SOLAR WATER PUMP

TECHNOLOGY ROADMAP

MAY 2019

EFFICIENCY FOR ACCESS COALITION

Acknowledgements

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Acronyms and Abbreviations

AC	Alternating current
BIS	Bureau of Indian Standard
BLDC	Brushless direct current (permanent magnet) motor
DC	Direct current
DOE	U.S. Department of Energy
ECM	Electronically commutated motor (permanent magnet)
EST	Energy Savings Trust
FCC	Federal Communications Commission
FI	Financial Institution
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
GSMA	Groupe Spéciale Mobile Association
IEC	International Electrotechnical Commission
IRENA	International Renewable Energy Agency
KSSI	Kenya Smallholder Solar Irrigation Project
LCC	Life Cycle Cost
LEIA	Low Energy Inclusive Appliances
MPPT	Maximum power point tracking
PAYG	Pay-As-You-Go
Psi	Pounds per square inch
PV	Photovoltaic
R&D	Research and Development
RMS	Remote Monitoring Systems
SHS	Solar Home System
SKY	Suryashakti Kisan Yojana
SWP	Solar Water Pump
TDH	Total dynamic head

Executive Summary

1.0 Introduction

Efficiency for Access (EforA) is a global coalition promoting energy efficiency as a potent catalyst in clean energy access efforts. Since its founding in 2015, Efficiency for Access has grown from a year-long call to action and collaborative effort under Global LEAP and Sustainable Energy for All to a coalition of 13 donor organizations. Coalition programmes aim to scale up markets and reduce prices for super-efficient, off- and weak-grid appropriate products, support technological innovation, and improve sector coordination. In an effort to accelerate the global market for highly energy-efficient appliances, Efficiency for Access introduced a new UKaid funded research and innovation program in early 2017, Low-Energy Inclusive Appliances (LEIA) program, with the goal to double the efficiency and halve the cost of a suite of appliances that are well-suited for energy access contexts.

Solar water pumps (SWPs) were selected as a LEIA focus technology due to the immense potential for productive use and agricultural productivity. Forty percent of the global population relies on agriculture as its main source of income, yet access to water remains an ongoing struggle for many. Cost reductions for SWPs has the potential to make modern irrigation accessible and cost-effective for nearly 500 million small-scale farmers worldwide.

The objective of the SWP technology roadmap is to provide a pathway to accelerate the availability and affordability of technologies that can help improve the efficiency and performance of solar water pumps used in weak- and off-grid areas. In this roadmap, we aim to identify and prioritize research and development (R&D) initiatives that provide the best opportunities for accelerating development and commercialization of emerging technologies for solar water pumps. For the scope of this roadmap, we focused on small (50W-1,000W) sized solar water pumps, as those are the majority of pumps used in Africa by small hold farmers.

2.0 Technology and Market Scope

Moving water using solar pumping systems offers a clean and simple alternative to electric and diesel-driven pump sets. SWPs are often used for agricultural operations in remote areas or where the use of an alternative energy source is desired. If properly designed, solar pumping systems can result in significant long-term cost savings and increased agricultural productivity to farmers.

Solar Water Pump Technology

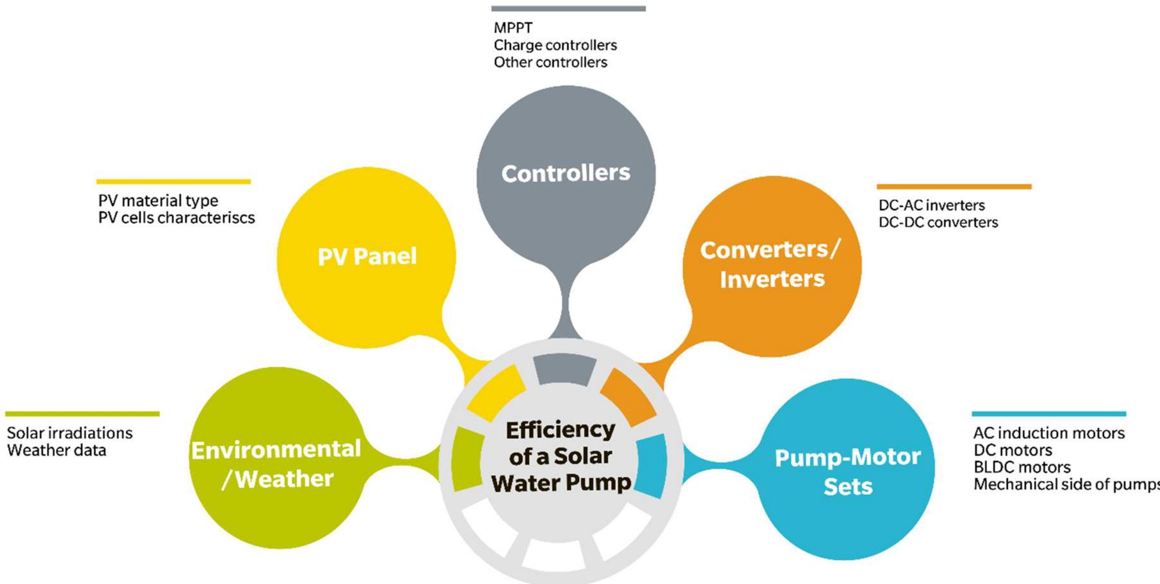
A solar pumping system consists of a number of key components, including a photovoltaic (PV) array, an electric motor, and a pump. Solar water pumping systems are broadly classified as either direct current (DC) or alternating current (AC) motor-based pumping systems. Recently, manufacturers have started using brushless DC (BLDC) motors for solar water pumping applications. BLDC motors are expensive compared to AC motors, but they are more efficient and require less maintenance.

There are two categories of pumps used in stand-alone solar pumping 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. Positive displacement pumps have a water output independent of the head but directly proportional to speed.

Pumps are also classified as submersible and surface pumps. A submersible pump remains underwater, such as in a well or any other water body, while a surface pump is mounted above the waterline or adjacent to the water source. Most submersible pumps have high lift capability, but they are sensitive to dirt and sand in the water and should not be run if the water level drops below the pump. Surface pumps are more accessible for maintenance and less expensive than submersible pumps, but not well suited for suction and can only draw water from about 6 vertical meters. Surface pumps are preferred for pushing water long distances horizontally.

The efficiency of a solar water pump is dependent on three variables: pressure, flow, and input power to the pump. Wire-to-water efficiency is the commonly used metric to determine the overall efficiency of a solar water pump; it 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. Based on discussion with Technical Working Group (TWG) members and other research, key factors influencing the performance and efficiency of SWPs are in Figure 1, below.

Figure 1: Key factors influencing the efficiency and performance of a solar water pump



The cost of solar water pumps has decreased significantly in the last two decades mainly because of a fall in PV panel prices. As prices have dropped, more small-sized solar water pumping systems have entered the market and are becoming more accessible to small scale farmers. In 2013, 80 percent of farms (or 33 million) in Africa were less than 2 hectares. Small pump systems typically range in cost from about $400-$3,000. A 20-year life cycle cost comparison between a fuel and solar powered pumping system for a 1-acre farm found that the breakeven point between the two systems occurs during the fifth year of operation. Additionally, Winrock International was able to provide data to financial institutions during their Kenya Smallholder Solar Irrigation (KSSI) project that shows payback periods of 1.5 years or less. Warranties for the pumps average between 1 to 2 years and require replacement every 5-10 years, depending on the pump and water quality. Solar panels have a typical lifespan of 20-25 years and typically come with 20-year warranties.

Global Solar Water Pump Market

Over the last two decades, the solar water pump market has grown rapidly. Factors driving the growth are: (1) reduction in prices of PV panels; (2) increase in the number of solar water pump manufacturers and suppliers across the globe; (3) increased awareness of solar water pumping due to various national and local governments' initiatives; and (4) expanded SWP system capacity and efficiency.

In developing countries, the agricultural sector presents an enormous opportunity for the solar water pump market. In rural areas, where farmers face erratic fuel prices, inconsistent access to the electric grid, and the desire for more environmentally sound solutions, solar pumps offer a great alternative to the traditional electric and diesel pumps. The most significant growth of the market has occurred in the Asia Pacific region, accounting for 40% of market share in 2017. Africa and the Middle East are two other major markets for solar water pumps, where there has been an increased water demand for irrigation and community water supplies as well as a growing trend away from fossil fuels.

Barriers to Adoption of Energy Efficient Solar Water Pumps

Despite significant market growth and technological innovation in the past decade, there are still significant barriers to the widespread adoption of high-quality energy efficient solar water pumps. Our research and discussions with industry stakeholders suggest that solar water pump technology has potential to improve, but broader market barriers to widespread adoption need to be addressed in parallel, such as lack of awareness and availability of financing. For example, there are limited number of financing tools currently available for solar water pumps, and of those, most small farmers are unable to meet the eligibility requirements to access the financing. We would recommend further research to explore how best to address in-country market barriers. Market barriers identified include: (1) relatively high cost of initial investment; (2) energy subsidies; (3) lack of education of solar water pump technology; and (4) concerns over the quality of products.

3.0 Roadmap Approach

The approach used for this technology roadmap was based on the Sandia report, "Fundamentals of Technology Roadmapping" and U.S. Department of Energy's (DOE) reports and technology roadmap for next-generation appliances. For the purposes of LEIA, the roadmap identifies critical technologies, gaps, and best practices to inform research and development investments.

We conducted preliminary research on use cases, market demands, and technologies. We also reviewed existing test methods and requirements to understand targets and parameters, and conducted desk research on reports, case studies, product information and published papers that exists on solar water pumps. This includes publications from the World Bank, academic institutions, non-profits, and donor funded programs.

The Solar Water Pump Technical Working Group was convened from May 2018 to May 2019, participating in a number of roundtable meetings, focus groups, and one-on-one calls. Industry input informed the crafting of this roadmap from the beginning, identifying key technologies to be investigated and providing feedback on working drafts.

Most technology roadmaps start with a focus on market needs and then develop the critical linkages to the products, technologies, and R&D activities necessary to meet them. Product requirements and performance targets are normally designated to be needed by a particular date and the associated technology options are then evaluated ahead of that date to inform any trade-offs necessary to achieve the desired performance, taking into account cost, availability, and other factors. This Roadmap is typical insofar as it has been prepared via consultation with a broad array of stakeholders in order to provide an industry-wide perspective on the solar water pump market. However, it includes recommendations for areas to achieve cost and efficiency improvements, but does not go as far as to develop performance targets and milestone dates.

4.0 Technical Working Group Findings

The technical working group's input and feedback was an integral component of the roadmap's development. This section briefly summaries our findings.

For the purposes of this roadmap, the product definition of a solar water pumping system is defined as, a PV pumping system in operation, may or may not connected to a mini-grid/ microgrid or any other form of renewable energy power supply. Critical system requirements, including technical, operational, and environmental, were considered. The working group members identified four major technology areas for the SWP roadmap: low-cost sensors and controllers; high efficiency motors; power systems; and saline water tolerance and filtration. In this roadmap, we are limiting our focus on remote monitoring systems, which include low cost sensors and controllers, and high efficiency motors use in SWPs.

We recommend further research on power systems and saline water tolerance and filtration. Also, modularity and operational requirements such as easy to use, easy to service, and availability of spare parts are critical to greater penetration of SWPs, but they were not considered in the limited scope of this technology roadmap. We highly recommend LEIA to conduct further research in these areas to understand issues and solutions related to operation and maintenance requirements of SWPs.

5.0 Technology Roadmap

This roadmap identifies technology alternatives that, if adopted, could improve the efficiency and performance of solar water pumps used in weak and off-grid contexts.

Remote Monitoring Systems (RMS)

Remote monitoring systems (RMS) allow manufacturers and service providers to remotely manage, service, and analyze solar water pumping systems, thus addressing one of the challenges associated with systems installed in isolated and remote locations. These systems can perform predictive maintenance, track system failures, and communicate directly with end-users to schedule maintenance. Not only do these systems contribute to the existing solar water pump's performance and end user experience, but they also help manufacturers improve their design and specifications for future products.

Basic components of an RMS include a microcontroller chip, a GSM/ GPRS module, a Bluetooth module (optional), and RS 232 interface. While remote monitoring systems can potentially provide a number of benefits to the end consumers, distributor, and manufacturers, they are not very prevalent in the market. Below, Table 1 provides an overview of technical and market barriers facing the widespread adoption of RMS and Table 2 highlights action items and key stakeholders identified.

Error! Reference source not found.1: Technical and Market Barriers for RMS

Technical Barriers	Market Barriers
Initial cost	Cost of global certification for communication modules
Limited availability of standardized RMS hardware products & interoperability issues	End-user marketability
Software and agricultural practices integration	
Data Privacy	

Table 2: Action Items and Key Stakeholders

Near-term Action Items (1-3 years)	Mid-term Action Items (3-5 years)	Key Stakeholders
Work with manufacturers & distributors to collect more comprehensive data on use cases for SWPs	Explore an open source platform/ simulation lab to perform simulations and designs for SWPs	Manufactures and Distributors
Standardization in data collection through RMS		Research and Development Organizations
		Groupe Spéciale Mobile Association (GSMA)
		Independent laboratories

Since the SWP market is in a nascent stage and growing in developing countries, SWPs with integrated RMS have the potential to transform the market. If the information collected through RMS is able to be aggregated across regions and sectors, that data has the potential to inform policies and best practices for a more efficient usage of solar water pumps. Finally, any technology improvements in RMS would also be leveraged in other off-grid application for RMS such as refrigerators and solar-home systems.

Brushless DC Motors

BLDC motors, often called permanent magnet motors or electronically commutated motors (ECM), are more efficient than alternative motors for a variety of reasons. Their power consumption is lower compared to induction motors because they do not require current to be induced in rotor windings and the elimination of brushes contributes to increased efficiency, reliability, and durability of these motors. BLDC motors are ideal for use in applications with varied loads such solar water pumps because they have either integrated controls or are paired with drives. Motors are the second most expensive component in SWPs after the PV panels.

Table 3, below, highlights the technical and market barriers facing BLDC motors.

Table 3: Technical and Market Barriers for BLDC Motors

Technical Barriers	**Market Barriers**
High initial cost of BLDC motors compared to traditional technologies	Low demand for BLDC motors
High cost and limited availability of scarce rare-earth metals used for permanent magnet	Feasibility of retrofitting high efficiency motors
Lack of research in lower-cost manufacturing techniques for BLDC motors	Limited availability of service and repair for BLDC motors in rural areas.

