian states in terms of geographical area. Therefore, these two have large wasteland resources as well. The state governments of Maharashtra and M.P. have ambitious solar power policies and plan to implement large-scale solar power projects in coming years. The state of Gujarat has the highest installed solar power capacity (Shahan, 2010) and has an estimated potential of 36 GW (MNRE, 2014d). Gujarat already has an installed capacity of close to 900 MW of solar power and has also developed utility-scale solar power projects over water canals.

The states of Punjab and Haryana have a dominant agricultural sector. However, these states rank low in terms of estimated solar power potential. Punjab and Haryana would find it difficult to make land available for large solar power projects and, therefore, expected to focus more on rooftop solar, over the canal, and solar pump set projects.

2.3. Solar Pump System Technology

Water pumping from the ground through solar pump system offers a clean and simple alternative to electric and diesel driven pump sets. Solar pump systems are often

used for agricultural operations, especially in remote areas or where the use of an alternative energy source is desired. A benefit of using solar energy to power agricultural pump sets is that increased water requirements for irrigation tend to coincide with the seasonal increase of incoming solar energy. Solar pumps are most effective during dry and sunny seasons and require no fuel deliveries. Their use naturally matched with solar radiation as usually water demand increases during summer when solar radiation is maximum (KPMG, 2014). If properly designed, solar pump systems can result in significant long-term cost savings and increased agricultural productivity to farmers.

2.3.1. Solar pump system: key components

A solar pump system consists of a number of components, including photovoltaic (PV) array, which converts solar energy directly into electricity as direct current (DC), an electric motor that converts the electrical energy into mechanical energy and drives the pump, and a pump that lifts the water using the mechanical energy. The characteristics of these components need to be matched to get the best performance from the overall system. A simple schematic of a typical alternating current (AC) solar pump system is shown in Figure 2, below.

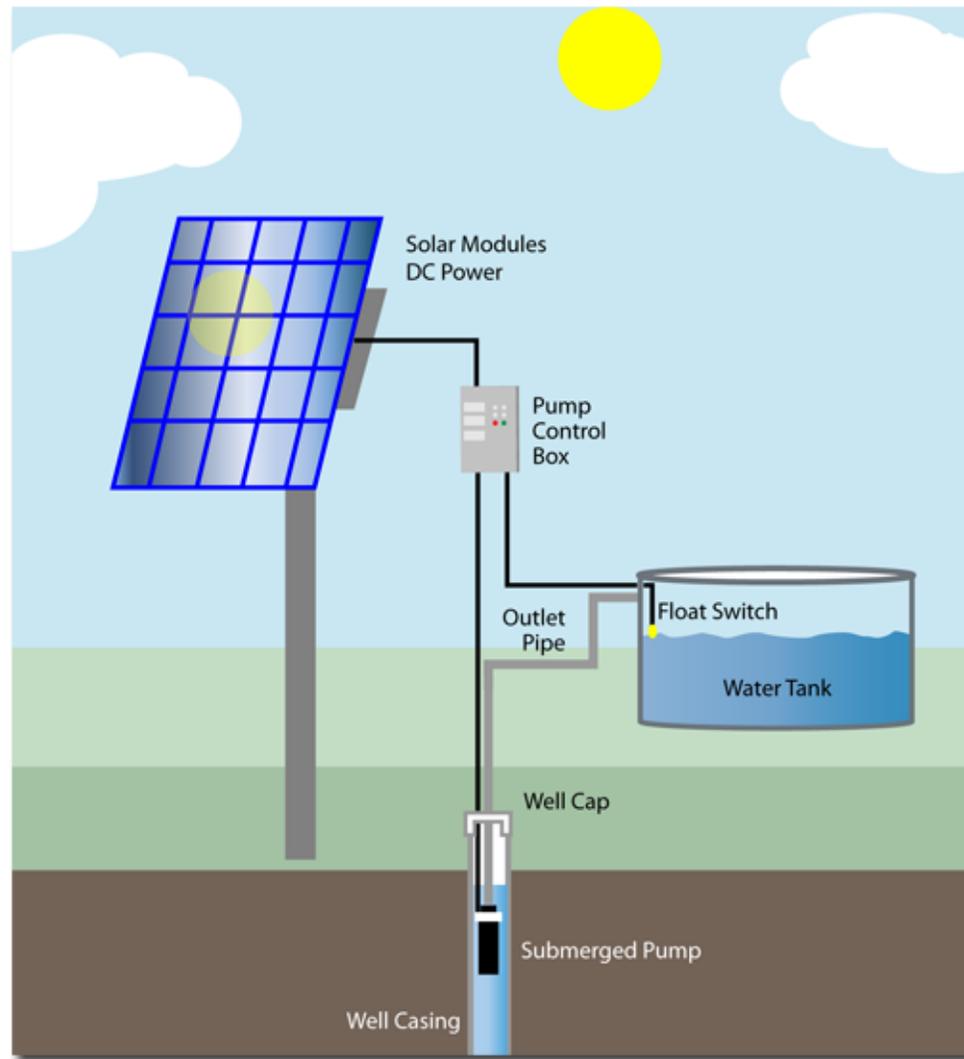


Figure 2: Block diagram of a typical solar pump system. Image Credit: (Saururja, n.d.).

Solar PV water pumping systems are broadly classified as DC and AC motor pumping systems. DC motor-based PV water pumping systems consist of a PV array, with or without an intermediate converter, and a motor coupled with a pump. The AC motor water pumping systems requires a DC-AC inverter (Periasamy et al., 2015). Solar pump systems with DC motor pump sets are generally more efficient. DC motor efficiency can reach up to 80% and, therefore, most DC motors are significantly more

efficient than AC three phase motors, which often have efficiencies in the region of 60% to 65% for the sizes of motors commonly used in small scale irrigation pumps (Desai, 2012). Recently, manufacturers have started using brushless DC (BLDC) motors for water pumping applications. BLDC motors are expensive compared to a brushed DC motors, but they are more efficient and require less maintenance compared to brushed DC motors, which require regular brush replacement (Desai, 2012; Periasamy et al., 2015).

Typically, there are two categories of pumps used in stand-alone solar pump systems: rotating and positive displacement pumps. Centrifugal pumps are one of the most commonly used types of rotating pumps. Centrifugal pumps are designed for fixed head applications and their water output increases in proportion to their speed of rotation (Barlow et al., 1993). The principle of operation is that water enters at the center of the pump and a rotating impeller throws water outwards due to centrifugal force. The water outlet is on the outside of the impeller cavity and thus a pressure difference is created between the inlet and the outlet of the pump. An open view of a centrifugal pump is shown in Figure 3, below.

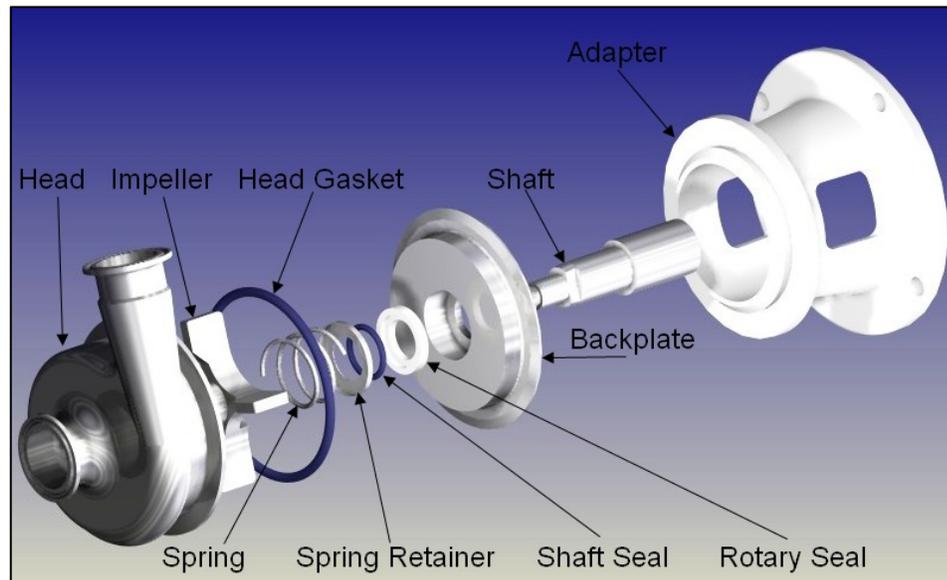


Figure 3: Open view of a centrifugal water pump. Image credit: (Thomsen, n.d.).

Centrifugal pumps have an optimum efficiency at a certain design head and design rotation speed. As head deviates from the design point, centrifugal pump efficiency decreases (USDA, 2010). However, because of their low starting torque, they offer the possibility of achieving a close natural match with a PV array over a broad range of operating conditions (Barlow et al., 1993).

While centrifugal pumps are designed for a particular head, positive displacement pumps have a water output independent of head but directly proportional to speed (Barlow et al., 1993). Water is forced against the entire head by employing a piston/cylinder arrangement. These pumps have higher frictional forces than centrifugal pumps because contact of moving surfaces is necessary to 'positively displace' the pumped water. At high heads and low speeds the frictional forces are small relative to the

hydrostatic forces. Consequently for high heads, positive displacement pumps may be the more efficient choice. At lower heads (less than about 15 m) the frictional forces are large compared to the hydrostatic forces and so efficiency is low and a displacement pump is less likely to be used (Barlow et al., 1993).

