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UKaid from the British people

Image Credit: Futurepump

EVALUATING APPLIANCE PERFORMANCE IN THE FIELD

RESULTS FROM SOLAR WATER PUMP TESTING

MARCH 2023

EFFICIENCY FOR ACCESS COALITION

ACKNOWLEDGEMENTS

The field-testing report for solar water pumps was developed by CLASP in partnership with EED Advisory on behalf of the Low Energy Inclusive Appliances programme, a flagship initiative of the Efficiency for Access Coalition.

Efficiency for Access 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 by Global LEAP and Sustainable Energy for All to a coalition of 20 donor organisations. 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. Current Efficiency for Access Coalition members lead programmes and initiatives spanning three continents, 62 countries and 34 key technologies.

CLASP is a non-profit organisation that works on climate mitigation and expanding clean energy access through efficient appliances. CLASP achieves this mission through a variety of instruments such as policy, research, awards and building tools such as the VeraSol database, MEPSY and the CPRC.

EED Advisory is a multidisciplinary pan-African consulting firm offering technical, analytical and advisory services in energy, water and climate change. Their main service offerings include research and data analytics, projects and programme design, policy and strategy, and fund management.

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Solar water pumps (SWPs) have the potential to transform agriculture by improving farm yields, increasing household income, and enhancing food security. Moreover, SWPs offer several advantages, including reducing the burden on women and children who are responsible for water collection, allowing them to engage in other productive activities such as education and income-generating work, thereby enhancing their overall quality of life.

Recent advancements in SWP technology have significantly improved efficiency and performance, including the use of permanent magnet motors/brushless Direct Current (DC) motors, Internet of Things (IoT) technology, and more efficient solar photovoltaic technologies. Solar PV efficiency improved from 8% in the 1950s to about 20% in the early 1990s, and in experimental settings, it has reached up to 44%. However, SWP performance is influenced by multiple factors, such as water quality, installation configurations, user behaviour, and site-specific conditions that affect pump performance while in use.

While lab testing provides an in-depth understanding of pump performance under ideal conditions, it may not provide comprehensive insights into a pump's field performance, considering other user-centric variables and site-specific conditions that affect pump performance while in use. Field testing provides an excellent opportunity to understand the long-term performance of SWPs and how user behaviour affects pump efficiency and performance.

About this report

This report presents the findings of a technical performance monitoring study conducted between 2021 and 2022 on several SWPs to understand how user behaviour affects the technical performance of these pumps. The study also provides insights into the users of these pumps by examining use cases, social demographic factors, water pumping practices, patterns, and experiences.

The first part characterises the users of these pumps by analysing their use cases, social demographic factors, water pumping practices and patterns, and their experiences and overall satisfaction with the performance of SWPs over time. This information was collected through surveys and interviews with users and provides valuable insights into how these pumps are used in real-world scenarios.

The second part of the report focuses on technical performance data collected from a range of SWPs using remote data loggers. This data includes voltage, current, pumping times, pumping duration, power consumption, and service delivery of the pump (volume of water pumped), recorded by a flow meter. Using this data, the report presents comparative analyses of wire-to-water efficiency and energy consumption across individual sites and pump models and compares lab performance and field performance.

The report concludes with recommendations for improving SWP design and functionality, enhancing performance appraisal at the lab level, and implementing future field-testing exercises. Overall, the study emphasises the importance of considering user behaviour and site-specific conditions in assessing SWP performance and highlights the need for ongoing research and development in this area.

Insights from Technical Performance Data

Most SWPs operate within the manufacturer's technical specifications, with the exception of the SWPs tested in Tanzania. These pumps recorded a voltage and current that exceeded the manufacturer's specifications by nearly 10%.

Solar water pumps (SWPs) are commonly reported to have a daily wire-to-water efficiency between 20-40%. However, individual SWP sites exhibit a wide range of efficiency, indicating that a pump's efficiency is highly influenced by various site-specific factors, such as the power output, horizontal and vertical distance between the pump and the water source, as well as the type and diameter of the pipes used.

SWP users cannot accurately predict how a SWP may perform when in use and may not understand how efficiency variability affects their water yield. This presents a learning opportunity to understand the specific variables that drive performance variability and to understand if farmers are burdened by this or would benefit from solutions that reduce the impact of SWP performance variability.

Portable SWPs were the most difficult to track performance in the field as site set-up conditions would continuously change. This was the case for portable SWPs in Kenya, where the end users would move around their pump, changing the depth and height from which the water had to be lifted and, in other instances, the horizontal length the water had to be pumped.