BLDC motors are a well-established technology, and sensorless control is also something that has been more or less driven to a commodity. TWG members and our research suggested that the challenge in the case of BLDC motors is not technology development, but how to develop awareness and encourage manufacturers to take up a solution which although currently more expensive, offers very significant benefits in performance, efficiency, reliability and total cost of ownership in the long run. Nevertheless, Table 4 identifies a few action items and key stakeholders that will help in removing the barriers for greater adoption of BLDC motors by SWP manufacturers within the scope of this roadmap.

Table 4: Action Items and Key Stakeholders

Near-term Action Items (1-3 years)	Recommendations	Key Stakeholders
Low cost sensorless drive development for BLDC motors Research and identify low cost BLDC motor manufacturing techniques.	Since BLDC motor is a cross cutting technology, we would encourage LEIA to take it up as a cross-cutting issue and propose a separate research piece needed to substantiate the state of development of the BLDC motors.	Research and Development Organizations SWP and Motor Manufacturers Test Laboratories Distributors

BLDC motors requires less maintenance with a longer lifespan, performs at higher efficiencies due to low losses in the motor, and offers increased productivity. The increased reliability and durability of the motor benefits both the end-users and the manufacturers/ distributors through a decrease in service and maintenance requests. As mentioned above, BLDC motor is a cross cutting technology and used in range of products used in off-grid areas. A Global LEAP analysis suggested that the expected market impact of BLDC motors in weak- and off-grid applications could cut energy consumption by 50%.

6.0 Summary and Recommendations

There were a number of topics that were discussed, researched, and ultimately excluded from the limited scope of this technology roadmap but can have significant impact on the affordability and efficiency of SWPs. The opportunities for the two agreed upon areas for collaboration, BLDC motors and remote monitoring systems, are outlined above. We recommend further research into the following areas: connectors and couplers for increased portability and durability; water quality and the impacts it has on durability and maintenance; use of drip irrigation through behavioral change; quality assurance concerns, as well as country specific barriers.

1.0 Introduction

Background

Efficiency for Access Coalition

The Efficiency for Access Coalition began in 2015 as a year-long collaborative effort led by Global LEAP and Sustainable Energy for All, working to harness the power of energy efficiency to accelerate universal access to modern energy services. Today, this coalition brings together twelve organizations, representing initiatives and programs spanning three continents, 26 countries, and 19 key technologies. These initiatives are focused on driving market scale in near-to-market weak- and off-grid appliance products, supporting innovation in horizon appliance technologies further from low income markets, and improving information and co-ordination among development sector and industry partners.

The Efficiency for Access Coalition is coordinated by CLASP, the leading international voice and resource for appliance energy efficiency policies and market acceleration initiatives, working alongside the UK's Energy Saving Trust (EST), which specializes in energy efficiency product verification, data and insight, advice and research. This coalition aims to achieve faster, higher-impact results by strengthening the coherence of support programs aligned with the needs of consumers and the market, based on a range of consumer research and industry consultation mechanisms.

Low Energy Inclusive Appliances (LEIA) Program

In an effort to accelerate the global market for highly energy-efficient appliances, Efficiency for Access introduced a new research and innovation program in early 2017 with the goal to double the efficiency and halve the cost of a suite of appliances that are well-suited for energy access contexts. The Low-Energy Inclusive Appliances program, funded by UK aid, will provide £18 million over five years to accelerate the availability, affordability, efficiency and performance of a range of appliances and related technologies suited to developing country contexts. LEIA was designed with extensive industry consultation regarding the specific challenges and opportunities of the off-grid clean energy access appliance market.

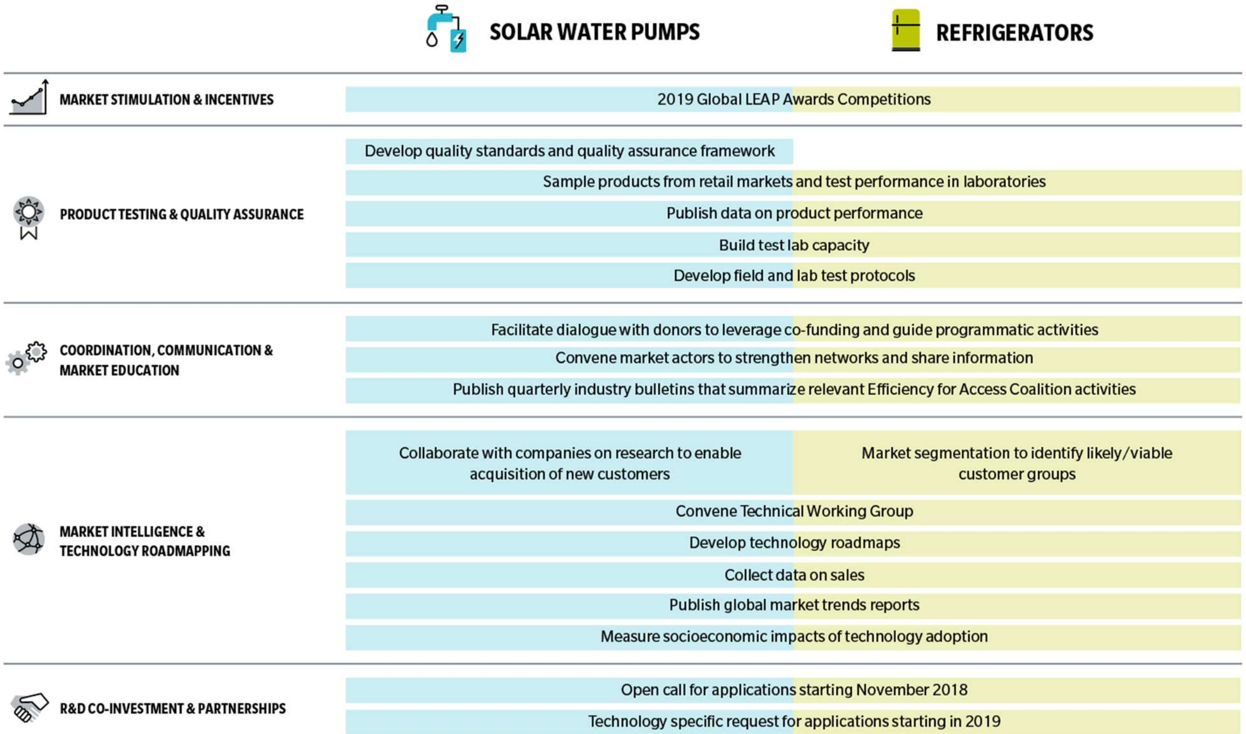


Figure 1: LEIA Activities on Solar Water Pumps and Refrigerators[1]

Through an extensive literature review, data and market analysis, a market survey, and expert consultation, four near-to-market products and five cross-cutting horizon and enabling technologies were identified. Figure 1, shows the number of activities currently ongoing in respect to two of the products selected, Solar Water Pumps (SWPs) and Refrigerators. The graphic is organized around LEIA's five principle components designed to address key market barriers: (1) market stimulation and incentives; (2) testing and quality assurance; (3) marketplace education, communications, and coordination; (4) market intelligence and technology roadmapping; and (5) R&D co-investments.

Solar water pumps were identified as one of the near-to-market products due to the immense potential for productive use and agricultural productivity. Forty percent of the global population relies on agriculture as its main source of income, yet access to water remains on ongoing struggle for many. Cost reductions for SWPs has the potential to make modern irrigation accessible and cost-effective for nearly 500 million small-scale farmers worldwide.

Technology Roadmap Objective

The objective of this roadmap is to provide a pathway to accelerate the availability and affordability of technologies that can help improve the efficiency and performance of solar water pumps used in weak- and off-grid areas. In this roadmap, we aim to identify and prioritize R&D initiatives that provide the best opportunities for accelerating development and commercialization of emerging technologies for solar water pumps. Key questions this roadmap seeks to address include: what is the current technology status of solar water pumps in off-grid areas; what are the market and technical barriers for greater adoption; and what technological options are available to manufactures in the short-, mid-, and long-term?

Key advantages of industry roadmaps are that they allow for a broad coalition of stakeholders and experts to pool together resources to avoid redundancy and enable greater access to technical, market, and policy expertise. This roadmap has been informed by desk research, multiple technical working group (TWG) meetings, small focus group calls, and one-on-one calls with industry experts.

Technical Working Group

The challenge of any industry roadmap is that it is a consensus process, requiring the active participation and buy-in of market stakeholders. This can be particularly difficult when members are concerned about sharing intellectual property or company strategies, an obstacle we faced throughout this roadmap. While participation in the TWG is voluntary, members devote significant time and effort towards achieving the goals of the roadmap. As stated in the Efficiency for Access Technical Working Group Charter, members are expected to bring sufficient knowledge of the sector, associated marketed, and products; and be able to meaningfully contribute to the development of the roadmap. The goal is to develop a consensus on key points, not to drive towards a single point of view to the exclusion of others.

In April 2018, Efficiency for Access hosted its first Global Market Development Roundtable in Nairobi, Kenya, bringing together over 40 industry leaders for in-depth discussions on challenges and opportunities facing the SWP market. During this two-day event, members identified priorities and action items for the Efficiency for Access Coalition, as well as helping to identify areas of focus for this roadmap. The topics identified for their potential impact include: promotion of R&D in low cost sensor development; advancements in low cost motors; portable and durable small-scale power systems; and improvements to saline water tolerance and filtration.

TWG members were recruited for this roadmap through three primary avenues: the Global Market Development Roundtable and ICF and LEIA's networks of technical experts. Over one-third of the SWP TWG Group members participated or their organization was represented at the meeting in Nairobi. Nearly a quarter of the members were invited by the TWG Chairperson, Amit Khare (ICF), while the remaining members were introduced to the working group through their connections with CLASP and/or LEIA.

2.0 Technology and Market Scope

Solar Water Pump Technology

Pumping water from the ground through solar pumping systems offers a clean and simple alternative to electricity- and diesel-driven pump sets. Solar pumping systems are often used for agricultural operations in remote areas or where the use of an alternative energy source is desired. Solar pumps are most effective during dry and sunny seasons and do not require fuel deliveries. Their use naturally aligns with solar radiation as water demands typically increase during the summer when solar radiation is at a maximum. If properly designed, solar pumping systems can result in significant long-term cost savings and increased agricultural productivity to farmers.

Key Components of a Solar Water Pumps

A solar pumping system consists of a number of components, including a photovoltaic (PV) array, which converts solar energy 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. To get the best performance from the overall system, the characteristics of these components need to align. Figure 2 shows a schematic representation of a solar PV water pump system with maximum power point tracking (MPPT) and DC motor.

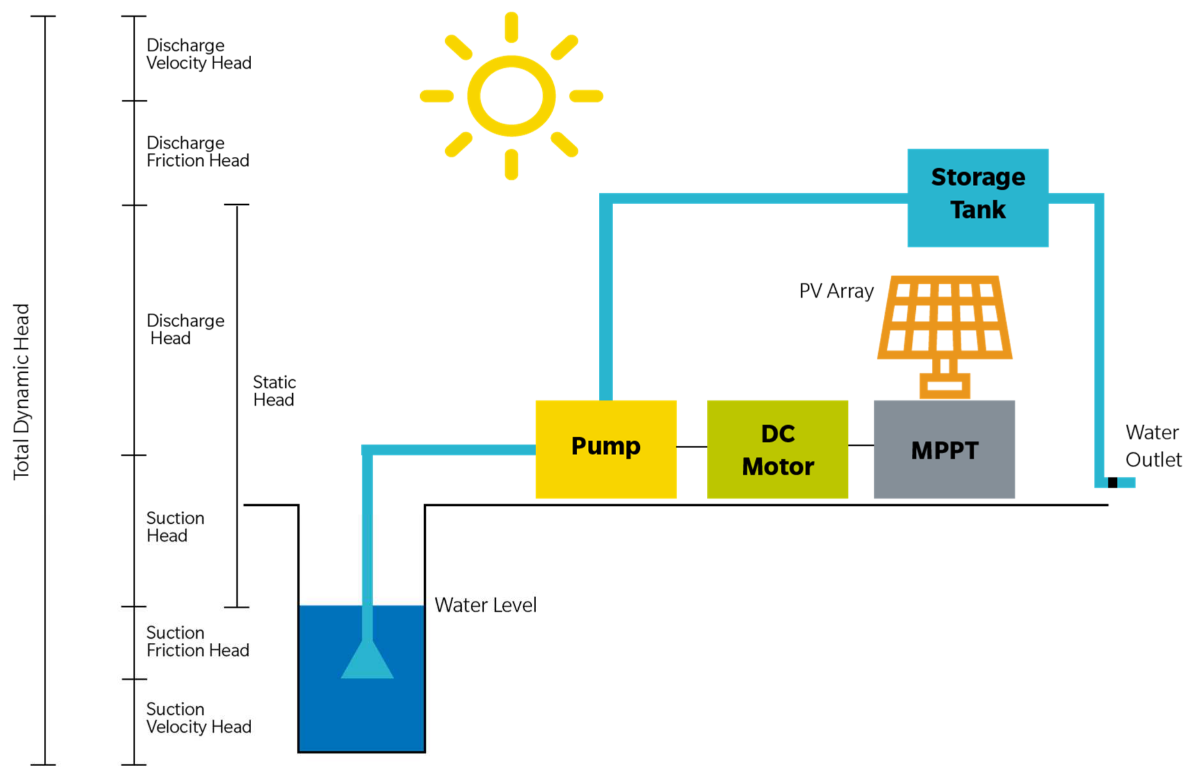


Figure 2: A schematic diagram of a PV water pump system with MPPT and DC motor[2]

Solar water pumping systems are broadly classified as either DC or alternating current (AC) motor-based pumping systems. DC motor-based solar water pumps consist of a PV array, with or without an intermediate converter, and a motor coupled with a pump. The AC motor water pumping system requires a DC to AC inverter to drive the motor coupled with the pump.

Solar pumping systems with DC motor pump sets are generally more efficient compared to AC motor driven pumps. DC motor efficiency can reach up to 80% compared to AC three-phase motors, which have efficiencies in the range of 60% to 65% for the sizes of motors commonly used in small-scale irrigation pumps.[3] Recently, manufacturers have started using brushless DC (BLDC) motors for water pumping applications. BLDC motors are expensive compared to brushed DC motors, but they are more efficient and require less maintenance compared to brushed DC motors, which require regular brush replacement.

Typically, there are two categories of pumps used in stand-alone solar pumping 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. 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.[4] 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.[5] An open view of different components of a centrifugal pump is shown in Figure 3, below.