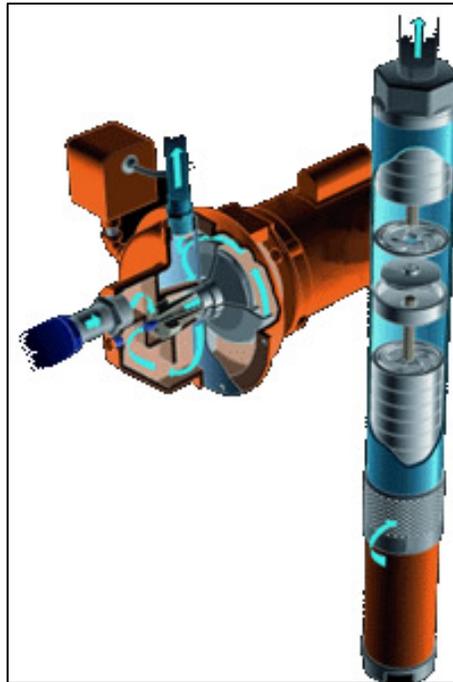


Figure 4: Positive displacement pump. Image credit: (Clean Energy Brands, n.d.)

Positive displacement pumps, when coupled with a PV array, impose a cyclically varying load on the electric motor. This causes variations in the electrical impedance of the load as seen by the PV array, and the array fluctuates around its maximum power point (Barlow et al., 1993). This means that electronic power conditioning is sometimes needed to smooth out these impedance changes by dynamically matching the array and motor impedances. Smoothing the motor torque can also be performed mechanically by

the addition of a flywheel or counterweight. These power-matching problems are not experienced by centrifugal pumps, which exert a smooth, constant torque on their motor.

Pumps are also classified as submersible and surface pumps. A submersible pump remains underwater, such as in a well or any other water body, as shown in Figure 5, while a surface pump is mounted at the top of the water as a floating pump or adjacent to the water source as shown in Figure 6, below.

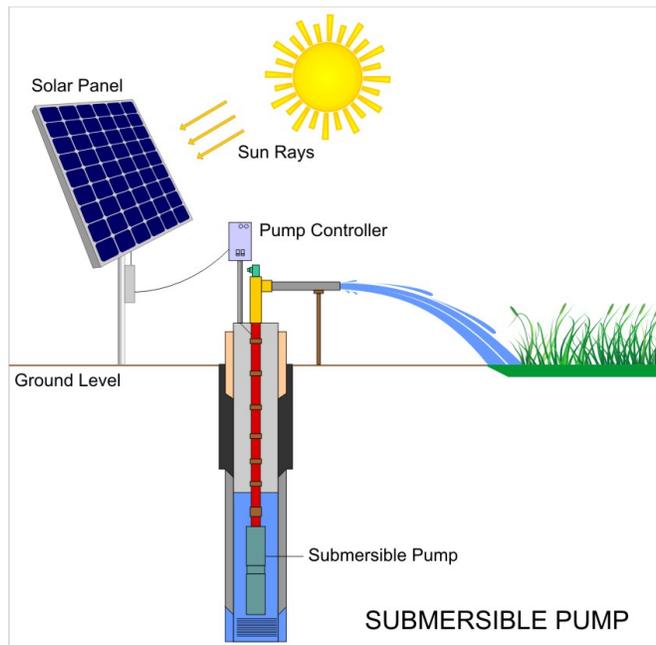


Figure 5: Representation of a submersible solar pump system. Image credit: (Taiyo, n.d.).

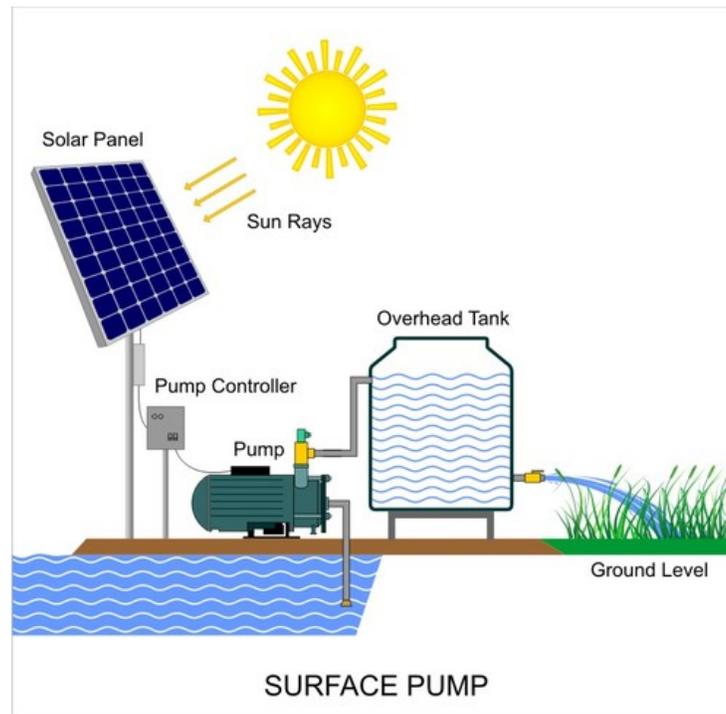


Figure 6: Representation of a surface solar pump system. Image credit: (Taiyo, n.d.).

Surface pumps are more accessible for maintenance and less expensive than submersible pumps, but they are not well suited for suction and can only draw water from about 20 vertical feet (Sinton et al., 2001). Surface pumps are excellent for pushing water long distances. Most submersible pumps have high lift capability, but they are sensitive to dirt/sand in the water and should not be run if the water level drops below the pump (Sinton et al., 2001).

The “Total Dynamic Head (TDH)” is an important parameter to calculate while designing any water pumping system. TDH determines the various head losses that the pump must overcome in order to deliver required amount of water. The TDH is a combination of two components - static head and friction head - and is expressed in feet

or meters (Wabwile, 2014). Static head is the actual vertical distance measured from the minimum water level to the highest point in the discharge piping whereas friction head is the additional head created in the discharge system due to resistance to flow within its components (Barlow et al., 1993; Wabwile, 2014). The total dynamic head is proportional to the hydraulic energy requirement, with the result that it is cheaper to pump through lower heads (Barlow et al., 1993).

2.4. Electricity Pricing and Subsidies and the Potential Role of an Energy Efficiency Labeling Program for Agricultural Pump Sets in India

Grid connected electric pumps used in the agriculture sector for irrigation consume about 25% of overall electricity consumption in India (Singh, 2009). This share is reported to be 49% in Gujarat, 43% in Haryana and 42% in Karnataka (Singh, 2009). Electricity to the farmers is heavily subsidized and, therefore, the share of revenue from the sale of electricity to the farmers by utilities is very low (Singh, 2009). In most of the states, farmers have to pay as per fixed flat rates determined based on the power rating of their pump sets irrespective of the actual electricity consumption (Singh, 2009; Badiani & Jessoe, 2011; Golden & Min, 2012).

2.4.1. Background to the electricity sector and subsidies in India

Private entities and local authorities generated approximately 80% of electricity in India before 1948 (Dubash & Rajan, 2001). The Indian parliament passed the Electricity Supply Act of 1948 and provided electricity generation control to states, and that led to setting up vertically integrated State Electricity Board (SEB) in each of the Indian states

(Badiani & Jessoe, 2011). Although jurisdiction over electricity is shared between the central and state governments, SEBs function as autonomous institutions (Dubash, 2007). SEBs are responsible for electricity generation, transmission and distribution and have the authority to set and collect electricity tariffs. While SEBs have the authority to fix the electricity tariff, in practice tariff setting has often been at the discretion of the state government and politicians rather than the SEBs (Gulati & Narayanan, 2003).

Electricity pricing in India emerged as a powerful political tool in the late 1970s during the post green revolution period. As agricultural profits and the need for a stable water supply increased during the green revolution, the farming workforce organized into a powerful political coalition (Badiani & Jessoe, 2011). In 1977, the Congress party, one of the main national political parties, made electricity pricing an election issue and started their campaign on the basis of free power to farmers (Badiani & Jessoe, 2011). By 1989, the state governments were spending up to 25% of their total expenditure on agricultural electricity subsidies, and politicians were required to maintain these subsidies to either gain election or remain in power (Dubash & Rajan 2001).

Beginning in the early 1990s, state governments passed a series of electricity reforms intended to introduce competition and to reduce the role of the state in the electricity sector (Badiani & Jessoe, 2011). The Electricity Laws (Amendment) Act of 1991 replaced the 1948 Electricity (Supply) Act. The new law allowed private generators to participate in the market under tariffs regulated by the government. But studies suggested that these reforms had relatively little impact on electricity distribution and

tariff setting in the electricity sector (Badiani & Jessoe, 2011; Golden & Min, 2012). The reforms were largely unsuccessful in attracting new entrants in the electricity generation side, due in part to strong safeguard policies, especially for agricultural and residential sectors (Badiani & Jessoe, 2011).

2.4.2. Energy efficiency standards and labeling program for grid connected agricultural pump sets

The farmers in India perceive no marginal benefit for efficient use of electricity because of highly subsidized energy cost, and, hence, they generally disregard energy efficiency in consumption. Farmers have preferred buying cheaper but inefficient pumps used for irrigations purposes (Singh, 2009). As per the two studies conducted by ICF International and Energy Efficiency Services Limited (EESL), the average operating efficiency of pump sets in Punjab was about 25% (ICF & EESL, 2013a) and in Haryana was about 29% (ICF & EESL, 2013b). The efficiencies were significantly lower compared to the efficiency of a new pump, which ranges between 55% and 65% (ICF & EESL, 2013a; ICF & EESL, 2013b). Clearly, there is a huge opportunity to reduce the overall energy consumption by encouraging farmers to buy more energy efficient pump sets.