Lab testing is not a good predictor of a pump's performance in the field, given the high variability in pump setups/conditions and without tightly controlled testing environments.

Current lab testing methodology and reporting may not include enough insight into real-world performance variability. There is an opportunity from this research to update current lab testing methodologies to include optimum pump performance ranges that consider installation set-up variabilities.

Insights from End User Surveys

SWP users across the three countries use their pumps for an average of four hours daily with an average start time of 6 AM. Users in Kenya had shorter pumping durations, with an average of two hours a day, while those in Tanzania and Senegal used their pumps for an average of six hours daily.

Battery-enabled pumps recorded the highest variance in pump start times, with some starting as early as 4 AM, while others would start at 2 PM. Compared to direct drive pumps, which had defined start and stop patterns, these battery-enabled pumps provided flexibility on when to pump and for how long, in addition to powering other appliances in the household.

There is a correlation between water sufficiency and storage practices. Users in Senegal reported the highest water insufficiency cases as well as the lowest water storage cases. Given that most SWPs in Senegal were used in arid areas of the country, awareness and sensitisation of sustainable water management and adaptation practices are crucial.

Submersible pumps used in wells are susceptible to clogging at pump inlets due to impurities in the water. Pump users sourcing their water from wells highlighted this challenge. This challenge may be attributed to increased water turbidity during the rainy season or when there is excessive siltation in the water source.

Users of low-power SWPs in Kenya reported the highest rate of breakdowns and dissatisfaction with the pumps not meeting their irrigation needs. While this dissatisfaction may be attributed to various reasons, it was noted that, on average, pump users in Kenya had 3 acres of farmland under irrigation, resulting in higher water needs against the low flow, low and medium head application pumps.

Recommendations

Proper training of installers and strict adherence to installation and operational guides during installation to mitigate against variability in SWP performance over time.

Adoption of water storage as a standard practice amongst SWPs users. Water storage can provide the flexibility of irrigating at night when evaporation by the sun is low, further reducing water wastage and increasing the crop yield to field water use ratio.

Exploring the use of second-life batteries from EVs and other applications for larger SWPs. This can contribute to lowering the cost of these batteries and provide SWPs users (the majority of whom are in off-grid areas) with cleaner energy sources to power productive use and other household appliances.

SWP manufacturers and distributors should encourage farmers to purchase a larger capacity pump that can accommodate any future changes, such as increased land acreage or a change in the current water source. These options should be emphasised during purchase, enabling users to understand that alterations to the recommended pump set-up may affect the pump's performance.

Image Credit: Aggrico

1. INTRODUCTION

1.1 Background

This report is part of a series of product testing resources designed to help practitioners better support the growth of the solar water pump industry and its impacts on millions of beneficiaries in off- and weak-grid communities globally. This report focuses specifically on SWP field testing, complementing other reports published by EforA, such as the Solar Water Pump Durability Research Memo, Field Testing Guide for SWPs and the Beta Testing of Remote Monitors report that have focused on laboratory testing and performance, as well as guidelines and resources for implementing a successful field testing exercise. It also includes recommendations for future laboratory and field testing.

While lab testing can provide a detailed analysis of a solar water pump's performance under ideal conditions and enable comparison with manufacturer specifications, it may not offer a complete understanding of the pump's performance in the real world. Various factors such as location, water source, water quality, installation configurations, and user behavior can impact the pump's efficiency and performance.

Therefore, we conducted a field-testing exercise for various solar water pumps used in different geographic locations and use cases to gain a more comprehensive understanding of their performance. By studying these pumps in real-world conditions, we could better evaluate their effectiveness and determine areas for improvement.

Field testing is the process of collecting, measuring, and analysing a product’s performance data, often but not necessarily by observing use in real-world settings over an extended period. Successful field testing provides information about the product’s performance, user behaviour, and experience. Additionally, the data and intelligence gathered from field testing inform decisions about product design, financing, business models and more. Finally, field testing informs laboratory testing methods, strengthening quality standards development.

1.2 Objectives, Scope, and Methods

This report contains the findings of SWP field testing in off-grid, peri-urban and rural areas in Kenya, Tanzania, and Senegal in 2021-2022. The objectives of this field testing include the following:

- Understanding and profiling SWP use cases and collecting the socio-demographic data of end users.
- Understanding the technical performance of SWPs in real-world environments, including how user behaviour affects pump efficiency
- Comparing real-world and laboratory performance
- Developing recommendations to improve laboratory and field-testing methods
- Developing suggestions for product developers on enhancing product design

1.2.1 Methods

This field-testing exercise can be summarised in three main stages: pre-deployment, monitoring and synthesis. (Figure 1).