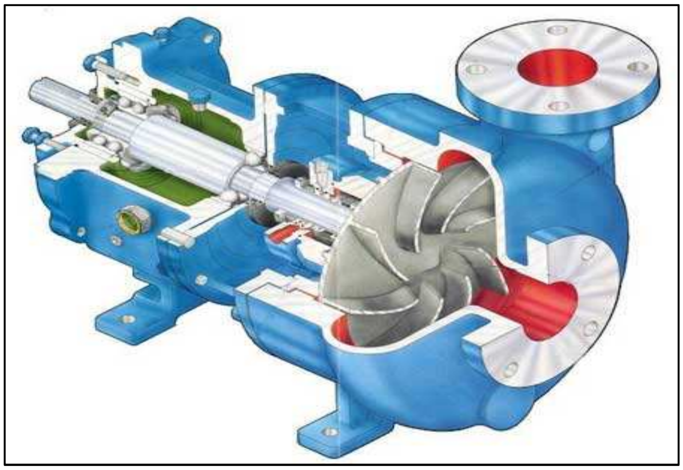


Figure 3: Open View of a Centrifugal Pump.[6]

Centrifugal pumps have an optimum efficiency at a certain design head[1] and design rotation speed. As the head deviates from the design point, centrifugal pump efficiency decreases. 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.[7]

While centrifugal pumps are designed for a particular head, positive displacement pumps have a flow independent of the head but directly proportional to speed. Water is forced against the entire head by employing a piston/cylinder arrangement. These pumps have higher frictional forces than centrifugal pumps because contact from moving surfaces is necessary to 'positively displace' the pumped water.

At high heads and low speeds, the frictional forces are small. Consequently, for high heads, positive displacement pumps may be the more efficient choice. At lower heads, the frictional forces are large compared to the hydrostatic forces, therefore efficiency is low and a displacement pump is less likely to be used.

Pumps are also classified as submersible and surface pumps. A submersible pump remains underwater, such as in a well or any other water body, while a surface pump is mounted at the top of the water or adjacent to the water source as shown in Figure 4. Surface pumps are more accessible for maintenance and less expensive than submersible pumps, but not well suited for suction and can only draw water from about 20 vertical feet[8] Surface pumps are excellent for pushing water long distances horizontally. Most submersible pumps have high lift capability, but they are sensitive to dirt and sand in the water and should not be run if the water level drops below the pump.[9] As noted by a TWG member, more pump manufactures are developing impellers and configurations that can handle silt and sand.

[1] Typically, "Head" is the maximum height that a pump can move the water or any other fluid against gravity.

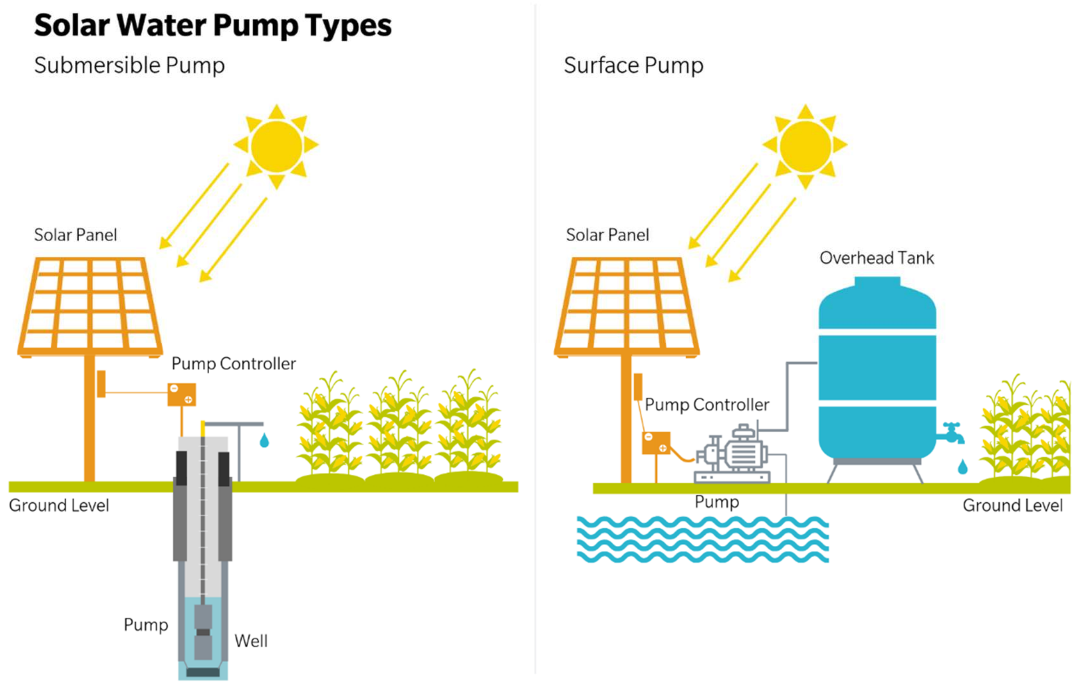


Figure 4: Representation of a submersible and surface pumps.[10]

Total Dynamic Head (TDH)

The "Total Dynamic Head (TDH)" is an important parameter to calculate while designing any water pumping system.[11] TDH determines the various head losses that the pump must overcome in order to deliver the required amount of water. The TDH is a combination of three components – static head, friction head, and residual head – and is expressed in both feet or meters, or PSI or pressure. Static head is the actual vertical distance measured from the minimum water level to the highest point in the discharge piping. Friction head is the additional head created in the discharge system due to resistance to flow within its components. Residual head ensures there is enough pressure at the delivery point. The total dynamic head is proportional to the hydraulic energy requirement, and the result is that it is more efficient and less expensive to pump through lower heads. Typically, the flow rate, which is the amount of water that a pump can move during a given time period, increases as the TDH decreases. Manufacturers generally provide a chart that indicates the range of heads and flow rates that a particular pump model can provide to help chose the right pump, depending upon the application.

Efficiency Metric for Solar Water Pumps

The efficiency of a solar water pump is dependent on three variables: pressure, flow, and input power to the pump.

Pressure: It is the amount of work that the pump must overcome to move a certain amount of water and is often expressed in either feet/meter of head or psi (pounds per square inch).[12]

Flow: It is the amount of water that a system can move during a given time period. It is usually measured in liter per hours or gallons per minute or gallons per hour. Pressure and flow have an inverse relationship for a fixed size of pump. In other words, for a fixed capacity of pump, the flow decreases when pressure increases and vice versa.[13] It is worth noting, that pumps are often marketed with the volume of water moved per day (m^3/day), which is still flow rate, but measured over a greater and therefore variable time.

Input power: It is the amount of power drawn by the pump as per the pressure that needs to be produced to deliver the water. For wire-to-water efficiency calculation, this is typically the output power produced by the PV array. Therefore, installing more PV than needed may help in turning on the pump earlier and later in the day, or under low-light conditions, but it might not help in increasing the flow rate when the sun is shining in full.[14]

Wire-to-water efficiency is the commonly used metric to determine the overall efficiency of a solar water pump. It includes the efficiency of the pump, pump motor, connecting wires, and inverter in the case of AC pumps. The wire-to-water efficiency metric also accounts for the losses in the pipe fittings that surround the pump. Essentially, it 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.

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

The International Electrotechnical Commission (IEC) 62253:2011- Photovoltaic pumping systems – design qualification and performance measurements, provides the following equation to determine the pump efficiency.

$$\eta\ (\%) = \frac{H * Q * g}{I * V}$$

As per the IEC test standard, the real water pumping head H [m] is determined using a pressure sensor. The flow rate of pumped water Q [l/s] is measured either with a calibrated flow meter or with the bucket method; g [m/s^2] is the acceleration due to gravity. The input power to the pump is estimated by measuring the converter DC voltage [V] and current I [A]. Finally, the efficiency of the converter-motor-pump subsystem is calculated using the equation above.

Key Factors Influencing Efficiency of a Solar Water Pump

This section provides an overview of factors and components that influence the efficiency and performance of a solar water pump. As described in the earlier section, a solar water pump typically has 1) PV module(s), 2) controllers, 3) converter or inverter unit, and 4) pump set (motor+pump combination). In addition to the above components, the performance of pumps is also impacted by the environmental and weather conditions. Based on discussion with TWG members and other research, key factors influencing the performance and efficiency of SWPs are shown in Figure 5.[15]

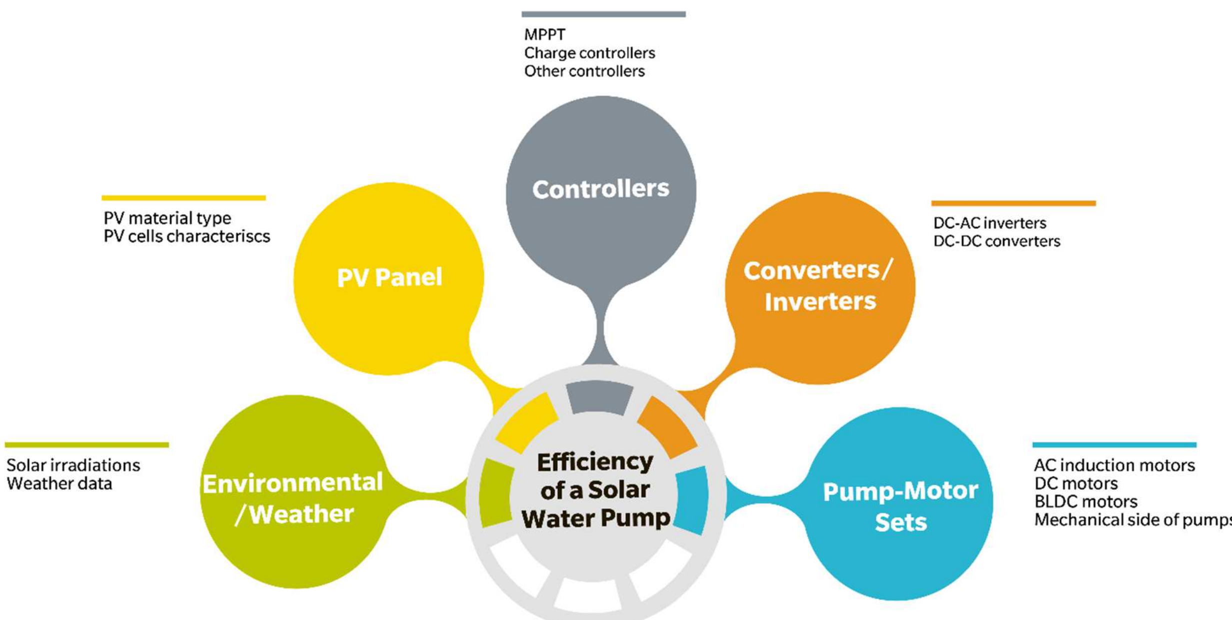


Figure 5: Key factors influencing the efficiency and performance of a solar water pump.

The environmental factors and weather conditions include solar irradiation and weather data in the field. The performance and efficiency of the PV panel are dependent upon the type of PV material used, the tilt angle and azimuth, and the characteristics of the PV cell. The type of controller used also influences the performance and efficiency of the system. The controllers are divided into MPPT, charge controllers, and other controllers. Since both AC and DC pump motor sets are used in SWPs, converter or inverter efficiencies are also important and both AC and DC pump efficiency is dependent on the MPPT efficiency. Finally, the motors, which have a significant influence on the efficiency and performance, can be AC, DC, or BLDC motors.

Cost of Solar Water Pumps

The cost of solar water pumps has decreased significantly in the last two decades mainly because of a fall in PV panel prices. Solar water pump systems have seen a price drop of 80 percent from $25/kWp in 1998 to $5/kWp in 2013. As prices have dropped, more small-sized solar water pumping systems have entered the market and are becoming more accessible to small scale farmers.[16]

In 2013, 80 percent of farms (or 33 million) in Africa were less than 2 hectares.[17] For the scope of this roadmap, we are focusing on small (50W-1,000W) sized solar water pumps, as those are the majority of pumps used in Africa. Small pump systems can typically range in cost from about $400-$3000, examples include: Futurepump Ltd's SF2 pump kit sells for $695[18]; Lorentz 280W PS150 Pump & Controller retails for $1,200[19]; SunCulture offers the Rainmaker1 pump kit for $480[20]; Graduate Farmer's 120W GF1 Solar Pump kit aimed at young farmers retails for less than $350[21]; and in 2017 SunCulture introduced the Rainmaker which includes the pump, controller, battery bank, portably solar panels, sprinkler, delivery and installation, and after-sales service all for $480.[22] These small sized, low powered systems are able to pump large quantities of water throughout the day, offering a more affordable solution to small-scale, rural farmers.[23]

Table 2 provides a life cycle cost (LCC) comparison between a fuel and solar powered pumping system for a 1-acre farm over a 20-year span. The table is developed based on information provided in "Solar Water Pumping for Irrigation: Case Study of the Kilimanjaro Region in Tanzania" a study published by the Minor Field Studies Scholarship Program, funded by the Swedish International Development Corporation Agency.[24]

Table 2: 20 Year LCC Comparison between a Fuel & Solar Powered Pumping System for a 1 Acre Farm

Parameters	Fuel	Solar
Investment cost	$331	$4,223 Pump & Controller (280 W) $1,252 2 Solar Panels (180 W) $479 Cables and pipes $698 Tank & mounting materials $1,006 Labor, transportation, & VAT $788
Maintenance cost	$125/year	$125/year
Operating cost	$804/year (Fuel)	-
Life of system	2 years	Solar panels – 20 years Pump & Controller – 10 years
Total Life Cycle Cost (20 years)	**$22,221**	**$7,975**

As evident in the cost comparison above, significant savings are achievable if the end-users are able to acquire the needed capital to make the initial investment. The breakeven point between the two systems above occurs during the fifth year of operation[25] Payback periods for medium-sized systems is typically 2-3 years[26], with smaller systems seeing payback periods under 1.5 years.[27] Warranties for the solar water pumps average between 1 to 2 years and require replacement every 5-10 years, depending on the pump and water quality. While the cost of fuel powered pumps was significantly less, farmers complained about needing to replace the pump every 1 to 2 years. The cost of replacing the pumps have been included in the cost comparison above. Solar panels have a typical lifespan of 20-25 years and typically come with 20-year warranties.[28][29] Limited information was provided on maintenance cost for this cost comparison but was calculated using the equation $\$(100+0.05 * W_p)$.[30]

Global Solar Water Pump Market

Over the last two decades, the solar water pump market has been growing at a significant rate. Factors driving the growth are: (1) reduction in prices of PV panels in recent years; (2) increase in the number of solar water pump manufacturers and suppliers across the globe; (3) increased awareness of solar water pumping due to various national and local governments' initiatives; and (4) expanded SWP system capacity and efficiency.[31]

The rapid expansion of PV technologies has benefited the deployment rate of solar water pumps tremendously in the last few years. Since the high initial cost of PV array is a main barrier to wide-scale deployment of solar water pumps, the rapid expansion of PV technologies and significant drops in price, helped solar water pump deployment to reach higher penetration levels. Coupled with the falling prices of PV, the cost of pumps and controllers have fallen 30 percent from 2009 to 2015.[32] As prices for PV continue to fall, as shown in Figure 6, it allows for larger solar pumping systems to become more affordable and widely available.