One of the ways to achieve this objective is by implementing an energy efficiency standards and labeling (S&L) program for electric pump sets. Energy efficiency standards are procedures and regulations that prescribe the energy performance of products. Mandatory adoption of Minimum Energy Performance Standards (MEPS) can prohibit the sale of equipment that is less efficient than a minimum required level. Once

implemented, a stringent MEPS policy can quickly transform the market towards higher efficiency.

The Bureau of Indian Standards (BIS) has specified minimum quality and performance standards for electric pump sets of different categories. The Indian Standard (IS) 9079: 2002 is applicable for “Electric Mono” set pumps, IS 8034: 2002 is for “Submersible” pump sets, and IS 14220: 1994 is applicable for “Open Well Submersible” pump sets. The IS 11346: 2004 is to be used for testing purposes of the above-mentioned types of pump sets (BEE, 2009). Manufacturers interested in obtaining BIS certification for their pump set models have to get their products tested in BIS recognized laboratories. Some of the key parameters that are tested for the BIS certification are electrical performance, head measurement, volume flow rate, and duty point efficiency. They are allowed to affix the ‘ISI mark’ on pump set models once their products comply with the requirements of appropriate BIS standards. Although BIS certification is voluntary, state governments procuring agricultural pump sets in bulk for distribution to farmers usually specify that the pump sets should carry the ISI mark. This motivates pump set manufacturers to obtain ISI marks for their products. Since the BIS scheme only specifies minimum quality and performance standards for pump sets, there remains a scope for manufacturers to produce pump sets with higher energy efficiency.

Energy efficiency labels are commonly used to recognize such higher energy efficiency equipment. While standards provide minimum performance criteria to meet for qualification, energy efficiency labels provide information to common consumers and

other stakeholders about the product's performance. These are informative labels, which are used to describe the energy performance of the products usually in the form of energy use, efficiency, or energy cost. These labels are typically affixed to the appliances with a goal of providing information to consumers.

To promote the manufacturing and adoption of energy efficient pump sets, the Indian Bureau of Energy Efficiency (BEE), a statutory body of the Ministry of Power, Government of India, formulated a voluntary 'Star Labeling' scheme for pump sets in May 2006. The star labeling scheme of BEE introduced 1-star to 5-star labels based on energy efficiencies of the equipment, with 1-star denoting the lower level and 5-star the highest energy efficiency. The star labeling scheme for pump sets covers 3-phase pump sets of up to 15 kW in following three categories: open well submersible pump sets, submersible pump sets, and mono block pump sets (BEE, 2009).

The energy efficiency performance criteria for pump sets under BEE's star labeling scheme is based on the existing BIS standards for the above specified three categories of pump sets (BEE, 2009). BEE has harmonized with the BIS level of energy efficiency as the 'baseline' case for each category of pump set. Therefore, the labeling program complements and strengthens the existing BIS certification scheme, as the existing BIS procedures for testing the performance of pump sets remain unchanged. The star labeling criteria for the three categories of pump sets is shown in Table 3, below.

Table 3: The energy efficiency star rating plan for electric pump sets under the BEE's standards and labeling program (BEE, 2009). The overall energy efficiency of a pump set is relative to the BIS minimum efficiency level. For example, to achieve BEE 3-Star label, a pump set is required to be 10 to 15% more efficient relative to BIS minimum efficiency level.

BEE Star Label	Overall energy efficiency of the pump set
1-Star	≥ 1.0 and < 1.05
2-Star	≥ 1.05 and < 1.10
3-Star	≥ 1.10 and < 1.15
4-Star	≥ 1.15 and < 1.20
5-Star	≥ 1.20

A representative label that is required to be affixed on the qualified pump sets under the BEE's scheme is shown in Figure 7, below.

		Overall Efficiency of the Pump set* :				Manufacturers Logo if available		IS - 8034		
		SUBMERSIBLE PUMPSET								
TYPE	<input type="text"/>	S.NO	<input type="text"/>	Model No/Year	<input type="text"/>	kW/HP	<input type="text"/>			
Del. SIZE mm	<input type="text"/>	HEAD m	<input type="text"/>	Dis. IPS	<input type="text"/>	CAPACITY RANGE Ips	<input type="text"/>	IPkW	<input type="text"/>	
rpm	<input type="text"/>	OVERALL EFF. %	<input type="text"/>	Operating Head Range m	<input type="text"/>	Min.Sub m:	<input type="text"/>			
V	<input type="text"/>	+6% -15%	Hz	<input type="text"/>	Min.Bore Size mm	<input type="text"/>	No.of Stages	<input type="text"/>	Max Current	<input type="text"/>
DUTY	S1	CONN	<input type="text"/>	Phase	<input type="text"/>	MONTH	<input type="text"/>	YEAR	<input type="text"/>	
Name of the manufacturer with complete address										
*Under test conditions when tested in accordance with relevant IS No., the actual energy Consumption will depend on how the equipment is being used										

Figure 7: A sample label that may be affixed to pump sets that are qualified for star rating under the BEE's star labeling scheme for electric pump sets (BEE, 2009).

2.4.3. Emission factor of the India's electricity generation from the grid

The grid emission factor is the measure of CO₂ emissions intensity per unit of electricity generation in the grid system (tCO₂/MWh) (UNFCCC, 2013). In other words, the grid emission factor defines how much CO₂ is emitted per kWh of electricity produced. In India, the emission factor data of the grid is published on an annual basis by the planning wing of the Central Electricity Authority (CEA). CEA has compiled a database containing information about CO₂ emissions for all grid-connected power stations in India.

The Indian electricity system is divided into two grids, the Integrated Northern, Eastern, Western, and North - Eastern regional grids (NEWNE) and the Southern Grid (CEA, 2014). As the grids are interconnected, there is inter-state and inter-regional exchange of power. A small amount of power exchange also takes place between India and the neighboring countries of Bhutan and Nepal. For each of the two Indian grids, the emission factors are calculated in accordance with the relevant methodologies approved by the United Nations Framework Convention on Climate Change (UNFCCC) (CEA, 2014).

The baseline emissions according to the data for the fiscal year 2012-13 are shown in Table 4, below. The calculations are based on generation, fuel consumption and fuel quality data obtained by CEA from the power stations (CEA, 2014).

Table 4: Weighted average emission factor for the two regional grids and average emission factor for India (CEA, 2014).

Grid	Average emission factor (tCO ₂ /MWh)
Integrated Northern, Eastern, Western, and North - Eastern regional grids (NEWNE)	0.82
Southern Grid	0.85
India	0.82

CHAPTER 3. METHODOLOGY

The overall research methodology is divided into four components: data collection, determining baseline and benchmark efficiency, techno-economical evaluation, and output analysis. The analysis was conducted using a Solar Pump Economic Analysis Model (SPEAM) developed in the context of this research.

The first step included collecting detailed technical data about the solar PV water pump systems that are available in the India market and information about availing subsidies under the MNRE's program. Information about state government subsidy programs was also collected. A comprehensive format for the data collection was prepared to gather the information required for the analysis. The data collection format is provided in Appendix E. The information was collected from manufacturers with the help of Energy Efficiency Services Limited (EESL) (Garg, Sandeep, personal communication, December, 2014).

The second step included determining the baseline and benchmark wire-to-water efficiency. The baseline efficiency was determined using the technical criteria laid out by MNRE in their subsidy scheme for different pump head sizes. The benchmark efficiency was determined by analyzing the range of efficiencies of the different pumps for which data were collected in the first step. A solar pump system having maximum efficiency, when compared with other pumps available for a given head size, was considered as a

benchmark pump, and its efficiency was considered as the benchmark efficiency for that head size or total dynamic head.

The third step was to conduct a techno-economic evaluation using the solar pump economic analysis model described in Section 3.2, below. The efficiency gain that can be achieved by replacing a baseline pump set with benchmark pump set was calculated. The reduction in the solar PV panel size was determined, and the cost savings were calculated for each energy efficiency solar pumping system. The fourth step included output analysis in which the additional number of solar pump systems that can be installed was determined. The output analysis also included the estimation of energy savings and GHG emissions reductions that could result due to the installation of the additional solar pump systems.

3.1. Wire-to-Water Efficiency

Wire-to-water efficiency is the best method of determining the overall efficiency of a solar water pumping system since it includes the efficiency of the pump, the pump motor, the connecting wires, and, in the case of AC pumps, the inverter (ASHRAE Journal, 2001). It also takes into account the losses in the pipe fittings that surround the pumps. Essentially, wire-to-water efficiency is the ratio of the hydraulic energy of the water coming out from the pipe outlet to the energy that came in over the electrical wires through solar panels. It is represented as shown in the equation below.

$$\text{Wire – to – water efficiency } (\eta) = \frac{\text{Output Hydraulic Energy}}{\text{Input Electrical Energy}}$$

where:

$$\text{Output Hydraulic Energy } \left(\frac{\text{Joules}}{\text{day}} \right)$$

$$= \text{Water flow rate } \left(\frac{\text{L}}{\text{day}} \right) \times \text{head (m)} \times \text{water density } \left(\frac{\text{kg}}{\text{L}} \right) \times \text{gravity } \left(\frac{\text{m}}{\text{s}^2} \right)$$

$$\text{Input Electrical Energy } \left(\frac{\text{Joules}}{\text{day}} \right)$$

$$= \text{Rated capacity of solar panel (W)} \times \text{peak sun hours } \left(\frac{\text{hours}}{\text{day}} \right) \times \left(\frac{3,600 \text{ s}}{\text{hour}} \right)$$

3.2. Approach to Economic Modeling and Analysis

An economic model, as defined by the International Monetary Fund (IMF), is a simplified description of reality, designed to yield hypotheses about economic behavior that can be tested (Ouliaris, 2011). It is a set of mathematical equations that describe a theory of economic behavior.