Location: This project carried out field testing in off- and weak-grid peri-urban and rural areas in Kenya, Senegal, and Tanzania.

Partners and respondents: The project leveraged partnerships from the Efficiency for Access Research and Development grants, Global LEAP Awards Competition and Results-Based Financing, among other LEIA partnerships. Four SWP manufacturers and distributors participated in this field-testing project, providing a pool of 100 SWP customers, including 50 in Kenya, 25 in Senegal, and 25 in Tanzania. Incentives were provided at the baseline and the endline as a token of appreciation for participating in the field testing. Of the 100 SWP users, 90 qualified and agreed to participate in the field-testing exercise.

Technologies: Factors that were considered when selecting which SWP brand to include in the field testing included: the availability of lab testing data under the Global LEAP framework, the presence of a willing partner in the target country and the availability of SWPs that had been in use for at least one year. In Tanzania, however, some SWP brands that were yet to be tested under the Global LEAP framework were included due to insufficient customers with Global LEAP-tested pumps.

Remote monitors selection: Before selecting the ideal sensor for each technical performance parameter, partner companies provided manufacturer datasheets to inform the selection of an ideal monitor. A beta testing exercise was carried out to evaluate the functionality and suitability of the monitoring equipment.

Two types of remote monitoring modules (RMMs) were developed:

- High power RMM – to record voltage and current for high power pumps (100V to 1000V and up to 20 A)
- Low power RMM – to record voltage, current and hours of operation for low power pumps (9V to 72 V and up to 12 A) – see Table 1 for more information about the SWP and RMM specifications

These RMMs would record power input at least once every minute, which would then be transmitted to an online platform at the end of each day. See Figure 2 for the final RMM used in the field.

Service delivery of the pumps was recorded using an ultrasonic flow meter and sent through a GSM network to a central repository. This flow meter recorded the cumulative volume of water moved per day [m^3]. (Figure 3).

Figure 1: Progression of Field Testing Activities

Stage 1
Pre-Deployment

- Partner Identification
- Product Identification
- Beta testing of RMMs
- RMM Development
- Customer Identification

Stage 2
Monitoring Phase

- RMM Installation
- Baseline Data Collection
- Midline
- Endline

Stage 3
Synthesis

- RMM Retrieval
- Data Cleaning
- Analysis
- Reporting

Table1: Breakdown of SWPs Covered and Remote Monitoring Units' Technical Specifications

Code	Pump Type	Country	No of Sites	RMM Type	RMM Voltage Range (V)	Max RMM Current (A)
SWP 1	Surface Direct Drive	Kenya	16	Low power	9V – 72V	12
SWP 2	Submersible with Battery	Kenya	26	Low power	9V – 72V	12
SWP 3.1	Submersible Direct Drive	Tanzania	7	High power	100V to 1000V	20
SWP 3.2	Submersible Direct Drive	Tanzania	4	High power	100V to 1000V	20
SWP 3.3	Submersible Direct Drive	Tanzania	3	High power	100V to 1000V	20
SWP 3.4	Submersible Direct Drive	Tanzania	7	High power	100V to 1000V	20
SWP 3.5	Submersible Direct Drive	Tanzania	1	High power	100V to 1000V	20
SWP 4.1	Submersible Direct Drive	Senegal	2	High power	100V to 1000V	20
SWP 4.2	Submersible Direct Drive	Senegal	2	High power	100V to 1000V	20
SWP 4.3	Submersible Direct Drive	Senegal	1	High power	100V to 1000V	20
SWP 4.4	Submersible Direct Drive	Senegal	16	High power	100V to 1000V	20
SWP 4.5	Submersible Direct Drive	Senegal	2	High power	100V to 1000V	20
SWP 4.6	Submersible Direct Drive	Senegal	2	High power	100V to 1000V	20