Over the last decade, we have seen a rise in the number of manufacturers and suppliers across the globe to meet the increased demand for solar water pumps. Major vendors include Bright Solar (India), Grundfos (Denmark), Lorentz (Germany), Shakti Pumps (India), SunCulture (Kenya), Future Pump (Kenya) and Tata Power Solar (India). While the competitive market has driven prices down, there is still a significant barrier to entry for small-scale operators who cannot afford the large initial investment. To meet this need, more regional and local manufacturers have begun entering the market offering lower cost solutions. This has allowed for the greater adoption of solar water pumps for small scale purposes while raising concerns that the quality of products used and poor installation practices will cause farmers to become less interested in solar water pumps.

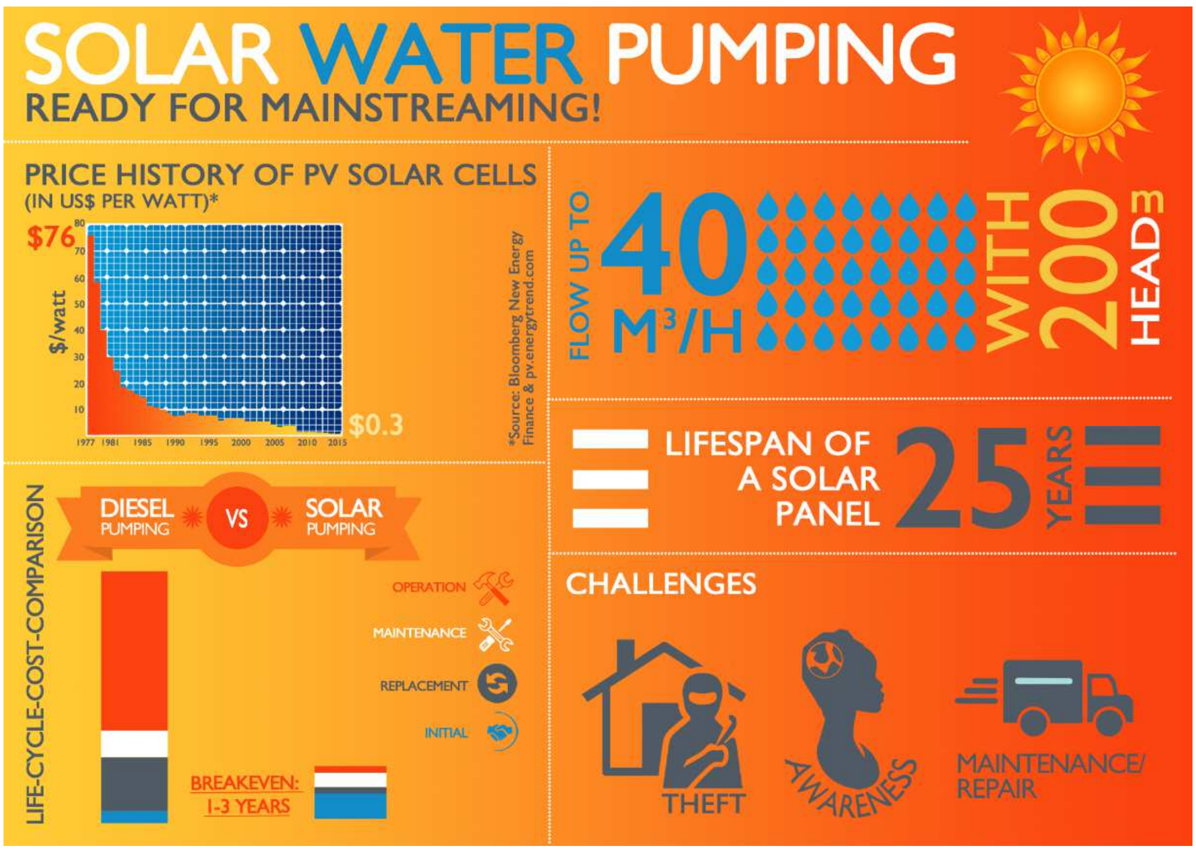


Figure 6: A summary of factors affecting solar water pump market.[33]

In developing countries, the agricultural sector presents an enormous opportunity for the solar water pump market. In rural areas, where farmers face erratic fuel prices, inconsistent access to the electric grid, and the desire for more environmentally sound solutions, solar pumps offer a great alternative to the traditional electric and diesel pumps. The most significant growth of the market has occurred in the Asia Pacific region, accounting for 40% of market share in 2017.[34] The top markets in this region include India, China, Bangladesh, Japan, and Pakistan, where there has been the rapid expansion of agricultural activities and demand for power consumption while lacking reliable power generation and infrastructure needed for irrigation and community water supplies. Government initiatives have also helped advance the market through the promotion of sustainable development and the adoption of solar photovoltaics. For example, India has set a target to deploy 100,000 solar pumps by 2020, with Bangladesh targeting 50,000 by 2025.[35] Market Research Future forecasts that the region will continue to lead the market for solar water pumps through 2023.[36]

Africa and the Middle East are two other major markets for solar water pumps, where there has been an increased water demand for irrigation and community water supplies as well as a growing trend towards moving away from fossil fuels. Kenya, Morocco, Namibia, and Nigeria are all driving the growth in this region.[37] The North American and Europe markets are also expected to continue to grow as consumer awareness increases around the technology and the environmental advantages it provides over traditional pumps.

The first solar pumps were introduced in the late 1970s and used centrifugal pumps powered by DC/AC motors with a range of 25 to 35 percent hydraulic efficiency. These had limited performance and could only be used for shallow, low water demand installations. Second generation systems introduced positive displacement pumps that are able to achieve hydraulic efficiencies of 70 percent. Current technology has begun utilizing electronic systems that increase output power, performance, and overall efficiency.[38] There have been significant advancements in the field of controllers, allowing for control of the pump speed, monitoring for storage, as well as maximum power point tracking technology. Advancements in reliability and efficiency are expected to drive continued growth in the market, specifically in more rural areas as the prices continue to decline.

Barriers to Adoption of Energy Efficient Solar Water Pumps

Despite significant market growth in the past decade, there are still significant barriers to the widespread adoption of energy efficient solar water pumps. Barriers include: (1) relatively high cost of initial investment; (2) energy subsidies; (3) lack of education; and (4) concerns over the quality of products. However, overcoming these barriers offers a significant opportunity for cost savings and reduction in GHGs. "In India, it is estimated that 5 million solar pumps can save 23 billion kilowatt-hours of electricity, or 10 billion litres of diesel fuel, resulting in the emissions reduction of nearly 26 million tonnes of CO_2."[39]

Relatively High Costs of Initial Investment and Financing

Access to financing continues to be a significant barrier to the wide-scale adoption of solar water pumps for small-scale farmers. These farmers often lack the capital needed to make the initial investment or are unaware of different financing options available. Many institutions lack the expertise to evaluate the credit risk for small-scale borrowers and have typically viewed investments in solar powered irrigation systems as high risk. Pre-conditions in many subsidy or loan programs inadvertently disqualify small farmers by requiring proof of land ownership, collateral, or proper registration with government ministries.[40] Microfinance institutions have tried to fill this critical funding gap, but often end users are unaware of the programs or funding vehicles available to them. Due to difficulty in securing financing as well as the high initial cost, many farmers prefer diesel power pumps, despite the higher long-term operations and maintenance costs.

In most cases, when the government does provide assistance to reduce the upfront costs of SWP for the end users, it is usually for large systems.[41] To better assist small-scale farmers, there is a need for both governments and financial institutions to take into account the current demand for SWPs and the lack of available financing options for smallholder farmers. In late 2015, while working to facilitate solar pump financing in Kenya through the Kenya Smallholder Solar Irrigation Project (KSSI), Winrock International could only identify one financial institution (FIs) with an existing loan product designed for smallholder farms. The majority of the applications for this product were rejected, due to perceived high credit risk. Interviews with a number of FIs showed that if classified as an agricultural loan, the majority of smallholder farmers would not be able to meet the necessary conditions to qualify. Annual interest rates are typically around 22% with a 20-30% down payment, with some requiring additional crop and credit insurance. Winrock noted, "FIs acknowledged the high demand for solar pumps from their clients but were hesitant to enter the market because of uncertainties about supply, performance, and cost of solar pump products." In an effort to develop a solar pumping financial product, Winrock provided farm-level data showing payback periods of one and half years or less and suggested offering the solar pump loans as asset financing, which carries less risk and typically requires less collateral. Winrock also provided technical training of FI management and branch loan offices.[42]

Key takeaways from the KSSI program included: co-guarantees in group lending can help ease some of the collateral requirements but require 3+ months of lead time; solar pumps offered must match the requirements of the smallholder and accessories (pipes, water tanks, irrigation drip kit) should also be available on credit; and aggregation offers economics of scale for service providers and provides the opportunity to reach thousands of more farmers. As more data is collected on pay back periods, this provides a greater opportunity to work with FIs to develop financing products that are designed for small scale farmers and offers the products required to meet their irrigation needs, as well as providing clear evidence for farmers that the up-front investment is worthwhile.[43]

Energy Subsides

Government policy and regulations can also affect the economic viability of solar water pumps. Energy subsidies designed to keep diesel and/or electricity artificially low, results in longer payback periods for solar water pump systems, and disincentivizes the adoption of renewable energy sources over fossil fuels. For example, Pakistan does not subsidize diesel or electricity and sees significantly shorter payback periods compared to Bangladesh and India, who do provide energy subsidies.[44] It should be noted, that in 2018 the Gujarat government introduced a piolet program, the Suryashakti Kisan

Yojana (SKY), where central and state governments will subside sixty percent of the installation costs to enable over 12,000 farmers across 33 districts to generate solar power to both irrigate land and sell surplus power back to the grid.[45]

Education

There is a significant need for both educational awareness around the benefits of solar water pumps and their daily operation and maintenance, as well as training of qualified professionals to install and service the pumps. Despite the recent advancements in technology and falling prices, a major barrier is that there are still many misconceptions regarding the cost and reliability of renewable technology. The adoption of solar water pumps is still limited in rural areas, so many farmers have never seen them before and require a live demo to believe that solar can provide sufficient energy to power a pump, adding overhead costs to the manufacturers and distributors.

Beyond lack of awareness, many farmers lack the knowledge required to determine the pump specifications such as size, type, and water requirements that would best fit their needs, as well as opportunities to identify cost-saving measures.[46] While solar water pumps require significantly less maintenance and upkeep compared to diesel pumps, shown in Figure 7, solar water pumps require expertise for both installation and service, if needed. Well-trained service professionals are hard to find, especially in more rural areas. If the systems were not designed or installed properly, farmers are likely to abandon the technology for traditional electric or diesel pumps, despite the potential cost savings.

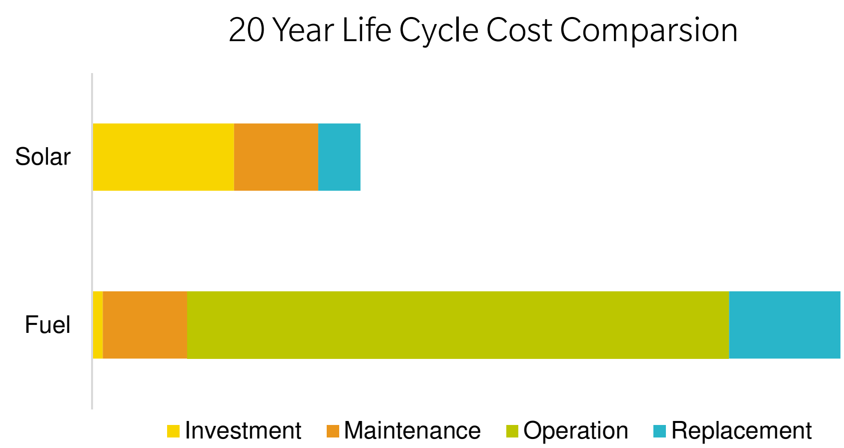


Figure 7: Pump cost comparison[47]

Quality Concerns

Because it is a relatively young market, many end users do not have easy access to distributors for replacements parts or have concerns regarding quality assurance. This contrasts with the mature market of diesels driven motors, where replacement parts and technicians are more prevalent and cheaper. As more manufacturers have joined the marketplace, many local and regional vendors are offering lower quality products at a lower price point. This can result in malfunctioning parts impacting the efficiency or life of the system and potentially cause increased concern around the adoption of solar water pumps in rural areas. A TWG member noted that in countries where there are guideline policies in place that would be suitable to SWPs, they are mostly tailored for solar home systems (SHS) and mini-grids. There is a critical gap in international standards for quality assurance of solar water pumps and an area where LEIA could play a significant role. Shared definitions and standards around product quality and best practices, as well as common language for components and parts, would result in lower transaction costs and increased quality assurance in the market.

3.0 Roadmap Approach

This section summarizes the approach used to identify and prioritize the technology alternatives outlined in the technology roadmap as shown in Figure 8. The approach was based on the Sandia report, "Fundamentals of Technology Roadmapping" and US Department of Energy's (DOE) reports and technology roadmap for next- generation appliances.[4849] For the purposes of LEIA, the roadmap identifies critical technologies, gaps, and best practices to inform R&D investments.

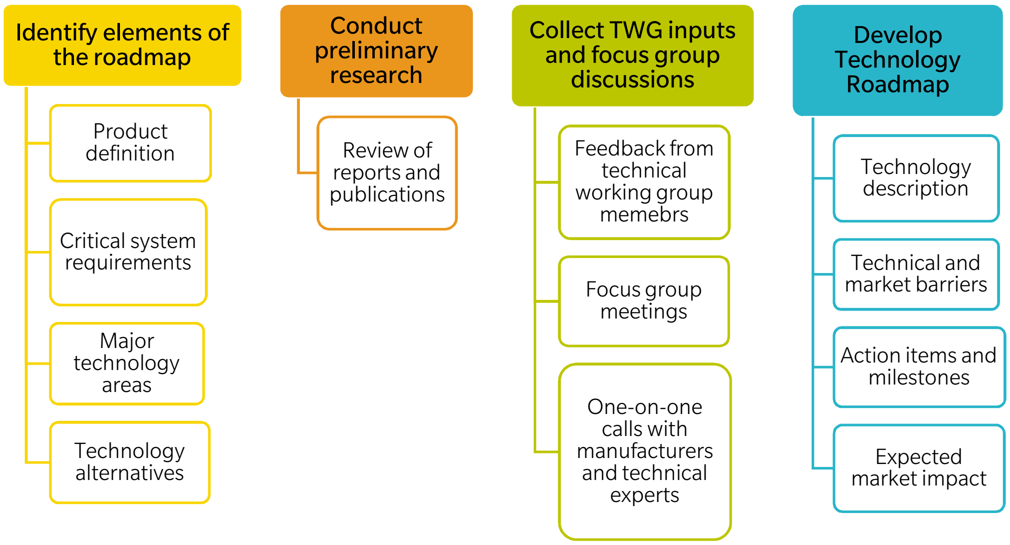


Figure 8: Approach to technology roadmap development for solar water pumps.