To conduct the analysis, a Solar Pump Economic Analysis Model (SPEAM) was prepared. The model interacts with the market, engineering and performance, and cost data of solar pump sets and analyzes those while taking central and state government policies into consideration. The model also evaluates the cost effectiveness of solar pump systems with respect to alternative technologies such as electric and diesel engine driven

pump sets that are available for irrigation in India. A simple block diagram of the solar pump set economic analysis model is shown in the Figure 8, below.

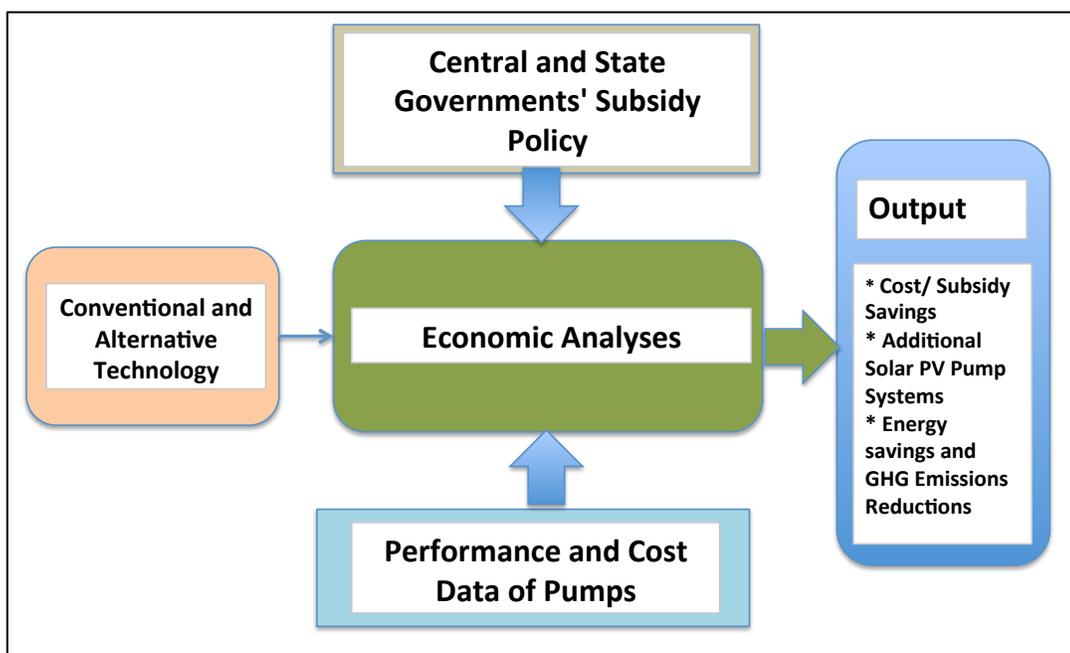


Figure 8: Block diagram of Solar Pump Economic Analysis Model (SPEAM).

The output of the Solar Pump Economic Analysis Model is the number of additional solar pump systems that can be installed under a policy regime in which central and state governments only give subsidy to energy efficient solar pump systems that use the most energy efficient pump set (benchmark pump set) available in the Indian market. The model also estimates energy savings and reductions in greenhouse gas (GHG) emissions associated with the installation of additional number of pump sets. The model conducts the analysis according to the following steps described below.

3.2.1. Step 1 – estimate pump set (motor and pump) baseline and benchmark efficiency

The model estimates baseline and benchmark efficiency of pumps (motor plus pump) by analyzing the water to wire efficiency of all the solar pump sets that are available in Indian market. The MNRE technical specification, specified in Appendix B, and the market data analysis provide two important sources of information: baseline wire-to-water efficiency of solar pump sets denoted by (η_{bs}) and benchmark wire-to-water efficiency (wire to water efficiency of the most efficient solar pump set) denoted by η_{bms} for each head size, respectively. Using these values, the baseline (η_{pb}) and benchmark pump set efficiency (η_{pbm}) are calculated. The pump set efficiency is essentially the efficiency of pump and motor combined in the overall solar pump system and determined using the following equations.

Baseline pump set efficiency (η_{pb})

$$= \frac{\text{Baseline Wire – to – water efficiency of solar pump set } (\eta_{bs})}{(\text{Wiring efficiency}) \times (\text{Inverter and electronics efficiency}) \times (\text{Piping efficiency})}$$

Benchmark pump set efficiency (η_{pbm})

$$= \frac{\text{Benchmark Wire – to – water efficiency of solar pump set } (\eta_{bms})}{(\text{Wiring efficiency}) \times (\text{Inverter and electroics efficiency}) \times (\text{Piping efficiency})}$$

The model makes the following assumptions, shown in Table 5 while conducting this analysis. The assumptions are made on the basis of the discussions with Soumitra Misra of Claro Energy Limited and Piyush Patidar of Shakti Pumps Limited in India (Mishra,

Soumitra, personal communication, November, 2014; Patidar, Piyush, personal communication, December, 2014).

Table 5: Component efficiency assumptions of the model.

Parameter	Assumption
Wiring efficiency	97%
Inverter efficiency	95%
Piping efficiency	98%

3.2.2. Step 2 – estimate pump set efficiency gain and cost increment

Once, the baseline and benchmark pump set efficiency is estimated, the efficiency gain and cost increment are determined. In general, the cost increases due to the higher cost of the benchmark pump set compared to the cost of the baseline pump set. The following equations are used for this analysis.

$$\text{Pump set efficiency gain } (\eta_{pg}) = \left(\frac{\eta_{pbm}}{\eta_{pb}} - 1 \right) \times 100\%$$

$$\text{Pumpset cost increase } (C_{pg}) = C_{pb} - C_{pbm}$$

where:

$$\eta_{pbm} = \text{Benchmark pump set efficiency}$$

$$\eta_{pb} = \text{Baseline pump set efficiency}$$

$$C_{pb} = \text{Retail cost of the baseline pump set}$$

$$C_{pbm} = \text{Retail cost of the benchmark pump set}$$

3.2.3. Step 3 – estimate size of solar array in benchmark pump set case and cost

In a scenario where the baseline pump set is replaced by the benchmark pump set in the baseline solar pump system, a smaller size of photovoltaic (PV) array would be required to produce same amount of water output. In this step, the size of the PV array is estimated using following equation.

$$\text{New PV array size } (PV_n) = (\text{Original PV array Size, } PV_o) \times \left(\frac{\eta_{pb}}{\eta_{pbm}} \right)$$

where:

$$\eta_{pbm} = \text{Benchmark pump set efficiency}$$

$$\eta_{pb} = \text{Baseline pump set efficiency}$$

In India, the installed cost of a PV array is \$1.7 per watt (Roston, 2012; Bijli, 2015). This cost rate is used to estimate the cost of the PV array for a solar pump system. Since, the new PV array size (PV_n) would be smaller compared to original PV array size (PV_o), there would be a cost saving. This saving is calculated by subtracting the cost of the original PV array size from the cost of new PV array size and is denoted by (C_{sg}). This is also represented in the following equation.

$$(C_{sg}) = ((\text{Original PV array size } (W), PV_o) - (\text{New PV array size } (W), PV_n)) \times 1.7 \left(\frac{\$}{W} \right)$$

3.2.4. Step 4 – estimate efficient solar pump system cost

Once, the increase in the pump set cost due to the efficiency gain and the decrease in PV array cost due to the smaller size are estimated, the overall cost of the energy

efficient solar pump system with the benchmark pump set is calculated using following equation.

$$\begin{aligned} &\text{Cost of the energy efficient solar pump system } (C_{bm\text{sp}s}) \\ &= \text{Cost of the baseline solar pump system } (C_{bs\text{p}s}) + (C_{pg} - C_{sg}) \end{aligned}$$

3.2.5. Step 5 – analyze technical potential

The Ministry of New & Renewable Energy (MNRE) has an ambitious plan to install 100,000 solar pump systems by providing subsidies to farmers. MNRE is providing a 30% subsidy whereas the state government subsidy component ranges between 40% and 60% (MNRE, 2014a). The number of additional solar pump systems that could be installed if government only provided subsidy to energy efficient solar pump systems having a benchmark (i.e., energy efficient) pump set can be calculated using the following equation.

$$\text{Additional number of pump sets} = \frac{100,000 * (C_{bs\text{p}s} - C_{bm\text{sp}s})}{C_{bm\text{sp}s}}$$

CHAPTER 4. RESULTS

To receive subsidy support from MNRE and state governments' programs, solar pump systems must have the following minimum water output at different total dynamic heads (TDH).

Table 6: MNRE technical performance criteria for solar pump systems (MNRE, 2014).