Figure 2: Example of Remote Monitoring Unit Used in the Field

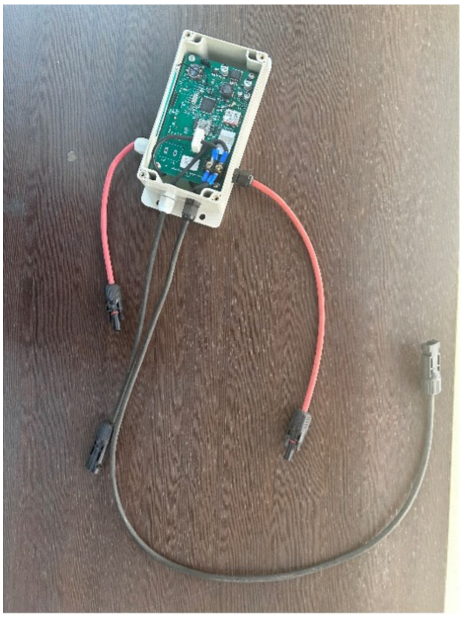


Figure 3: BECO X GSM Ultrasonic Flow Meter Installed in the Field

1. Evaluating Appliance Performance in the Field: Results from Remote Monitoring Solutions Beta Testing, Efficiency for Access, September 2021.

Site Descriptions and Setup: The pumps were typically located adjacent to the respondent's homestead, although some operated in a separate field away from the dwelling place. Most of the pumps adjacent to the home also had a battery storage unit, which doubled up as a power source for domestic appliances such as televisions, phones, and lights. Surface portable pumps would be moved depending on usage and the sun's position for maximum solar irradiance. The ultrasonic flow meter was installed along the main pipe from the water pump to ensure accurate capture of the total volume of water pumped.

Data collection/Monitoring Phase: Technical performance data and survey data were both collected during this phase. We collected data on household demographics, pump usage patterns, use cases, consumer experiences, vertical depth and height of water source from the pump, and physical location (geolocation), among others. In-person and phone interviews were carried out during the installation of the remote monitoring equipment, three months after installation and during the completion of the monitoring phase (6 months after baseline). Midline and end-line surveys captured any changes in behaviour that may affect pump performance and can be co-related to technical performance data.

As part of the data quality control process, instances of prolonged data gaps were double-checked with the respondents through phone calls to confirm an issue with the remote loggers or whether the SWP was no longer in use.

Synthesis, analysis, and reporting: Data cleaning of the technical performance data and the user surveys was done midway through field testing and again at the end of field testing to ensure consistency and comparability. The analysis and reporting of the field test are presented as follows.

- Demographic and user profiles
- Technical performance data

2. RESULTS

2.1 Customer Demographics & Use Cases

The following results are from Kenya, Tanzania, and Senegal survey data. Table 2 provides a snapshot of demographic information for respondents across each country.

As highlighted in Table 2, most of the respondents (84%) who participated in this field testing were male, while female respondents constituted only 16% of the respondent base. This was also mirrored in the main pump operator, where the male-female split stood at 81% and 19%, respectively, indicating a considerable gender gap towards the use and ownership of SWPs across the three countries.

Occupation: The main occupation of most respondents was farming, with 78% of the respondents engaged in this activity. Others include business, formal employment, or wage labour at 3%, 9% and 10%, respectively (Figure 4). Respondents in Kenya have the most varied occupation options, with about 5% in business, 7% working as wage labourers, 28% in employment and 60% in farming. For respondents whose main occupation was farming, 71% of these farmers practice a hybrid commercial and subsistence farming system. Tanzania has the highest number of respondents involved exclusively in commercial farming at 72% of respondents.

Crops grown: Respondents mentioned that they grow several crops at once or within the planting season. The main crop grown in each country includes maize in Kenya (53%), onions in Senegal (78%) and tomatoes in Tanzania (30%). The types of crops grown by a respondent are very dependent on the location and agri-climatic conditions of the site, and thus may not be an indicator of the major crops grown in each of the countries. Figure 5 indicates the types of crops/value chains by respondents whose main occupation is farming.

Table 2: Descriptive Statistics of Sociodemographic Characteristics Per Country

Characteristics	Kenya (n-43)	Tanzania (n=22)	Senegal (n=25)	All (n=90)
Average age	50	45	42	46
Share of female respondents	26%	9%	4%	16%
Share of male respondents	74%	91%	96%	84%
Average Household size	5	5	8	6
Average years of farming	17	6	25	16
Average size of the farm in acres	3.0	9.5	3.1	5.2