Elements of the Roadmap

We identified key elements of the technology through preliminary research and discussions with the technical working group members. The roadmap is not prescriptive, but rather a collaborative plan to help the industry achieve its goals.

Product Definition

Due to variations in performance, a critical first step was defining the solar water pump technology. Research on existing definitions was conducted.

Critical System Requirements

A set of requirements were developed that specify the critical technology parameters. Technical, operational, and environmental requirements were considered.

Major Technology Areas

During a roundtable hosted by the Efficiency for Access Coalition in Nairobi, four focus areas for solar water pumping systems were identified: low cost sensors and controllers due to their impact on technical, operational, and environmental requirements; high efficiency, low cost AC/DC motors to reduce energy consumption and improve efficiency and durability of solar pumps; portable and durable small-scale power systems as a means to increase portability; and improvements to saline water tolerance and filtration. The latter area was given a lower priority and dropped from the roadmap development.

Technology Alternatives

Technology alternatives were identified based on their ability to meet product needs. Several alternatives were researched and discussed with the technical working group members to ensure that the proper technologies were then prioritized for research and development.

Preliminary Research

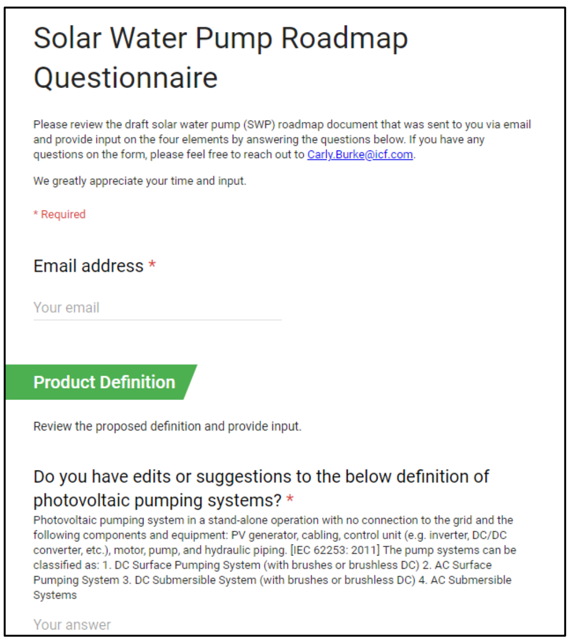
We conducted preliminary research on use cases, market demands, and technologies. We also reviewed existing test methods and requirements to understand targets and parameters. The International Electrotechnical Commission test method defines the requirements for design, qualification and performance measurements of stand-alone photovoltaic pumping systems.[50] Additionally, the Bureau of Indian Standard (BIS) specifies the technical requirements for solar powered water pumps.[51] These two test methods were analyzed and compared and a brief note was shared with the CLASP team.

We also conducted desk research on reports, case studies, product information and published papers that exists on solar water pumps. This includes publications from the World Bank, academic institutions, non-profits, and donor funded programs.

Technical Working Group Inputs and Focus Groups

In May 2018, the solar water pump technical working group held its first meeting. The Low Energy Inclusive Appliance program was introduced, along with the objectives of the technical working group: to develop a technology roadmap; and identify and prioritize R&D initiatives that will accelerate the development and commercialization of emerging technologies. Members provided feedback on available test methods, lab capacity and testing, and common use cases.

The second meeting was held in July 2018, which reviewed the key elements of the solar water pump technology roadmap. Members were asked to review and provide input on the definition, system requirements, technology areas, and drivers. A questionnaire was developed to simplify and encourage feedback from members as shown in Figure 9, below. The questions were broken up into six sections: (1) product definition; (2) critical system requirements; (3) major technology areas; (4) technology drivers and targets; (5) additional input; and (6) focus groups. The feedback collected from this questionnaire is explored in further detail below (see *Summary of Feedback).*


Solar Water Pump Roadmap Questionnaire

Please review the draft solar water pump (SWP) roadmap document that was sent to you via email and provide input on the four elements by answering the questions below. If you have any questions on the form, please feel free to reach out to Carly.Burke@icf.com.

We greatly appreciate your time and input.

* Required

Email address *

Your email

Product Definition

Review the proposed definition and provide input.

Do you have edits or suggestions to the below definition of photovoltaic pumping systems? *

Photovoltaic pumping system in a stand-alone operation with no connection to the grid and the following components and equipment: PV generator, cabling, control unit (e.g. inverter, DC/DC converter, etc.), motor, pump, and hydraulic piping. [IEC 62253: 2011] The pump systems can be classified as: 1. DC Surface Pumping System (with brushes or brushless DC) 2. AC Surface Pumping System 3. DC Submersible System (with brushes or brushless DC) 4. AC Submersible Systems

Your answer

Figure 9: SWP Questionnaire

From August to September 2018, small focus group meetings and individual calls were held to dive deeper into key technology areas, such as power systems; low-cost sensors and controllers; and motors. These small focus groups helped identify technology drivers and gaps for further research in each of the technology areas.

In addition to the meetings and focus groups, there were a number of one-on-one calls to further engage with TWG members on specific topic areas. Feedback and key insights from the discussions are included in Table 3, with overall industry participation reflected in Table 8.

Table 3: Feedback and Key Insights from the One-on-one with TWG Members

One-on-One Calls

• Advanced Equipment Functionality and Information would be beneficial - allows market to more proactively engage and hopefully prevent damage to the system.
• For more wide scale adoption of RMS, would need suppliers to optionally integrate with equipment or third-party companies that are experts in it that could offer the service at economies of scale.
• Experience software issues, specifically with time zones. If you do not have enough power to the pump, it doesn't know what day or time it is, resulting data being generated but the end user is unsure of day/time it was recorded. Output of the monitoring system was not smart enough to determine what data was coming through, and it took time to develop use of more advanced software.
• LEIA could support the industry by developing a standardized communication device, where it is out of the control equipment and have a module that has preapprovals, base communication software, and minimum requirements that every system would give.
• Need technological and agricultural expertise to translate data into information, translate that information into actions for farmers that work towards behavioral change that they can digest. If you can gather additional data that can result in very precise and instructive action, that could be very beneficial to farmers.
• LEIA could push forward hardware so people can collect the data and then could do further research on behavioral change, different types of farming practices that could be impactful in changing practices. Views the role of LEIA as being more of a convener of conversation to see if one day they could take the data to change behavior. Thinks it would be unwise to undertake software development as we do not know enough information yet. LEIA can also assist in creating standards around the data, so it can be aggregated across companies and countries.
• TWG member expressed the idea that LEIA could help with interoperability issues. *A similar sentiment was expressed by TWG members during the third technical working group.*
• Brought up the need for waterproofing. Having multiple connectors into the same box presents more issues than a completely closed box that is separate from connectors.
• Portability is extremely important, and something they believe should be further investigated.
• A reason given for why manufacturers are not switching to BLDC motors is compatibility issues with the current pumps being used.
• An example from one supplier shows the cost to switch from brush to brushless would be $300 but can get up to 10x the life expectancy from BLDC.
• Does not believe R&D is needed for hardware. LEIA could focus on setting up an open source fluid dynamic lab to try different impeller or screw configurations.
• Estimation coming out of China is that 2-3 percent of pumps have BLDC motors, 5-6 percent have brush dc because of the low cost. Most pump manufacturers are using AC. Already relatively low price point for high efficiency, high quality BLDC motors. Motor manufacturers need to see 1 million pieces a year to switch from hand wind to automatic wind. Significant market size relative to where we are today.
• Water quality has a huge impact on the life of the pump. Failures in the field often come from a buildup of debris, essentially running dry. They have seen numerous homemade solutions of nets, trying to stop debris. Similar to diesel pumps, they do not respond well to water movement (waves), so they can only be used when winds are low.
• One TWG member expressed that they view the market in three streams:
  o Cheap and as portable as possible: All you need is a panel and a pump
  o Irrigation in morning/evening to avoid heat of the day: Requires battery
  o Desires continuous pumping into tank: Requires sufficient battery to pump all day
• A lack of understanding of how SWP work and required maintenance is a major obstacle to the adoption of SWP.
  o Challenges to determine which pump is needed/correct sizing. Smaller the system, the more affordable, but end-users often want larger systems for higher flow.
  o The estimated life of the system is often shorter because usage is greater than anticipated. This can be from different reasons, including increased demand as end-users view it as "free energy" so they continue pumping throughout the day. This can significantly alter the lifespan of a brush motor.
• Customers perceive changing flow as an unreliable product.

- Awareness of this technology is probably their greatest barrier. Often time requires in-field demo of a SWP in action for a farmer to believe solar could create the power required to pump water.
- Beyond market trend analysis, TWG member hadn't seen a long-term cost analysis. Could be useful to conduct bomb cost assessment - percentage of the typical solar powered irrigation system is going to what components. Which component has the biggest delta because the min and materials cost. Need to look at materials cost forecasting. It would be useful to include impact of falling PV and inverter/converter prices on the financial analysis and summarized in line with a timeline of action items and milestones.

Table 4: Industry Participation in Solar Water Pump Technical Working Group

Company Name	Feedback on Google Form & Draft Roadmap	TWG Members	1-on-1 Calls
Aptech Africa Ltd	X	X	
Azuri	X	X	
Beyond Wireless			X
Energy Savings Trust (EST)	X	X	
Factor(e) Ventures	X	X	X
Futurepump		X	X
GOGLA		X	
Greenlight Planet	X	X	X
GSMA			X
Khethworks		X	
Lighting Global/ World Bank	X	X	
Lorentz	X	X	X
Mundra Solar Private Limited		X	
Schatz Energy Research Center (SERC)	X	X	X
Simusolar	X	X	X
Strathmore Energy Research Centre	X	X	
SunCulture	X	X	X
Sunny Irrigation		X	
Underwriters Laboratories (UL)	X	X	

As previously mentioned, the key to a successful roadmap is the active participation of industry stakeholders throughout the process. A concern we heard from both those who decided to as well as those who decided not to participate in the technical working group, was that they were hesitant about potentially sharing any information regarding their organization's technology, strategies, or innovations that were not already publicly known. This was particularly a problem during the larger meetings and focus groups. To help mitigate those concerns, there was a shift away from hosting focus groups towards targeted one-on-one calls. This allowed for a deeper dive into specific technology areas as well as creating a more relaxed and personal atmosphere, helping the TWG member feel more comfortable sharing their insights.

The first draft of the technology roadmap was sent to the technical working group members in early November 2018 and were invited to join one of two proposed days for the third working group meeting later in November. Members were asked to review the draft roadmap in advance of the meeting and provide general feedback either during the third working group meeting or via email. Discussion during the meetings focused on technical and market barriers for remote monitoring systems and BLDC motors. Key insights from this meeting included:

- There is a consensus regarding the need for aggregated data on the performance of SWPs, including factors from the field that affect the life of the pump;
- It would be beneficial to work with GSMA and/or the Federal Communications Commission (FCC) to clarify certification requirements and any steps to prevent redundancies;
- There is an opportunity to explore the cross-cutting issue of connectivity options across LEIA working groups;
- Barriers to the expansion of BLDC motors seems to be attributed more to market failures and may be out of scope of this roadmap; and

- There is a need to further explore whether irrigation systems should be included within the scope of this roadmap.

4.0 Technical Working Group Findings

Summary of Feedback

The technical working group's input and feedback was an integral component of the roadmap's development. Below is a brief summary of our findings.

Product Definition

The initial definition proposed to the technical working group members was based on IEC 62253: 2011, "Photovoltaic pumping system in a stand-alone operation with no connection to the grid; having the following components and equipment: PV generator, cabling, control unit (e.g. inverter, DC/DC converter, etc.), motor, pump, and hydraulic piping." The pump systems were classified as DC surface pumping systems (with brushes or brushless DC motors); AC surface pumping system; DC submersible system (with brushes or brushless DC motors); and AC submersible systems.

The majority of the technical working group members agreed that the product definition should be broadened to include solar water pumps that can connect to other inputs versus a stand-alone operation. Specifically, the power conversion module would be capable of receiving inputs from biomass, diesel, mini-grids, microgrids, PV panels, etc. The technical working group members explained that by doing so, the roadmap would be inclusive of a range of popular solar water pumps.

Solar water pumping systems are either configured as a battery-coupled or direct-coupled system. In direct-coupled systems, the electric current generated from the PV panels directly powers the pump, resulting in the movement of water. Since direct-coupled systems can only pump during the day, they are sized to store extra water on sunny days to meet the demand at night or on cloudy days. For battery-coupled systems, electric current generated through the PV panels during daylight charges the battery, providing power to the motor at night or in low light periods. While batteries provide the benefit of consistent pumping no matter the weather, they can result in higher maintenance costs and reduce the overall efficiency of the system since it is the battery, not the PV panels that dictate the operating voltage. Direct-coupled systems are typically used for livestock irrigation, as it is easier and more cost effective to store three to ten days' worth of water than storing electricity.[52] Based on our research and discussions, technical working group members agreed that batteries are not necessary and may increase installation and maintenance costs and negatively affect system's performance and reliability.

For the purposes of this roadmap, a solar water pumping system is defined as, a PV pumping system in operation, may or may not connected to a mini-grid/ microgrid or any other form of renewable energy power supply.

Critical System Requirements

Technical, operational, and environmental requirements were considered. The majority of members agreed that greater wire-to-water efficiency and durability were important technical requirements. Some members also noted that cost efficiency should be included. Most members agreed that a 50 percent minimum for wire-to-water efficiency was sufficient. However, additional research is needed to hone in on the efficiency goal for varying pump sizes. The members agreed that PV modules must be warranted for output wattage, which should not be less than 90 percent at the end of 10 years, and 80 percent at the end of 25 years; and that the whole system including submersible/surface pumps should be warranted for two years. Some members noted that the durability of a solar water pumping system should include the water piping infrastructure.