Technology (brushless DC (BLDC) pumps, DC positive displacement, AC centrifugal)	Maximum total dynamic head (TDH) (meters)	Liters of water per day per watt peak of PV array (L/Wp/day)
DC motor with or without BLDC	10	100
DC motor with or without BLDC	20	55
DC motor with or without BLDC	30	35
DC motor with or without BLDC	50	21
DC motor with or without BLDC	70	14
AC Induction motor	10	90
AC Induction motor	20	50
AC Induction motor	30	32
AC Induction motor	50	19
AC Induction motor	70	13

The baseline wire-to-water efficiency (η_{bs}) is calculated using MNRE technical performance criteria shown in the Table 6, and the output hydraulic energy and input electrical energy equations described in Section 3.1, above. The average daily solar radiation is specified as 7.15 kWh/m² on the surface of the PV array in the MNRE scheme. As per the calculations, the solar pump system should have an average wire-to-water efficiency greater than 36% in case of alternating current (AC) pump sets and 39% in case of direct current (DC) pump sets to qualify for receiving subsidy. The wire-to-water efficiency calculations are shown in the Table 7, below.

Table 7: Wire-to-water efficiencies of baseline solar pump systems as a function of their total dynamic head.

Technology (brushless DC (BLDC) pumps, DC positive displacement, AC centrifugal)	Max Total Dynamic Head (TDH) (meters)	Input Energy (Joules/Wp/day)	Output Hydraulic Energy (Joules/Wp/day)	Baseline Wire-to-water Efficiency (η_{bs})
DC motor with or without BLDC	10	25,740	9,800	38%
DC motor with or without BLDC	20	25,740	10,780	42%
DC motor with or without BLDC	30	25,740	10,290	40%
DC motor with or without BLDC	50	25,740	10,290	40%
DC motor with or without BLDC	70	25,740	9,604	37%
AC Induction motor	10	25,740	8,820	34%
AC Induction motor	20	25,740	9,800	38%
AC Induction motor	30	25,740	9,408	37%
AC Induction motor	50	25,740	9,310	36%
AC Induction motor	70	25,740	8,918	35%

The wire-to-water efficiency of a solar pump system depends on the pump motor technology and the total dynamic head (TDH). For example, the baseline wire-to-water efficiency (η_{bs}) for a DC pump (with or without brushless DC (BLDC) motor) for 50 meters TDH is 40%. The baseline wire-to-water efficiency (η_{bs}) for an AC induction motor pump for the same TDH is 36%.

Performance data and specifications of solar pump systems that are using subsidies from the central and state governments were also collected from their websites and other public documents to conduct the analysis. The detailed data are provided in the Table E-1 of Appendix E. The wire-to-water efficiency of the solar pump systems were

analyzed based on their liter per watt water output, head size, and average daily solar radiation specified by MNRE.

The wire-to-water-efficiency of all of the alternating current (AC) solar pump systems as a function of their total dynamic head (TDH) is presented in Figure 9, below.

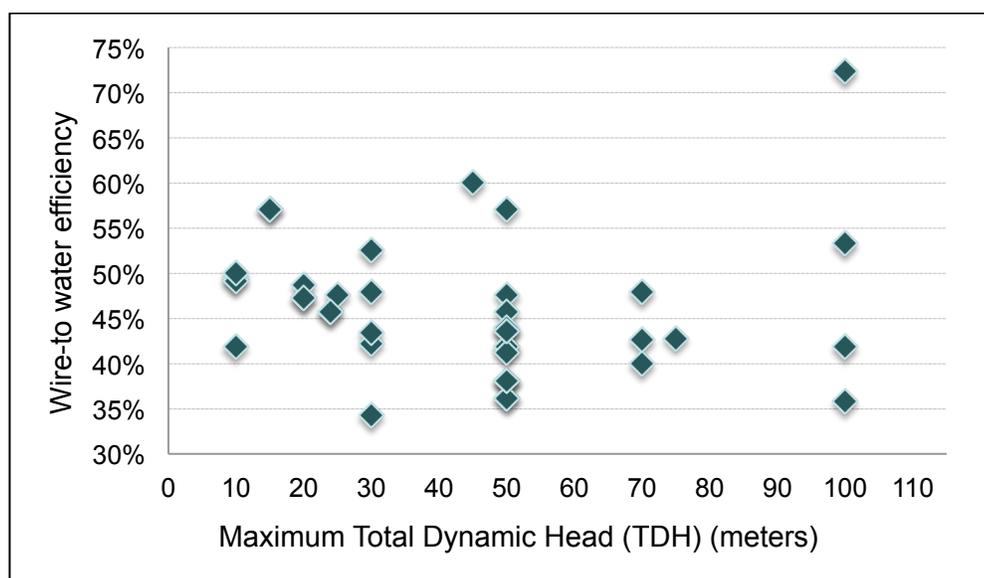


Figure 9: Wire-to-water efficiency distribution of AC solar pump sets against their total dynamic head (TDH).

A wide variation in efficiency values were observed for the solar pump systems with respect to their TDH. For example, the efficiency varied from 36% to 57% in case of 50 meter TDH. The MNRE subsidy criteria, explained in Appendix D, allow all the solar pump systems that have efficiency greater than 36%, in case of AC pump sets, and 40% in case of direct current (DC) pump sets, for 50 meter TDH, to avail the government subsidy. While manufacturers have the technology to manufacture systems having

efficiencies up to 57% in case of 50 meter TDH, there is little or no incentive for them to prioritize sales of such efficient pump sets.

Based on market efficiency analysis, 36% and 57% wire-to-water efficiency were considered as baseline (η_{bs}) and benchmark (η_{bs}) efficiency, respectively, for a 50 m TDH solar pump system. Based on the wiring efficiency, piping efficiency, and inverter efficiency values indicated in Table 5, baseline pump set efficiency (η_{pb}) and benchmark pump set efficiency (η_{pbm}) were calculated as defined in step 1 above. The summary of the results of step 1 is provided in the Table 8, below.

Table 8: Baseline and benchmark solar pump system and pump set (motor and pump combined) efficiency.

Parameter	Efficiency
Baseline wire-to-water efficiency (η_{bs})	36%
Benchmark wire-to-water efficiency (η_{bs})	57%
Baseline pump set efficiency (η_{pb})	40%
Benchmark pump set efficiency (η_{pbm})	63%

Typically, for a deep well submersible type system with a THD of 50 meters, a pump set having a capacity ranging between 3 HP and 5 HP would be required to meet the MNRE technical specification. A 3 HP solar pump system set typically costs around \$7,232 (INR 450,000) in India (Paliwal & Gupta, 2013).² Also, a 3 HP baseline solar pump system would require a PV array of 3,000 W to deliver the required per day water output (Jain & Jolly, 2012). As per the standards and labeling for electric pump sets, designed by Bureau of Energy Efficiency (BEE), 40% efficient would fall in the category

² 1 USD = INR 62.22 in February 2015, source: <http://www.bloomberg.com/markets/currencies/>

of 1-Star label and 63% efficient pump set would qualify for 5-Star label. The cost of typical 1-Star labeled and 5-Star labeled electric pump sets is \$402 and \$563, respectively. Other key parameters considered for the analysis are shown in Table 9, below.

Table 9: Key parameters considered for the solar pumps economic analysis.

Parameter	Value	Unit
Baseline solar pump system cost (C_{bsps})	7,232	USD
Baseline pump set cost (C_{pb})	402	USD
Benchmark pump set cost (C_{pbm})	563	USD
Baseline solar pump system PV array size (PV_n)	3,000	Watt
Useful life of solar pump system (NABARD, n.d.)	10	Years
Average grid emission factor (CEA, 2014)	0.82	tCO ₂ /MWh

The solar pump economic analysis model analyzed the above parameters and produced following output based on the steps 2, 3, 4, and 5 defined in the methodology section, above. The output of the model is shown in Table 10, below.

Table 10: Output of Solar Pump Economic Analysis Model.

Result	Equation	Result
Pump set efficiency gain (η_{pg})	$\left(\frac{\eta_{pbm}}{\eta_{pb}}\right) - 1 \times 100\%$	58%
Pumpset cost increase (C_{pg})	$C_{pb} - C_{pbm}$	\$161
New PV array size (PV_n)	$(Original\ PV\ array\ Size,\ PV_o) \times \left(\frac{\eta_{pb}}{\eta_{pbm}}\right)$	1,904 W
Cost saving because of smaller PV array (C_{sg})	$((PV_o) - (PV_n)) \times \$1.7 \left(\frac{\$}{W}\right)$	\$1,864
Cost of the efficient solar pump system (C_{bmmps})	$(C_{bsps}) + (C_{pg} - C_{sg})$	\$5,529
Cost savings on each energy efficient solar pump systems	$(C_{bsps} - C_{bmmps})$	\$1,703
Number of additional efficient solar pump systems that can be installed with same amount of Government subsidy budget	$\frac{100,000 * (C_{bsps} - C_{bmmps})}{C_{bmmps}}$	30,801
Lifecycle energy savings ³		597,405 MWh
Lifecycle GHG emissions reduction ⁴		477,924 tCO ₂ e

The subsidy from the central government is typically augmented by a subsidy from the state government. For example, in Bihar state, the total subsidy is 90% of the total capital cost (30% provided by MNRE and 60% provided by the state government). A farmer has to pay only 10% of the capital cost of the solar pump system. Therefore, \$1,703 cost saving on each solar pump system because of energy efficient pump set

³ Lifecycle energy savings calculated assuming that all the additional solar pump systems that can be installed will replace existing grid connected electric pump sets in the field.