Figure 4: Main Occupation of Respondents Across the Three Countries

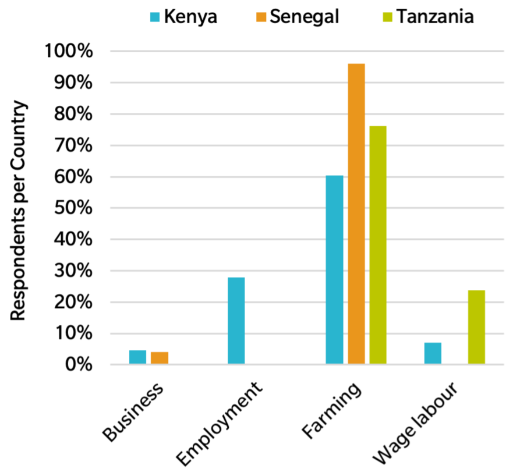


Figure 5: Type of Farming Practised by Respondents Across Kenya, Senegal, and Tanzania

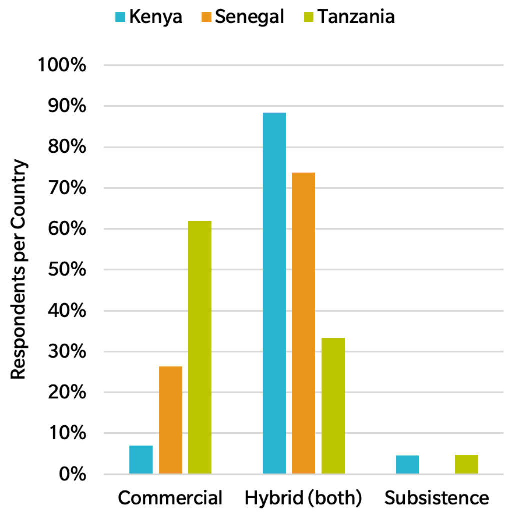
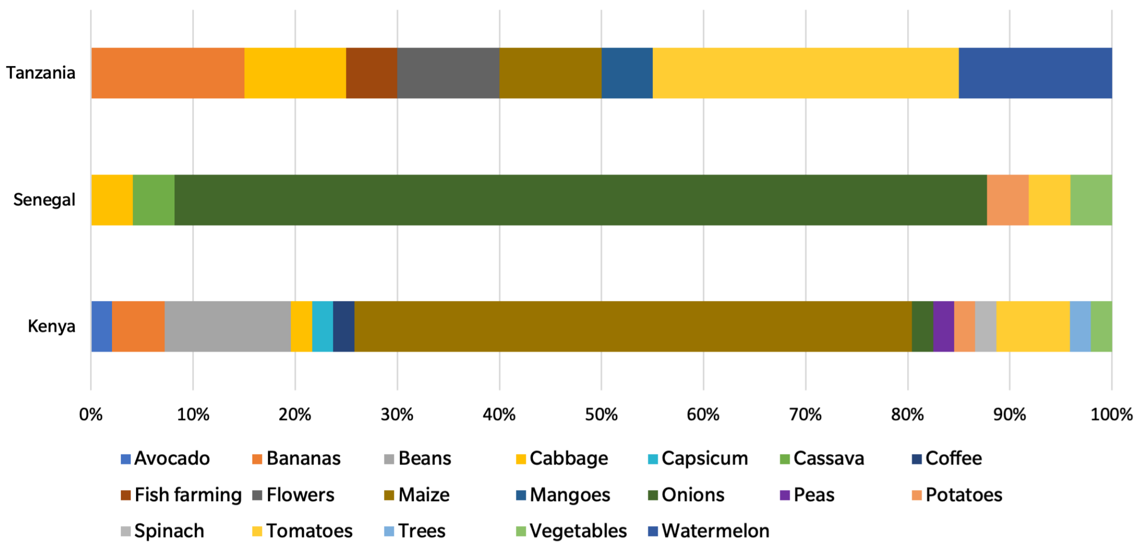
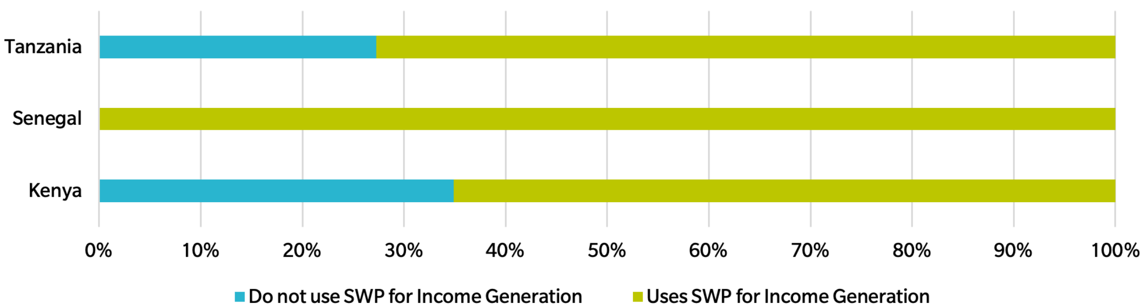