Regarding operational requirements, the members agreed that easy to use; easy to service; inclusion of spare parts; and portability were important to solar water pumping systems. Additionally, the members identified the following environmental requirements: minimal negative impacts on soil; water table; and crop production and drip irrigation to maximize water usage. Noise pollution was also noted by two members.

Major Technology Areas

The working group members identified the following four major technology areas for the SWP roadmap development document:

- Low-cost sensors and controllers;
- High efficiency motors;
- Power systems; and
- Saline water tolerance and filtration.

In this roadmap, we are limiting our focus on remote monitoring systems, which include low cost sensors and controllers, and high efficiency motors use in SWPs. We recommend conducting further research on power systems and saline water tolerance and filtration in future revisions of the roadmap.

Also, operational requirements such as easy to use, easy to service, availability of spare parts are critical to greater penetration of SWPs, but they were not considered in the limited scope of this technology roadmap. We highly recommend LEIA to conduct further research in these areas to understand issues and solutions related to operation and maintenance requirements of SWPs.

5.0 Technology Roadmap

Overview

This roadmap identifies technology alternatives that, if adopted, could improve the efficiency and performance of solar water pumps used in off- and weak-grid contexts. As discussed in previous section, there are solar water pumps in market that are coupled with batteries to store the generated energy and to be used later by the pump in the absence of sufficient sun light. However, the TWG members and our secondary research provided mixed feedback about such pumps. Research suggested that there could be benefits of using batteries, as it could reduce the cost of system because it may need fewer PV panels. But the disadvantages could include increase in maintenance cost and decrease in system's performance and reliability. Therefore, battery-coupled SWPs are not considered in the product definition of this roadmap.

The roadmap explored two technology areas: (1) low cost sensors and controllers; (2) high efficiency motors.

The following is provided for each priority technology alternatives identified for each of the technology areas identified in the previous section:

- Description
- Technical Barriers
- Market Barriers
- Timeline and Milestones
- Expected market impact

Remote Monitoring Systems (RMS)

Description

Remote monitoring systems (RMS) allow manufacturers and service providers to remotely manage, service, and analyze solar water pumping systems, thus addressing one of the challenges associated with systems installed in isolated and remote locations. These systems can perform predictive maintenance, track system failures, and communicate directly with end-users to schedule maintenance.

Higher asset utilization is strongly correlated with higher end-user repayment rates. By continuously capturing in-field performance and usage metrics, manufacturers can engage end-users to encourage behavior that maximizes the system's performance. Water usage and crop yield can be maximized by deploying soil sensors and analyzing weather-related information. RMS also have features to protect the solar pump from dry running, over/low input voltage, over current and overload protection, and reverse polarity etc.[53] Not only do these systems contribute to the existing solar water pump's performance and end user experience, but they also help manufacturers improve their design and specifications for future products. An example of a pump with remote monitoring system is shown in Figure 10 and Figure 11, below.

Figure 10: Futurepump's SF2 pump offers built-in GSM monitoring systems[54]; Lorentz P2 pump offering built-in CONNECTED infrastructure[55]

Basic Components of RMS and its Usage

Expansion of telecom services in rural areas has helped monitor and control solar water pumping systems remotely. RMS, which are mostly used to monitor the system voltage, current, and power, typically consist of; level controllers; basic hardware consisting of relays, integrated circuits, and power electronic components; and a communication module (Global System for Mobile Communications/General Packet Radio Service [GSM/GPRS]) that communicates with a host machine, or back-end applications. In some cases, RMS also have provision for other sensors and controllers, such as soil moisture sensors and flow sensors. RMS provide useful information to manufacturers and end-users such as geographical location, solar system voltage, current, power generated, usage, and total water output. A block diagram of a typical RMS is shown in Figure 11.

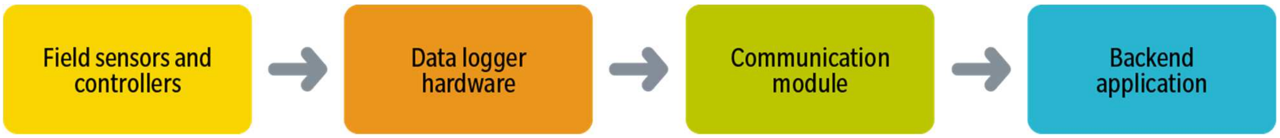


Figure 11: A basic block diagram of a remote monitoring system.

Typical hardware of an RMS includes a microcontroller chip, a GSM/ GPRS module, a Bluetooth module (optional), and RS 232 interface. The microcontrollers are interfaced with different sensors for controlling different applications. The RMS is mainly used to do the followings:[56]

1. Remote monitoring
    a. System voltage, current, power
    b. Data from sensors (pressure sensor, soil moisture sensor, etc.)
    c. Status of irrigation valves
    d. Status of pumping equipment
2. Control
    a. Opening and closing of irrigation valves
    b. Turning on and off of the pump
3. Information transfer and communication
    a. Automatic incorporation of environmental data into decision support system and crop models
    b. Real time weather and operational information
    c. Text, graphical, and voice and video messages
4. Equipment tracking
    a. Coordinates of irrigation equipment etc.

Depending upon the field requirements, a Bluetooth based solution or GSM based solution is typically used in RMS for agricultural purposes. The Bluetooth based solution eliminates the usage cost of network to a great extent but its range of operation is limited to a few meters. Interferences is also a problem in Bluetooth based RMS. GSM based solution are preferred for RMS since the penetration of mobile networks has significantly increased in the rural areas. Manufacturers have also used GSM-Bluetooth combination for remote monitoring. In such system, GSM is used for remotely monitoring and controlling the devices via mobile phone over GSM network and Bluetooth is used for controlling and communication with components within a range of few meters.

RMS has also enabled the spread of pay-as-you-go (PAYG) financing, as seen with mobile phones[57], solar home systems and more recently for SWPs. As previously discussed, affordability is one of the largest if not the largest barrier to adoption of SWP for small-scale farmers, and the spread of PAYG and RMS offers a huge opportunity in the SWP market. The ability of the provider to be able to remotely activate and/or deactivate the device based on the end-user's payment reduces the risk of both default and theft, allowing for more pumps to be distributed through credit. With PAYG, consumers typically pay a fixed amount upfront and then smaller, more flexible payments. Specific payment conditions and requirements varies depending on the PAYG provider. The flexibility in payment options allows customers who once would not qualify for credit, to not only be able to access financing, but also build a good credit history.[58] A number of SWP manufactures, including SunCulture and Futurepump, are already using remote monitoring through the integration of a third-party software.

Technical and Market Barriers

While remote monitoring systems can potentially provide a number of benefits to the end consumers, distributor, and manufacturers, they are not very prevalent in the market. One of the reasons is that these are new and there is not a long history of these being used, even among developed farmers or markets.[59] In the past, RMS are mainly used for research and technology monitoring and demonstration purposes. There are still limited providers of this technology and those currently available are not sold in line with solar water pumping systems. This requires the supplier/distributor to find a compatible product and integrate it themselves, requiring expertise and added overhead costs. Some of the other technical and market barriers for RMS are described in the Table 5 and Table 10, below.

Table 5: Technical Barriers – Remote monitoring systems

Technical Barrier	Description
High initial cost	Remote monitoring systems have a high initial cost. This is because of the significant initial investments made by the manufacturers for the software and hardware development for RMS. As RMS are new to the market, there is skepticism from the end-users whether the high is worth the investment, despite the potential benefits, specifically from the integration with irrigation.
Limited availability of standardized RMS hardware products and interoperability issues	Standardized hardware products for RMS are not readily available. Third party RMS hardware boards are sometime not compatible with manufacturers' design. Integration of different hardware boards in the system is difficult. Standardization could help.
Software and agricultural practices integration	Not all manufacturers have in-house capacity to develop software programs for RMS that are design to improve irrigation practices or guide end-user's behavior. There are third-party software/applications for RMS available in the market. However, they lack in the integration of software with irrigation practices. There is a lack of coordination and discussions between technological (software experts) and agricultural/ farming experts, and hydrology experts. This is much needed to translate data collected by RMS into information, which will help guiding farmers to take right actions for increasing their productivity and income. Open source software programs and modules could help further innovation in this area.
Data Privacy	Remote monitoring offers numerous benefits as addressed in this section but as more information is collected and transmitted across networks, data privacy becomes of greater concern. As is in any circumstance where data is being collected, there is the possibility that a bad actor will try to access and use that data for unintended purposes. That concern grows as vast amounts of data are being shared and/or stored on cloud platforms. Standards or regulatory frameworks around handling and storing user's data could provide clarity and prevent misuse.

Table 6: Market Barriers - Remote Monitoring Systems

Market Barrier	Description
Cost of global certification for communication modules	GSMA and FCC certifications require significant upfront investments from manufacturers and therefore increase the cost of communication modules for RMS. For example, a globally approved 3G module may cost 10 to 15 times more compared to an unapproved module.[60]
End-user marketability	End-users are reluctant to pay the additional costs for RMS and sensors as the added value is not clearly perceived by them right now.

Timeline and Milestones

Table 7 identifies action items and milestones that will help in removing the technical and market barriers resulting in greater adoption of RMS technology by SWP manufacturers and end-users.

Table 7: Summary of Research and Development Milestones

Near-Term (1 – 3 Years)	
Action Items	Milestones
Work with manufacturers and distributors to collect more comprehensive data on use cases for solar water pumps.	Although, at this stage, this action item doesn't have a direct link to technical innovation and R&D, this could lead more R&D as we will understand more about the use cases of SWPs and associated issues. The milestones could be: • Select manufacturers and distributors for a use case identification study • Select pump types and features • Select geographies and sites • SWP installation • Data collection and monitoring • Data Evaluation • Stakeholder discussions • Identification of technological innovation and R&D action items • Publish findings
Standardization in data collection through RMS. This will help in aggregation of data across the companies and geographies. While we propose to collect a minimum set of data related to the performance of SWPs, we do not propose to collect any consumer data or any other data that might give advantage to one manufacturer over others. Raw data collected must not be shared or published. Only the analysis and results of aggregated data should be disseminated. Careful consideration on data sharing and publication must be given when developing the data collection roadmap.	• Identify key metrics and parameters, definitions, and formats for data collection • Prepare and publish standard protocols • Identify interested manufacturers, non-profits, research institutions, and associations • Demonstration of benefits of standardized data collection • Develop roadmap for ongoing data collection, analysis, and results dissemination

Mid-Term (3 – 5 Years)	
Action Items	Milestones
Explore an open source platform/ simulation lab to perform simulations and designs for SWPs.	• Define requirements in consultation with TWG members • Collaborate with research or academic institution • Prepare an expression of interest document • Select technology supplier • Platform testing and demonstration • Platform launch

Key Stakeholders

Table 8: Key stakeholders for remote monitoring systems

Key Stakeholders	Roles and Responsibilities
Manufacturers and Distributors	• Technical and field inputs/ support • Participation in pilots and demonstrations
Research and Development Organizations	• Technical inputs and research support • Scientific evaluation
Groupe Spéciale Mobile Association (GSMA)	• Inputs for certification requirements • Confirmation of design
Independent laboratories	• Validation and testing

Expected Market Impact

Remote monitoring systems can have a significant impact on the SWP market. RMS can help empower farmers and other end-users with real time information and guidance on farming practices, water usage, soil conditions, crops, and weather conditions. All of these are critical to the efficient use of SWPs, optimization in water drawn from the source, and improved productivity and income of end-users. The RMS also helps manufacturers/distributors to remotely collect critical data about the performance of the SWP resulting in better maintenance and preventive services. This reduces the downtime of the system for service and repair and increases the end-user's confidence in technology. In addition to the above, the data collected by manufacturers to learn about their customer is of tremendous value. This could help in improving their product line and increase more services based on end-users' needs. The data can also be used and leveraged with third parties for many other purposes, including other social impact programs. The data can also be used by investors, technology sponsors, and local FIs to track asset's performance, program/ technology impact, and risk mitigation.

Since the SWP market is in a nascent stage and growing in developing countries, SWPs with integrated RMS have the potential to transform the market. If the information collected through RMS is able to be aggregated across regions and sectors, that data has the potential to inform policies and best practices for a more efficient usage of solar water pumps. Finally, any technology improvements in RMS would also be leveraged in other off-grid application for RMS such as refrigerators and solar-home systems.

Brushless DC Motors

Description

The motor is a critical part of a solar water pumping system. Typically, AC and DC motors are used. AC induction motors operate using the principle of electromagnetic induction to produce a motor torque. The stator and rotor make up the two primary motor components, as shown in Figure 12.

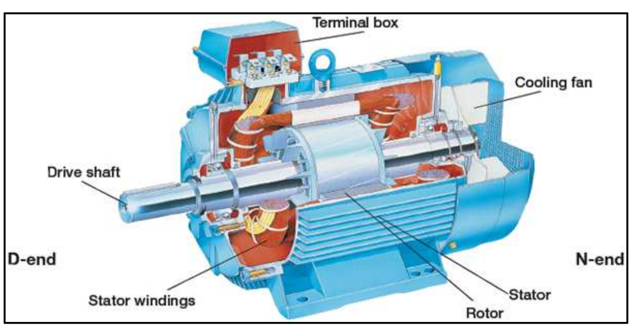


Figure 12: Key components of an AC induction motor.[61]

The drawback of using brushed AC and DC motors in pumps is efficiency losses, which include resistive losses in the stator or rotor, hysteresis and eddy current losses in the stator's steel laminations, an also losses resulting from friction in the bearings and shaft seals.[62]

AC and DC motors also need regular maintenance because of commutator and brushes. Brushless DC (BLDC) motors require less maintenance and provide high output torque resulting in higher efficiency of the motors. BLDC motors are also called permanent magnet motors or electronically commutated motors (ECM).

BLDC motors are more efficient than alternatives for a variety of reasons. Their power consumption is lower compared to induction motors because they do not require current to be induced in rotor windings. The elimination of brushes contributes to increased efficiency, reliability, and durability of these motors. BLDC motors are ideal for use in applications with varied loads such solar water pumps because they have either integrated controls or are paired with drives. Efficiency of permanent magnet motors tends to be constant over a range of speeds instead of a high peak efficiency at a single speed.[63] A simple comparison of AC and DC electrical motors used in SWPs is provided in the Table 13.[64]

Table 9: A simple comparison of electrical motors used in SWPs

Feature	AC Induction Motor	Conventional DC Motor	BLDC Motor
Mechanical structure	Stator has windings and AC lines are connected to the stator	Field magnets on the rotor and stator are made up of permanent magnet or electromagnet	Field magnets on the rotor and stator are made up of permanent magnets
Efficiency	Low – losses in both rotor and stator	Moderate – losses in the brushes	High – no losses in the brushes
Maintenance	Low maintenance	Periodic maintenance because of brushes	Low or no maintenance
Speed torque characteristics	Nonlinear	Moderate loss in torque at higher speed because of losses in brushes	Flat – no losses in the brushes
System cost	Low	Low	High – because of controller requirement

As per a TWG member who is also a leading SWP manufacturer, the SWPs with BLDC motors have observed significant efficiency improvement over standard AC induction motors. At 100% loading, the BLDC motors observed 20 to 30 percent peak efficiency improvement over standard AC motors. Table 10 provides observation in water delivery from SWPs with BLDC motors compared to a similar size pump with high efficiency AC induction motor.