⁴ GHG emissions reduction calculated assuming that all the additional solar pump systems that can be installed will replace existing electric pump sets in the field.

would result in \$1,533 subsidy saving to the government and \$170 saving to the individual farmer in Bihar.

The Solar Pump Economic Analysis Model concluded that by adopting a policy of incentivizing efficient solar pump systems only, the government could install 30,801 additional systems in the field. Assuming that all the additional solar pump systems will replace grid connected electric pumps sets, lifecycle electricity savings of 597,405 MWh and lifecycle GHG emissions reductions of 477,924 tCO₂e would be achieved from the same amount of subsidy.

CHAPTER 5. DISCUSSION

While preliminary analysis demonstrates that opportunities are available for improving the efficiency of solar pump systems and achieving additional energy savings and GHG emissions reductions, further work is needed to understand the key gaps and corresponding government, industry, and market actions to fully capitalize on the potential.

Currently, there is low awareness about importance of energy efficiency in solar pump systems among practitioners, and the opportunities and gaps have not yet been identified. A detailed market intelligence study to collect component wise costs and efficiency improvement data is needed to produce accurate results by conducting a techno-economic analysis. Such an analysis would provide more confidence to the stakeholders including policymakers.

In the current analysis, it is assumed that the baseline wire-to-water efficiency of solar pump systems is the same as the minimum efficiency calculated using MNRE technical criteria of water output as a function of total dynamic head (TDH). However, based on the sales of different solar pump systems in the market and their respective wire-to-water efficiencies, the baseline wire-to-water efficiency could be different and the assumption may not hold true. Therefore, going forward, it is necessary to collect product/model wise sales data of solar pumps systems to determine an accurate baseline wire-water-efficiency. Also, the average daily solar radiation specified by MNRE on the

surface of PV array for solar PV water pumping systems is 7.15 kWh/m^2 . This value is relatively high compared to the national average on a horizontal plane of 5.5 kWh/m^2 (MNRE, 2014e). There may be two reasons for this difference. First, the value specified by MNRE is for the solar energy in the plane of the solar PV array rather than the amount on a horizontal surface. Second, the specified value may refer to the solar energy during the primary irrigation season, which corresponds to a several month period during a dry (sunny) season of the year. The solar energy available during this period is generally considerably higher than the annual average solar energy availability.

The additional number of energy efficient solar pump systems that can be installed because of increase in the efficiency of pump sets is independent of the central and state governments' subsidy components. The number directly depends upon the overall target number of solar pump systems that governments plan to subsidize through their schemes. Therefore, any change in governments' original target of subsidizing 100,000 solar pump systems will impact the output of this research.

Energy-efficient irrigation pumps were identified as a high-impact opportunity in Sustainable Energy for All (SE4All) Agenda for Action (SE4All, 2014). However, to date, it appears that there has been relatively little progress within the SE4All framework toward developing a strategy and identifying resources to expand deployment of efficient solar pump sets. Revitalizing the discussion and stakeholder consultations around this topic with a wider audience in the context of climate change and energy access would

help in achieving rapid technology, policy, and deployment gains. Distributed irrigation solutions have not been accorded their due attention in the global arena either.

Overall efficiency gains by using efficient pump sets can further improve with more research & development. Recent developments in the solar PV market, in conjunction with advances in pumping technology, have opened up a window for deployment of a large number of solar agricultural pump systems (Shahan, 2014). The India government is focussing on renewable energy development, especially solar. This will help in further bringing down the cost of PV arrays in next few years. Solar pump systems manufacturers would be able to leverage the benefits of cheaper PV modules in the Indian market. Therefore, the government's policy to recognize higher efficiency solar pump systems and only subsidize those that achieve a high level of performance such as a five-star BEE rating will increase their penetration, reduce solar pump set system cost, and provide energy savings to both end users and society.

CHAPTER 6. CONCLUSION

Solar pump systems for irrigation are an emerging product segment in India. The government is well positioned to create a positive environment for deployment of a large number of solar pump systems with the help of schemes such as “Solar Pumping Program for Irrigation and Drinking Water”. However, relaxed energy efficiency requirements and indicative specification of the size of the PV array as a function of total dynamic head in the central and state governments’ schemes are leading to oversizing of solar PV components, thus increasing system cost considerably. Given a limited government subsidy budget, a higher system cost reduces the overall number of solar pump systems that can be installed in the field.

There are multiple benefits of deploying energy efficiency solar PV water pumping systems. The results indicate that \$1,000 up-front cost saving per solar pump system would enable installation of over 30,000 additional energy efficient solar pump systems under the MNRE’s program for irrigation and drinking water. This is possible because of the reduced amount of subsidy that would be needed for the installation of each energy efficient solar pump system. Also, farmers’ contributions would be smaller due to a decrease in the initial cost of an energy efficient solar pump system. A reduced burden on farmers in terms of their upfront contribution in buying a solar pump system would encourage more farmers to participate in the solar PV water-pumping program.

Assuming that all of the 30,000 additional solar pump systems will potentially replace grid connected electric pumps sets, lifecycle electricity savings of 600,000 MWh and GHG emissions reductions of 500,000 tCO₂e could be achieved.⁵ It is clear that the government's policy to recognize higher energy efficient solar pump systems will increase their penetration and result in significant money and energy savings for both end users and society. This would be a win-win situation for all stakeholders including manufacturers and farmers. Therefore, it is critical to act swiftly to move the market towards energy efficient solar pump systems in India in order to reduce GHG emissions and save money.

One of the ways to achieve this objective is by adopting a more stringent energy efficiency criteria for solar PV water pumping systems in India. The Indian Bureau of Energy Efficiency (BEE) has an energy efficiency labeling scheme in place for electric pump sets. The pump sets are rated from one to five-star rating based on their energy efficiency with five-star being the most efficient ones. The research recommends that MNRE and state governments can potentially harmonize with BEE's energy efficiency labeling criteria in their subsidy schemes. Governments can promote energy efficiency in solar pump systems by making five-star energy efficiency rating of pump sets a mandatory criterion to be eligible for availing central and state governments' subsidies.

While setting up a stringent energy efficiency standard for solar pump systems would help in eliminating the inefficient systems from the market, an energy efficiency

⁵ The life of the solar pump system is assumed to be 10 years in this analysis.

label would help policy makers and consumers to easily identify energy efficient solar pump systems. This would be a win-win situation for all stakeholders including manufacturers and farmers. Therefore, it is critical to act swiftly to move the market towards energy efficient solar pump systems in India, thereby reducing GHG emissions and saving money.

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APPENDIX A: HYDREGEOLOGICAL MAP OF INDIA

India has 17% of world population and 4% of world water (WRISI, 2015). The per capita water availability in India in the year 2010 was 1588 m³ and is likely to be reduced to 1401 m³ and 1191 m³ by 2025 and 2050, respectively (WRISI, 2015). The rise in water demand and falling per capita availability is leading to water scarcity in many Indian states. The geographical distribution of hydrogeological units along with their ground water potential is shown in Figure A-1, below.

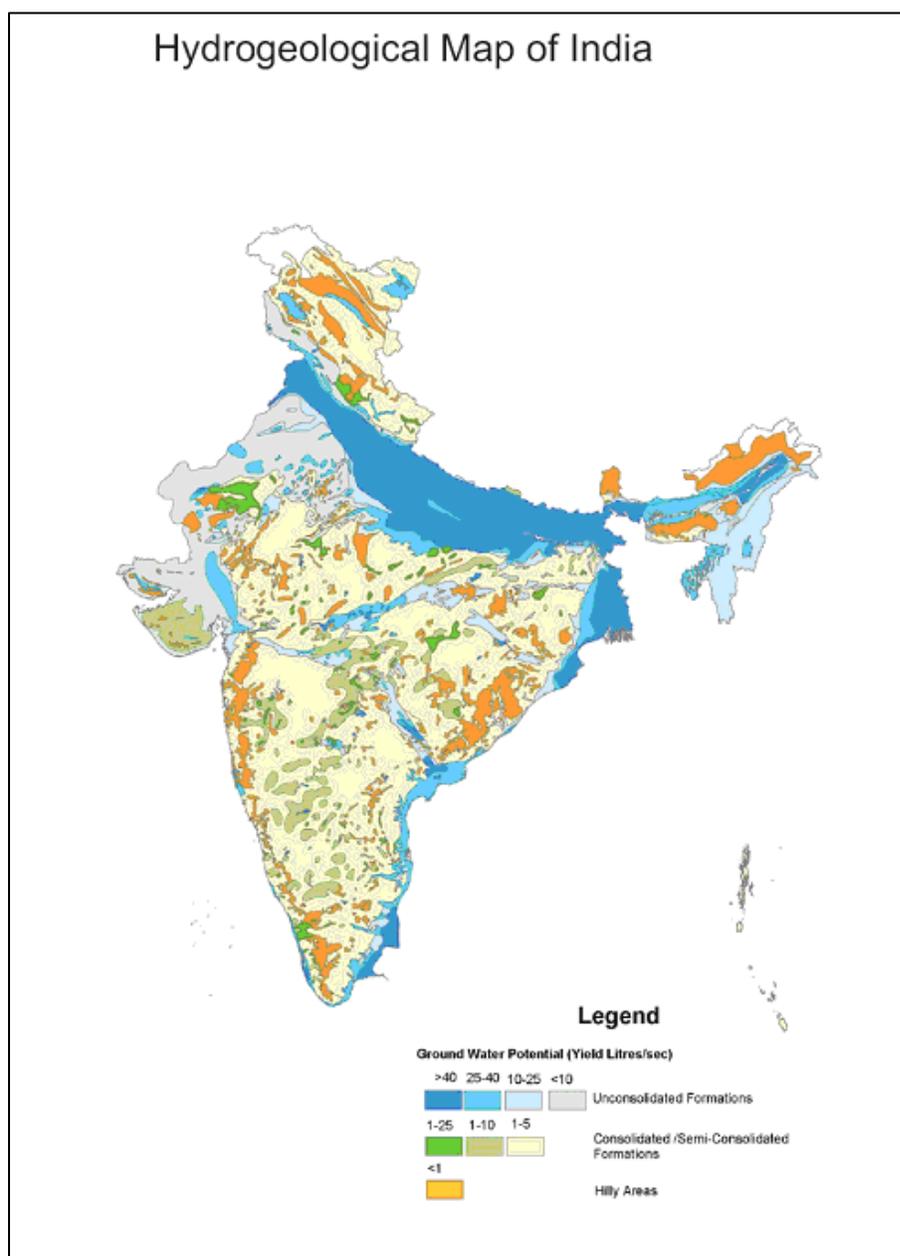


Figure A-1: Hydrogeological map of India. Source: Source: Groundwater Year Book 2011-12, Ministry of Water Resources, Government of India.