Table 10: Water Efficiency Comparison between SWPs with BLDC and AC induction motor[2]

Day Condition	Water output
Perfect solar day	36% more water
Cloudy day	60% more water
Overcast day	1,460% more water

A typical BLDC motor construction is shown in Figure 13, below.

[2] The data in the table is provided based on information shared by a TWG member for a couple of SWP models tested under specified day conditions and may not represent the water efficiency comparison between SWPs with BLDC and AC induction motor for all types of pump configurations.

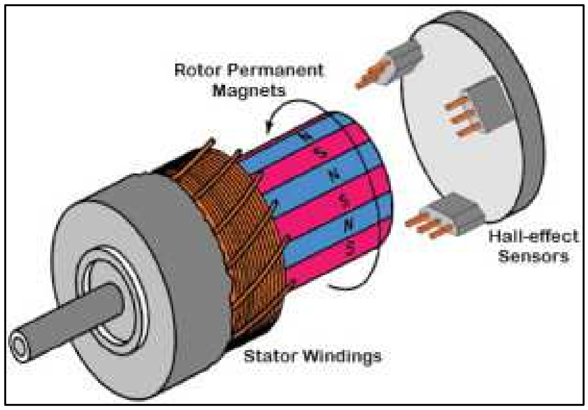


Figure 13: BLDC motor construction.[65]

BLDC motors require sensors, Hall-effect sensors[3], for electronic commutation, which increases the complexity of the design of BLDC motors. Recently, manufacturers have developed sensorless BLDC motors and eliminated a few of these drawbacks. Some vendors provide drive systems for BLDC motors, which do not need a hall sensor for determining the position of the rotors. Sensorless BLDC motors are expected to be one of the major trends in the global motors market in coming decades.

Motors are the second most expensive component in SWPs after the PV panels. Because of their high initial cost, BLDC motors are not preferred by pump manufacturers, although, because of relatively low maintenance and longer life, they tend be cheaper over the life of the pump. As per discussion with the TWG members, only 2% to 3% of pumps currently available in the market use BLDC motors; most of them use AC induction motors.

Technical Barriers

Table 11 and Table 12 identifies technical and market barriers for adoption of BLDC motors by SWP manufacturers.

Table 11: Technical Barriers – BLDC Motors

Technical Barrier	Description
High initial cost of BLDC motors compared to traditional technologies (AC induction motors)	The current cost of BLDC motors is higher compared to traditional AC induction motors and will need to be decreased for wider adoption in solar water pump market.
High cost and limited availability of scarce rare-earth metals used for permanent magnet	There are supply issues for rare-earth metals, which provide the magnetic material for the motor. Research and investment for possible alternatives to rare-earth metals will ensure that high efficiency motor options remain cost-effective and that alternatives are available if rare-earth metals become scarce.
Lack of research in lower-cost manufacturing techniques for motors	The US DOE observed that there is a need to continue research and develop lower-cost manufacturing techniques so that motors of all types and variable speed drives can be produced as cheaply as possible. For BLDC motors to be cost competitive, they must be simple to manufacture, in addition to having the material composition be inherently less expensive. Addressed further in the Table 17 below, there should be close collaboration with motor manufacturers to identify the greatest savings opportunities.

[3] For more information on the hall-effect https://sensing.honeywell.com/hallbook.pdf

Market Barriers

Table 12: Market Barriers – BLDC Motors

Market Barrier	Description
Low demand for BLDC motors	Currently, the demand for BLDC motors from solar pump manufacturers is low. Motors manufacturers need to see a significant demand to supply BLDC motors to SWP manufacturers at lower cost points.
Feasibility of retrofitting high efficiency motors	Field retrofits of high efficiency BLDC motor in existing pumps where AC or DC motor is used are unrealistic. Motor-related energy savings can be attained only through manufacturer by integration of BLDC motors in new pumps.
Limited availability of service and repair for BLDC motors in rural areas.	BLDC motors are relatively more reliable and require lesser maintenance and repair. However, the service and repair of BLDC motors in rural area is not easy available. There is a perception among local distributors and farmers that if they choose to buy a BLDC motor driven SWP and if it requires maintenance or service for some reasons, then it would be relatively expensive and the down time could be long.

Timeline and Milestones

BLDC motors usage is not limited to solar water pumps and they are used in many other applications including, fans, compressors, and industrial processes. There is a significant amount of research and development already in progress for these motors in the motors industry. Also, BLDC motors are a well-established technology, having been around for a good number of years. Sensorless control is also something that has been more or less driven to a commodity. TWG members and our research suggested that the challenge in case of BLDC motors is not really technology development, but how to develop awareness and encourage manufacturers to take up a solution which although currently more expensive, offers very significant benefits in performance, efficiency, reliability and total cost of ownership in the long run. Nevertheless, Table 17 identifies a few action items and milestones that will help in removing the barriers for greater adoption of BLDC motors by SWP manufacturers.

Table 13: Summary of Research and Development Milestones

Near-Term (1 – 3 Years)	
Action Items	Milestones
Low cost sensorless drive development for BLDC motors Research and Identify low cost BLDC motor manufacturing techniques	Since BLDC motor is a cross cutting technology, used in a variety of applications, we would encourage LEIA to take it up as a cross-cutting issue and propose a separate research piece needed to substantiate the state of development of the BLDC motors. As a next step, we would recommend to collaborate and discuss with motors manufacturers, who were not part of the SWP TWG, to identify additional actions items and specific milestones for the two action items.

Key Stakeholders

Table 14: Key stakeholders for motors development for SWPs

Key Stakeholders	Roles and Responsibilities
Research and Development Organizations	• Determine techniques of low cost motor manufacturing and sensorless drive development • Scientific evaluations
SWP and Motor Manufacturers	• Technology roll-out, pilot demonstration, technical training
Test Laboratories	• Validations and testing
Distributors	• Sales, product demonstration, education and awareness

Expected Market Impact

Farmers can benefit tremendously by having BLDC motor driven solar water pumps. They will have lower ownership cost because of low or no service and maintenance requirements and longer life of the system, higher efficiency of system because of low losses in BLDC motors, and increased productivity due to higher water output in varied weather conditions. Manufacturers and distributors will also benefit because of system's increased reliability and lesser service needs.

Also, as explained above, BLDC motor is a cross cutting technology and used in range of products used in off-grid areas including refrigerators and flour mills. A Global LEAP analysis suggested that use of BLDC motors in off- and weak-grid applications could cut energy consumption by 50%.[66]

6.0 Summary and Recommendations

Summary

In 2017, the Low Energy Inclusive Appliances (LEIA) program was introduced by the Efficiency for Access Coalition, coordinated by CLASP and the UK's Energy Savings Trust, with the goal to double the efficiency and halve the cost of a suite of appliances well-suited for energy access contexts. Solar water pumps were one of the near-to-market products identified because of the enormous potential for agricultural productivity. Cost reductions for SWPs has the potential to make modern irrigation accessible for nearly 500 million small-scale farmers.

Efficiency for Access hosted the first Global Market Development Roundtable in Nairobi in April 2018, bringing together industry leaders to discuss the opportunities and challenges facing the solar water pump market, setting priorities for the coalition, and identifying potential focus areas for this technology roadmap. These topics included: promotion of R&D in low cost sensor development; advancements in low cost motors; portable and durable small-scale power systems; and improvements to saline water tolerance and filtration. The SWP TWG was convened from May 2018 to April 2019, where they participated in three working group meetings, focus groups, and a number of one-on-one calls. Discussing the focus areas identified during the roundtable in Nairobi, TWG members helped identified the key technologies, RMS and BLDC, that were focused on in this roadmap, as well areas for additional R&D.

Remote Monitoring Systems (RMS)

Remote Monitoring Systems, which include low cost sensors and controllers, were identified as a key technology that has the potential to improve the efficiency and performance of solar water pumps in weak or off-grid environments. RMS provides manufacturers and service providers the ability to remotely manage, service, and analyze solar water pumping systems. The ability to remotely monitor a system, including the ability to turn the service on or off, addresses some of the biggest challenges associated with systems installed in isolated or remote areas. These systems can perform predictive maintenance, track system failures, communicate directly with end-users, and by continuously collecting in-field performance and usage metrics, manufactures are better able to engage with end-users to encourage behavioral change regarding water usage and irrigation methods. RMS has also enabled the spread of PAYG financing, making credit available to those previously who would be unable to qualify.

While RMS offers numerous benefits to the end user, distributor, and manufacturer, they are still not prevalent in the market. Technical barriers identified include: high initial costs and skepticism on whether the added cost is worth the investment; limited availability of standardized RMS hardware and interoperability concerns with third party providers; lack of coordination between software experts and agricultural and hydrology excerpts to translate the collected data into actionable information; and concern over data privacy. Market barriers include the cost of global certification for communication modules, and the end-user's marketability as the added value is not clearly perceived. Action items that were identified are: work with manufacturers and distributors to collect more comprehensive data on use cases for SWPs; standardization of the data collected to assist with aggregation across companies and geography; develop open source software programs and modules for RMS in close consultation with agricultural and farming experts; and explore the possibility of an open source platform or simulation lab to test SWPs simulations and designs. The data that RMS collects has the potential to inform policies and best practices designed to encourage efficient usage of SWPs.

Brushless DC Motors (BLDC)

The second key technology identified that could improve the efficiency and lower the cost of SWPs was high efficiency motors. After PV panels, motors are the most expensive component of SWPs. BLDC motors require less maintenance and are more efficient than typical AC and DC motors and is used in a range of products in off-grid contexts. Data provided by a TWG member who is also a leading SWP manufacturer, shows SWPs with BLDC motors at 100% loading, observed 20 to 30 percent peak efficiency improvement over standard AC motors. BLDC motors require less power consumption; the elimination of brushes increases efficiency, increased reliability and durability of the motors; they are ideal for varied loads because of the integration of controls or paired devices; and the efficiency of permanent magnet motors tends to be constant over a range of speeds.

Despite the known benefits of BLDC, only 2% to 3% of pumps currently available in the market use BLDC motors, with the majority using AC induction motors. Technical barriers preventing further adoption include: high initial cost of BLDC motors in comparison to traditional AC induction motors; the high cost and limited availability of scarce rare-earth metals used for permanent magnets; and a lack of R&D into lower-cost manufactures techniques for motors. Market barriers include low market demand for BLDC motors, questions regarding the feasibility of retrofitting deployed pumps, and the limited availability of service providers in rural areas. The near-term action items identified in this roadmap are low cost sensorless drive development for BLDC motors and to conduct further research to identify low cost BLDC motor manufacturing techniques. TWG members and our research suggested that the main challenge in the case of BLDC motors is not technology development, but rather how to develop awareness and encourage manufacturers to take up a solution which although currently more expensive, offers significant benefits in performance, efficiency, reliability and total cost of ownership in the long run. For this reason, we recommend LEIA to take up BLDC motors as a cross-cutting issue and propose engaging with motor manufacturers to develop an additional research piece to substantiate the state of development of BLDC motors.

Recommendations for Further Research

While performing research for this roadmap, a number of topics were discussed and investigated due to their potential impact on the efficiency, cost and durability of SWPs. Below are areas where we believe additional research would be beneficial in driving the SWP market.

Connector and Couplers

One aspect of SWPs that TWG members raised was the increasing desire for more portable and durable solar systems. A key component of portability is the solar pump connector. A TWG member who is also a leading pump manufacturer, mentioned they are currently looking into developing a better, simpler connector that is waterproof and designed to be removed frequently. Many connectors on the market today requires a soldering connection or crimping tool which is difficult to release and prone to breakage. Recognizing the potential impact that more durable, waterproof connectors could have, we attempted to engage a number of manufactures for their participation in the TWG, however was unsuccessful. We recommend further R&D into potential improvements of solar pump connectors and the potential impact on the market.

Saline Water Tolerance and Filtration

One area of design that is often overlooked by manufacturers is saline water tolerance and filtration as it does not directly influence the efficiency and costs of SWPs, despite the impact is can have on maintenance and repairs. If there is too much debris in the water, the pumps can become clogged causing the system to stop working or require servicing. TWG members shared their personal experiences both in the field and talking to farmers on how water quality continues to be a major concern. One member noted that in their experience, farmers will create make-shift nets to prevent the debris from entering the pump. When pumps are unable to draw water to power the system due to the water quality, the farmer faces the prospect of loss of income and loss of trust in the product. We recommend further R&D to identify factors in the field that can affect the efficiency and durability of SWPs, including saline water tolerance and filtration.

Behavioral Change and Irrigation Systems

A concern that raised with SWPs is that they will often have the adverse effect of wasteful water usage and over-abstraction of groundwater by end users. One way to mitigate this concern is the adoption of drip irrigation, which shows increases of 100% of water-use efficiency in properly designed and maintained systems. Drip irrigation not only increases water-use efficiency, but also decreases tillage requirements and increases crop yields.[67] Despite the benefits from drip irrigation, it can be extremely difficult to convince farmers to change their behavior, a sentiment underscored by multiple TWG members. We believe there is the opportunity as more data becomes available on the success of SWPs with drip irrigation systems, especially with new data tracking capabilities introduced by RMS, to work with agricultural and hydrology experts to take transform that data into actionable information that can drive behavioral change.

Quality Assurance

As previously addressed in the Barriers to Adoption section, there is a critical gap in international standards for quality assurance of solar water pumps and an area where LEIA could play a significant role. Shared definitions and standards around product quality and best practices, as well as common language for components and parts, would result in lower transaction costs and increased quality assurance in the market.

In-country Barriers

Research and discussions with TWG members suggest that rather than technological shortcomings preventing the adoption of SWPs, it has more to do with in-country barriers, such as existing policies and regulations which continue to impede the market shift, the inability to access financing by small farmers, and lack of service providers in rural or isolated areas. We would recommend further research to explore how best to address in-country market failures on a more global scale.

Access to clean, reliable water sources is critical to human life. About forty percent of the global population relies on agriculture as its main source of income, yet access to water remains an ongoing struggle for many. We believe that with the recommendations identified in this roadmap and further R&D in the areas identified could make SWPs more accessible to millions of small-scale farmers worldwide and help increase their productivity and income.