APPENDIX B: DEPTH OF WATER LEVEL MAP (PRE-MONSOON)

The depth of the water level in India is shown in Figure B-1, below. The depth to water level in the areas marked in green color is 2-5 meters below ground water level. These areas are ideal for solar PV water pumping systems.

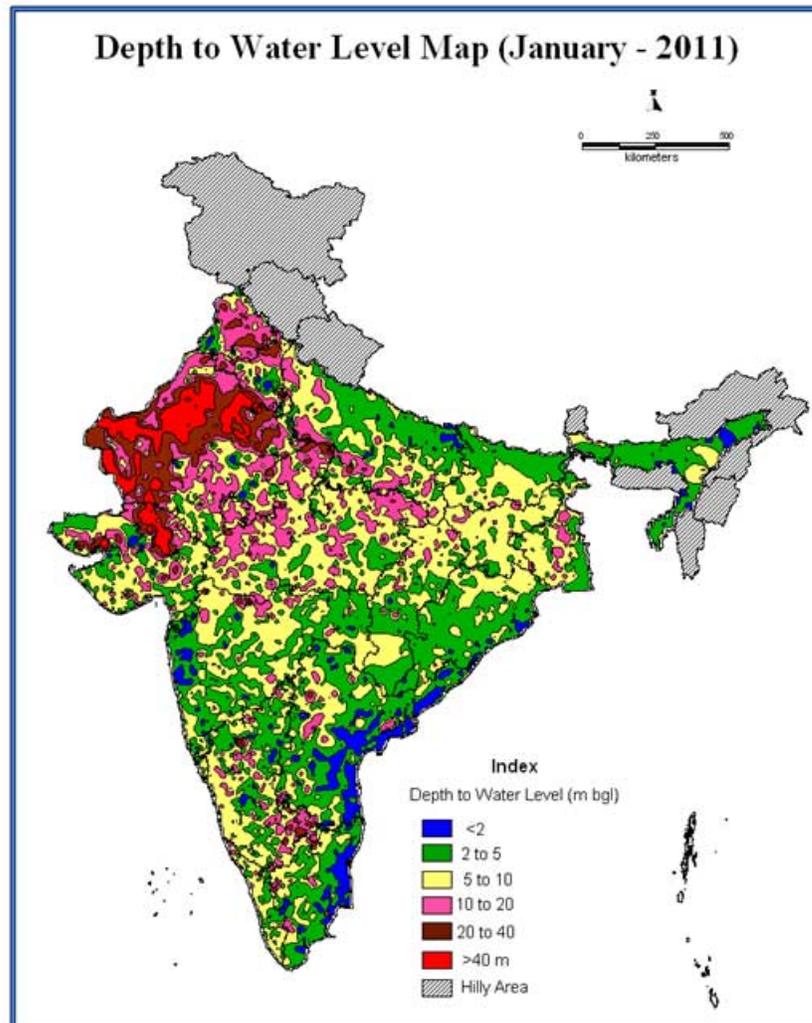


Figure B-1: Depth of water level map of India. Source: Groundwater Year Book 2011-12, Ministry of Water Resources, Government of India.

APPENDIX C: SOLAR RESOURCE AVAILABLE IN INDIA

The Ministry of New and Renewable Energy (MNRE), the Indian Metrological Department (IMD), and the US National Renewable Energy Laboratory (NREL) conducted a detailed study and prepared high-resolution solar resource maps and data for India. The annual average direct normal irradiance in kWh/m²/day is shown in the map in Figure C-1 and C-2, below.

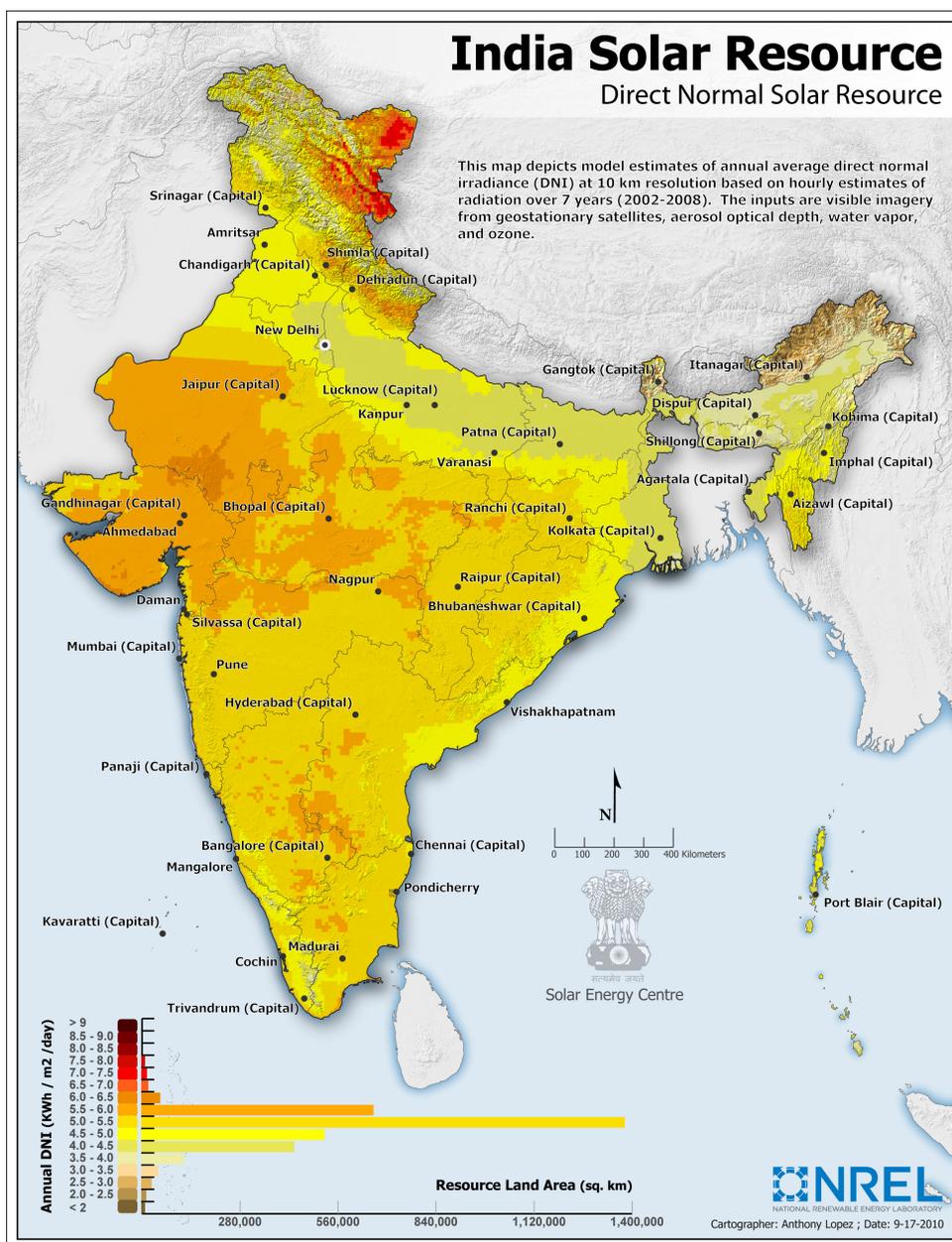


Figure C-1: Annual average solar resource available in India. Source: http://mnre.gov.in/sec/DNI_Annual.jpg

APPENDIX D: MINISTRY OF NEW AND RENEWABLE ENERGY CRITERIA FOR
SOLAR PHOTOVOLTAIC (PV) WATER PUMPING SYSTEMS (MNRE, 2014a)

The Ministry of New and Renewable Energy (MNRE) in India had laid out following performance criteria for solar water pumping systems under their subsidy program (MNRE, 2014a).

Performance Specification and Requirements

Solar photovoltaic (PV) water pumps with PV array capacity in the range of 200 Watt to 5 kWp could be installed on a suitable bore-well, open well, Water Reservoir, Water stream, etc.

Under the “Average Daily Solar Radiation” condition of 7.15 KWh/ sq.m. on the surface of PV array (i.e. coplanar with the PV Modules), the minimum water output from a Solar PV Water Pumping System at different “Total Dynamic Heads” should be as specified below :

For D.C. Motor Pump Set with Brushes or Brush Less D.C. (B.L.D.C.):

- 100 liters of water per watt peak of PV array, from a Total Dynamic Head of 10 meters (Suction head, if applicable, minimum of 7 meters) and with the shut off head being at least 12 meters.
- 55 liters of water per watt peak of PV array, from a Total Dynamic Head of 20 meters (Suction head, if applicable, up to a maximum of 7 meters) and with the shut off head being at least 25 meters.

- 35 liters of water per watt peak of PV array, from a Total Dynamic Head of 30 meters and the shut off head being at least 45 meters.
- 21 liters of water per watt peak of PV array, from a Total Dynamic Head of 50 meters and the shut off head being at least 70 meters.
- 14 liters of water per watt peak of PV array, from a Total Dynamic Head of 70 meters and the shut off head being at least 100 meters.

The actual duration of pumping of water on a particular day and the quantity of water pumped could vary depending on the solar intensity, location, season, etc.

For A.C. Induction Motor Pump Set with a suitable Inverter:

- 90 liters of water per watt peak of PV array, from a Total Dynamic Head of 10 meters (Suction head, if applicable, minimum of 7 meters) and with the shut off head being at least 12 meters.
- 50 liters of water per watt peak of PV array, from a Total Dynamic Head of 20 meters (Suction head, if applicable, up to a maximum of 7 meters) and with the shut off head being at least 25 meters.
- 32 liters of water per watt peak of PV array, from a Total Dynamic Head of 30 meters and the shut off head being at least 45 meters.
- 19 liters of water per watt peak of PV array, from a Total Dynamic Head of 50 meters and the shut off head being at least 70 meters.
- 13 liters of water per watt peak of PV array, from a Total Dynamic Head of 70 meters and the shut off head being at least 100 meters.

The actual duration of pumping of water on a particular day and the quantity of water pumped could vary depending on the solar intensity, location, season, etc.

Photovoltaic Array

The solar PV water pumping system should be operated with a PV array capacity in the range of 200-Watts peak to 5000-Watts peak, measured under Standard Test Conditions (STC). Sufficient number of modules in series and parallel could be used to obtain the required PV array power output. The power output of individual PV modules used in the PV array, under STC, should be a minimum of 74-Watts peak, with adequate provision for measurement tolerances. Use of PV modules with higher power output is preferred.

Indigenously produced PV module (s) containing mono/ multi crystalline silicon solar cells should be used in the PV array for the SPV. Modules supplied with the SPV water pumping systems should have certificate as per IEC 61215 specifications or equivalent National or International/ Standards. Modules must qualify to IEC 61730 Part I and II for safety qualification testing. The efficiency of the PV modules should be minimum 14% and fill factor should be more than 70%.

APPENDIX E: SOLAR PUMP SYSTEM PERFORMANCE DATA COLLECTION FORMAT

The solar PV water pumping systems' performance data was collected in the format shown in the Table E-1, below. The format was shared with Dr. Sandeep Garg at Energy Efficiency Services Limited in India. The data were provided as per the format and used in the analyses. The input energy, output hydraulic energy, and wire-to-water efficiency were determined for each model as per the equations defined in the methodology section.

Table E-1: Energy performance data of solar PV water-pumping systems enrolled with the MNRE. (Data source: Garg, Sandeep, personal communication, December, 2014)

Sl. No.	Manufacturer / Company Name	Type of pump (Surface, Submersible, Floating)	Technology (brushless DC pumps, DC positive displacement, AC centrifugal)	PV array size (Wp)	Motor Capacity (1 - 5 HP)	Max TDH (meters)	Liters of water per watt peak of PV array	Input Energy (Joules)	Output Hydraulic Energy (Joules)	Wire-to-water Efficiency
1	Shakti Pumps (India) Ltd.	Submersible	AC centrifugal	3000	3	10	130	25,740	12,740	49%
2	Shakti Pumps (India) Ltd.	Submersible	AC centrifugal	3000	3	20	62	25,740	12,152	47%
3	Shakti Pumps (India) Ltd.	Submersible	AC centrifugal	3000	3	30	42	25,740	12,348	48%
4	Shakti Pumps (India) Ltd.	Submersible	AC centrifugal	3000	3	50	25	25,740	12,250	48%
5	Shakti Pumps (India) Ltd.	Submersible	AC centrifugal	3000	3	70	15	25,740	10,290	40%
6	Shakti Pumps (India) Ltd.	Submersible	AC centrifugal	3000	3	100	9	25,740	9,212	36%
7	Shakti Pumps (India) Ltd.	Submersible	AC centrifugal	5000	5	10	129	25,740	12,642	49%

Sl. No.	Manufacturer / Company Name	Type of pump (Surface, Submersible, Floating)	Technology (brushless DC pumps, DC positive displacement, AC centrifugal)	PV array size (Wp)	Motor Capacity (1 - 5 HP)	Max TDH (meters)	Liters of water per watt peak of PV array	Input Energy (Joules)	Output Hydraulic Energy (Joules)	Wire-to-water Efficiency
8	Shakti Pumps (India) Ltd.	Submersible	AC centrifugal	5000	5	20	64	25,740	12,544	49%
9	Shakti Pumps (India) Ltd.	Submersible	AC centrifugal	5000	5	50	24	25,740	11,760	46%
10	Shakti Pumps (India) Ltd.	Submersible	AC centrifugal	5000	5	70	18	25,740	12,348	48%
11	Shakti Pumps (India) Ltd.	Submersible	AC centrifugal	5000	5	100	11	25,740	10,780	42%
12	Shakti Pumps (India) Ltd.	Monoblock	AC centrifugal	1800	2	20	20	25,740	3,920	15%
13	Shakti Pumps (India) Ltd.	Monoblock	AC centrifugal	2700	3	20	20	25,740	3,920	15%
14	Shakti Pumps (India) Ltd.	Monoblock	AC centrifugal	5000	5	30	30	25,740	8,820	34%
15	Crompton Greaves Ltd	Submersible	Brushless DC	1200	1	100	14	25,740	13,720	53%
16	Crompton Greaves Ltd	Surface	AC centrifugal	1800	2	15	100	25,740	14,700	57%
17	Crompton Greaves Ltd	Surface	AC centrifugal	1800	2	24	50	25,740	11,760	46%
18	Crompton Greaves Ltd	Surface	AC centrifugal	2700	3	15	100	25,740	14,700	57%
19	Crompton Greaves Ltd	Surface	AC centrifugal	2700	3	25	50	25,740	12,250	48%
20	Crompton Greaves Ltd	Surface	AC centrifugal	4800	5	24	50	25,740	11,760	46%
21	Crompton Greaves Ltd	Submersible	AC centrifugal	1800	2	100	19	25,740	18,620	72%
22	Crompton Greaves Ltd	Submersible	AC centrifugal	1800	2	45	35	25,740	15,435	60%
23	Crompton Greaves Ltd	Submersible	AC centrifugal	3000	3	170	10	25,740	16,660	65%
24	Crompton Greaves Ltd	Submersible	AC centrifugal	4800	5	270	6	25,740	15,876	62%

Sl. No.	Manufacturer / Company Name	Type of pump (Surface, Submersible, Floating)	Technology (brushless DC pumps, DC positive displacement, AC centrifugal)	PV array size (Wp)	Motor Capacity (1 - 5 HP)	Max TDH (meters)	Liters of water per watt peak of PV array	Input Energy (Joules)	Output Hydraulic Energy (Joules)	Wire-to-water Efficiency
25	Crompton Greaves Ltd	Submersible	AC centrifugal	4800	5	150	12	25,740	17,640	69%
26	Rotomag	Submersible	DC		2	30	37	25,740	10,878	42%
27	Shakti	Submersible	AC centrifugal		5	50	19	25,740	9,310	36%
28	Rotomag	Submersible	DC		3	50	22	25,740	10,780	42%
29	Rotomag	Surface	DC		2	10	132	25,740	12,891	50%
30	Rotomag	Submersible	DC		3	30	38	25,740	11,172	43%
31	Shakti	Submersible	AC centrifugal		5	50	30	25,740	14,700	57%
32	Rotomag	Surface	DC		2	10	110	25,740	10,780	42%
33	Rotomag	Submersible	DC		2	50	19	25,740	9,310	36%
34	Lubi	Submersible	AC centrifugal		3	50	20	25,740	9,800	38%
35	Shakti	Submersible	AC centrifugal		5	50	20	25,740	9,800	38%
36	Shakti	Submersible	AC centrifugal		5	50	22	25,740	10,780	42%
37	Kirloskar	Submersible	AC centrifugal		5	50	20	25,740	9,800	38%
38	Rotomag	Submersible	DC		3	70	16	25,740	10,976	43%
39	Rotomag	Submersible	DC		3	30	46	25,740	13,524	53%
40	Rotomag	Submersible	DC		3	50	23	25,740	11,319	44%
41	Rotomag	Submersible	DC		3	20	62	25,740	12,152	47%
42	KSB	Submersible	AC centrifugal		5	50	22	25,740	10,623	41%
43	Shakti	Submersible	AC centrifugal		5	50	23	25,740	11,221	44%
44	Shakti	Submersible	AC centrifugal		5	50	23	25,740	11,221	44%
45	Shakti	Submersible	AC centrifugal		3	75	15	25,740	11,025	43%