References

[1] Efficiency For Access. “Low Energy Inclusive Appliances (LEIA) Programme.” Accessed January 7, 2019. https://efficiencyforaccess.org/leia
[2] Chandel, S., Chandel, R., and Nagaraju Naik, M, “Review of solar photovoltaic water pumping system technology for irrigation and community drinking water supplies,” Elsevier 49 (April 2015): 1084-1099.
[3] One-on-one call with a TWG member, October 2018.
[4] Barlow, Roy, McNelis, Bernard, and Derrick, Anthony, “Solar pumping: An introduction and update on the technology, performance, costs, and economics,” World Bank technical paper: WTP 168 (January 1993).
[5] Ibid.
[6] Global Pumps & Spares. “Spare Parts suitable for Johnson Pumps.” Digital Image. Accessed October 25, 2018. http://www.globalpumps.in/johnson-pump-spares.html.
[7] Barlow et al. “Solar pumping: An introduction and update on the technology, performance, costs, and economics.”
[8] Sinton, Christopher W., Roy, Butler, & Winnett, Richard (2001). Guide to solar powered water-pumping systems in New York State, NYSERDA.
[9] Ibid.
[10] Adapted from Galaxy Energy Systems. “Solar Pumping Systems.” Digital Image. Accessed October 25, 2018. http://galaxyenergysystems.in/solar-pumping-systems.html.
[11] World Bank. “Solar Pumping: The Basics.” Last modified May 30, 2017. http://www.worldbank.org/en/topic/water/brief/solar-pumping.
[12] Challahan, Chris and Waterman, Ben, “Solar Water Pumping Basics,” *The University of Vermont,* May 16, 2013. https://www.uvm.edu/vtvegandberry/Pubs/Solar_Water_Pumping.pdf
[13] Ibid.
[14] Ibid.
[15] Gouws, Rupert and Lukhwareni, Thendo, “Factors influencing the performance and efficiency of solar water pumping systems: A review,” International Journal of Physical Sciences no. 7(48) (November 2012): 1-2, https://academicjournals.org/journal/IJPS/article-full-text-pdf/BDC695519286.
[16] Kunen, Emily & Pandey, Bikash & Foster, Robert & Holthaus, Jennifer & Shrestha, Binod & Ngetich, Bernard. “Solar Water Pumping: Kenya and Nepal Market Acceleration,” International Solar Energy Society, in *Solar World Congress 2015,* (Daegu, Korea: International Solar Energy Society,2016).
[17] African Union Development Agency (AUDA). “Agriculture in Africa: Transformation and outlook.” (South Africa, African Union, 2013), 8. Page 8 http://www.un.org/en/africa/osaa/pdf/pubs/2013africanagricultures.pdf
[18] TWG Member, Personal Communication, April 25, 2019.
[19] Bengtsson, Niclas and Nilsson, Johan, “Solar Water Pumping for Irrigation: Case Study of the Kilimanjaro Region in Tanzania,” Minor Field Studies Scholarship Programme, Halmstad University, 2015. https://www.diva-portal.org/smash/get/diva2:822995/FULLTEXT01.pdf
[20] Kunen et al. “Solar Water Pumping: Kenya and Nepal Market Acceleration.”
[21] Graduate Farmer. “Save Big with the New GF1 Solar Water Pump.” Last modified October 30, 2017. https://graduatefarmer.co.ke/2017/10/30/save-big-with-the-new-gf1-solar-water-pump/
[22] SunCulture. “New Solar Powered Water Pump Poised to Transform Agricultural Output.” Last accessed December 19, 2018. www.sunculture.com/press/new-solar-powered-water-pump-poised-to-transform-agricultural-output
[23] Kunen et al. “Solar Water Pumping: Kenya and Nepal Market Acceleration.”
[24] Bengtsson “Solar Water Pumping for Irrigation: Case Study of the Kilimanjaro Region in Tanzania”.
[25] Bengtsson “Solar Water Pumping for Irrigation: Case Study of the Kilimanjaro Region in Tanzania”.
[26] Kunen et al. “Solar Water Pumping: Kenya and Nepal Market Acceleration.”
[27] Holthaus, Jennifer & Pandey, Bikash & Foster, Robert & Ngetich, Bernard & Mbwika, James & Sokolova, Evgenia & Siminyu, Philip. “Accelerating Solar Water Pump Sales in Kenya: Return on Investment Case Studies,” in *Solar World Congress 2017: IEA SHC International Conference on Solar Heating and Cooling for Building and Industry,* (Abu Dhabi, United Arab Emirates: International Solar Energy Society, 2017).
[28] Kunen et al. “Solar Water Pumping: Kenya and Nepal Market Acceleration.”
[29] Engineering For Change. “Product Database.” https://www.engineeringforchange.org/solutions/products
[30] Bengtsson “Solar Water Pumping for Irrigation: Case Study of the Kilimanjaro Region in Tanzania”.
[31] World Bank, “Solar Pumping: The Basics.”
[32] Hartung, Hans and Plusche, Lucie, “The benefits and risks of solar-powered irrigation – a global overview”, Food and Agriculture Organization (FAO) of the United Nations and Deutsche Gesellschaft für Internationale Zusammenarbeit, (2018): VIV, 6. http://www.fao.org/3/i9047en/I9047EN.pdf.
[33] World Bank. “Solar Water Pump: Ready for Mainstreaming!” Digital Image. Accessed October 25, 2018. http://pubdocs.worldbank.org/en/588661492006666777/Solar-Water-Pumping-full.pdf.

[34] QYReserach. ““Global Solar Water Pumps Industry Research Report, Growth Trends and Competitive Analysis 2018-2025.” Last modified August 21, 2018. https://www.qyresearch.com/index/detail/670454/global-solar-water-pumps-industry-research-report-growth-trends-and-competitive-analysis.
[35] Modor Intelligence. ““Solar Water Pumps Market Size - Segmented by Product (DC Surface Suction, AC Submersible, DC Submersible AC Floating), By End User (Agriculture, Drinking Water Industrial), and Geography - Growth, Trends, and Forecast (2018 - 2023).” Last modified September 2018, https://www.mordorintelligence.com/industry-reports/solar-water-pumps-market.
[36] Market Research Future, “Solar Water Pumps Market Research Report – Global Forecast to 2023.” Last modified October 2018, https://www.marketresearchfuture.com/reports/solar-water-pumps-market-3980.
[37] Ibid.
[38] Chandel, et al. “Review of solar photovoltaic water pumping system technology for irrigation and community drinking water supplies.” 1086-1088, 1097.
[39] International Renewable Energy Agency (IRENA). “Renewable Energy benefits: Decentralised Solutions in the Agri-food Chain,” The International Renewable Energy Agency, Abu Dhabi. 2016: 31.
[40] FAO, “The benefits and risks of solar-powered irrigation – a global overview,” 30.
[41] Hartung, Hans and Plusche, Lucie, “The benefits and risks of solar-powered irrigation – a global overview”, Food and Agriculture Organization (FAO) of the United Nations and Deutsche Gesellschaft für Internationale Zusammenarbeit, (2018): VIV, 6. http://www.fao.org/3/i9047en/I9047EN.pdf.
[42] Holthaus et al. “Accelerating Solar Water Pump Sales in Kenya: Return on Investment Case Studies.”
[43] Holthaus et al. “Accelerating Solar Water Pump Sales in Kenya: Return on Investment Case Studies.”
[44] FAO, “The benefits and risks of solar-powered irrigation – a global overview,” 20.
[45] Garg, Vibhuti. “India: Vast Potential in Solar-Powered Irrigation,” (Cleveland, Ohio, Institute for Energy Economics and Financial Analysis, 2018).
[46] FAO, “The benefits and risks of solar-powered irrigation – a global overview,” 25. Ibid, 25.
[47] Bengtsson “Solar Water Pumping for Irrigation: Case Study of the Kilimanjaro Region in Tanzania”.
[48] Garcia, Marie and Bray, Olin. 1997. Fundamentals of Technology Roadmapping. United States: Department of Energy. https://prod.sandia.gov/techlib-noauth/access-control.cgi/1997/970665.pdf.
[49] Foley, K, Goetzler, W, and Sutherland, T. 2014. Research & Development for Next-Generation Appliances. United States: Department of Energy. https://www.energy.gov/sites/prod/files/2014/12/f19/Research%20and%20Development%20Roadmap%20for%20Next-Generation%20Appliances.pdf.
[50] International Electrotechnical Commission. “IEC 62253:2011.” Geneva, Switzerland: International Electrotechnical Commission, 2011.
[51] Bureau of Indian Standard. 2018. WC - Draft Indian Standard on Solar Photo Voltaic Water Pumping Systems — Part 1 – Centrifugal Pumps – Specification, (MED 20(11177)). BIS, http://www.bis.org.in/sf/med/MED20(11177)_19032018.pdf.
[52] Eker, Bülent. “https://www.researchgate.net/publication/268199675_Solar _powered _water _pumping _systems,” in Trakia Journal of Sciences no. 3(7) (2005): 7-11.
[53] Unique Technologies. “Solar Solutions.” Accessed October 25, 2018. http://www.uniqutechnologies.com/productdetails.php?pro_url=solar-solutions.
[54] Futurepump Ltd. “Futurepump’s SF2 pump.” Digital Image. Accessed October 25, 2018. URL https://www.lorentz.de/products-and-technology/products/ps2-solar-pumping-systems
[55] https://www.lorentz.de/products-and-technology/products/ps2-solar-pumping-systems
[56] Purnima, Reddy. “Design of remote monitoring and control system with automatic irrigation system using GSM-Bluetooth.”
[57] Moreno, Alejandro and Bareisaite, Asta. “Scaling Up Access to Electricity: Pay-as-You-Go Plans in Off-Grid Energy Services. (Washington DC, World Bank, 2015).
[58] Walrdon, Daniel and Faz, Xavier. “Digitally Financed Energy: How Off-Grid Solar Providers Leverage Digital Payments and Drive Financial Inclusion. (Washington DC, Consultative Group to Assist the Poor (CGAP), March 2016). http://openknowledge.worldbank.org/bitstream/handle/10986/24566/Digitally0fina00financial0inclusion.pdf
[59] TWG Member, Personal communication, October 25, 2018
[60] TWG Member, Personal communication, October 16, 2018.
[61] Goldberg, Lee. “EV Drive Electronics Evolve to Support Rare Earth-Free Motor Technologies.” Digital image. Digi-Key Electronics. September 26, 2018. Accessed October 25, 2018. https://www.digikey.com/en/articles/techzone/2012/sep/ev-drive-electronics-evolve-to-support-rare-earth-free-motor-technologies.
[62] National Electrical Manufacturers Association (NEMA). “Energy management Guide for Selection and Use of Fixed Frequency medium AC Squirrel-Cage Polyphase Induction Motors.” Rosslyn, Virginia, 2001.
[63] Goetzler, W, Reis, C, and Sutherland, T. 2013. Energy Savings Potential and Opportunities for High Efficiency Electric Motors in Residential and Commercial Equipment. United States: Department of Energy. https://www.energy.gov/sites/prod/files/2014/02/f8/Motor%20Energy%20Savings%20Potential%20Report%202013-12-4.pdf.
[64] Sharma, Pragati, Sindekar A.S. Suitability and comparison of electrical motors for water pump application.” https://www.ijareeie.com/upload/2016/march/26_Suitability.pdf

[65] Agarwal, Tarun. "BLDC Motor Construction." Digital image. EFXKits. August 8, 2014. Accessed October 25, 2018. https://www.efxkits.co.uk/speed-control-of-brushless-dc-motor/3-14/.
[66] CLASP. "Motors." Accessed April 2, 2019. https://clasp.ngo/impact/motors.
[67] Kumar, Syresh and Palanisami, K. "Impact of Drip Irrigation on Farming System: Evidence from Southern India," in Agricultural Economics Research Review 23 (July-December 2010): 265-272.

Appendix – Solar Water Pump Roadmap Questionnaire

Product Definition
Do you have edits or suggestions to the below definition of photovoltaic pumping systems? *Photovoltaic pumping system in a stand-alone operation with no connection to the grid and the following components and equipment: PV generator, cabling, control unit (e.g. inverter, DC/DC converter, etc.), motor, pump, and hydraulic piping. [IEC 62253: 2011] The pump systems can be classified as: 1. DC Surface Pumping System (with brushes or brushless DC) 2. AC Surface Pumping System 3. DC Submersible System (with brushes or brushless DC) 4. AC Submersible Systems* Open Response. Should mini-grid solar water pumps be included (versus solely stand-alone)? Yes; No; Maybe; Other. Are there other innovations, such as integrated batteries, that we should consider incorporating into the definition? Open Response.
Critical System Requirements
What technical requirements should be included? Greater wire-to-water efficiency; Durability; Other. Do you have edits or suggestions to the definition below? *Greater wire-to-water efficiency: 50% minimum, per India's MNRE requirements* Open Response. Does the wire-to-water efficiency metric account for all critical parameters in a SWP system (e.g. total dynamic head and the L/day, performance at different levels of isolation)? Yes; No; Maybe; Other. Do you have edits or suggestions to the definition below? *Durability: The PV modules must be warranted for output wattage, which should not be less than 90% at the end of 10 years and 80% at the end of 25 years. The whole system including submersible/surface pumps shall be warranted for 5 years.* Open Response. What environmental requirements should be included? No negative impacts on soil, water table crop production, etc.; Drip irrigation to optimize water usage; Other. What additional critical system requirements should be considered in the SWP roadmap? Open Response.
Major Technology Areas
What technology areas should be included? Low cost sensors and controllers; Portable & durable small-scale SWP power systems (power system + panel); Complete portable systems (power system + pump + piping); High efficiency, low cost AC/DC (brushed or brushless) motors for pumps; Improvements to saline water tolerance; Low cost, durable, well-designed irrigation piping; Water filtration; Other.
Technology Drivers and Targets
What technology drivers should be considered? Low cost sensors (level sensors, soil moister sensors, etc.); Portable and durable (overall pump and irrigation infrastructure, weatherproof box for electronics, portable and moveable PV mounting system, etc.); High efficiency motors (brushless DC motors); Salinity/saline water tolerance; Irrigation infrastructure (durable materials, standardized sizing and interoperability, etc.); Other.
Additional Input
Please share ideas, resources, etc. in regard to the SWP roadmap below. Open Response.

Focus Groups
We would like to divvy participants into smaller groups based on their area of expertise/interest. This will allow us to have targeted conversations in between the TWG meetings. Which focus group(s) would you like to participate in? *Groups will be contacted via email with the option to schedule brief calls.* Low cost sensors and controllers; Testing and test method; Power systems Motors; Salinity and water filtration; None; Other.