Figure 6: Livestock and Crops Grown by Respondents



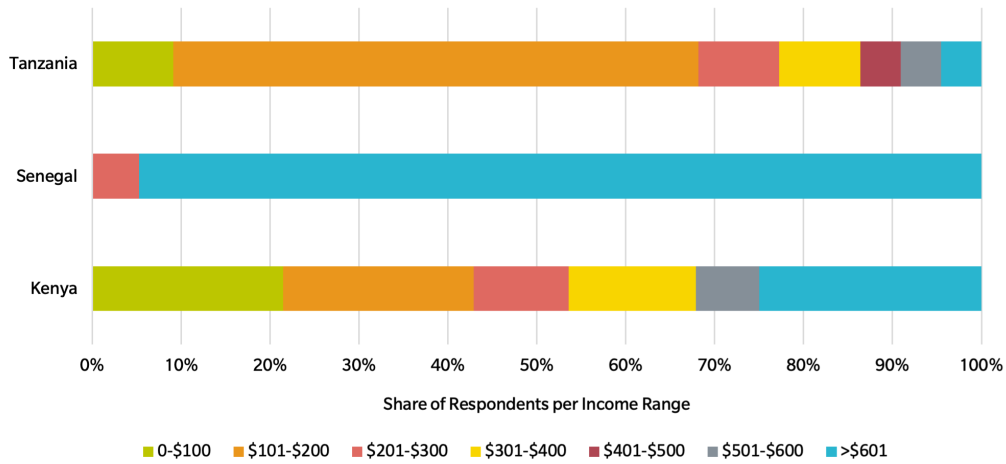
Income: Most respondents use the water pump for income-generating activities, except for 35% and 27% of respondents in Kenya and Tanzania, respectively. In Senegal, all the respondents indicated that they use their SWP for income generation (Figure 6). Uses of the SWP ranged from crop irrigation, fish farming, brick making, livestock rearing, sale of water, cultivating tree nurseries, and own consumption.

Figure 7: Respondents' Use of Solar Water Pump for Income Generation



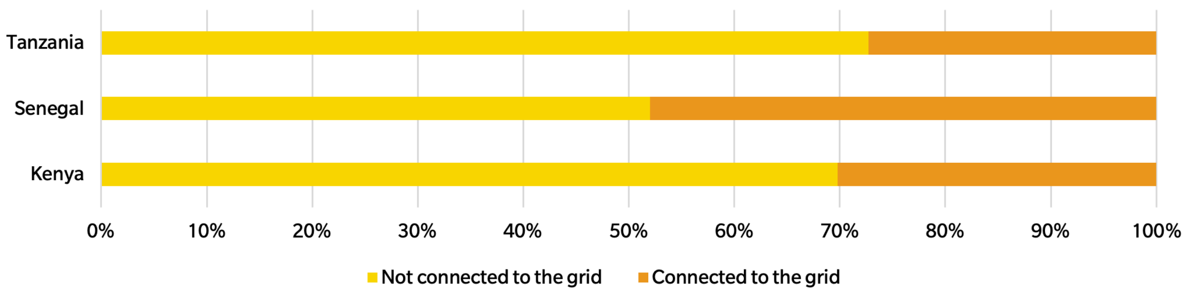
Most respondents (38%) who use their SWP for income generation earn above US$600 monthly, followed by 28% who fall within the US$100-200 a month income bracket. Senegal has the highest number of respondents earning above US$600, with 95% falling under this bracket. This uniformity may be attributed to most farmers growing one crop variety (onions), unlike in Kenya and Tanzania, where farmers are involved in diverse crop value chains, some of which are grown for subsistence purposes. Figure 8 shows the distribution of income across the three countries.

Figure 8: Monthly Income Generation from SWP



Energy usage: 66% of the total respondents did not have a connection to the national/local utility, as most of these SWP locations were largely rural farms away from the main grid network. Tanzania had the highest share of SWP users without a national grid connection at 73%, followed by Kenya at 70% and Senegal at 52% (Figure 8). Most SWP users connected to the grid mentioned that they got the connection before the baseline study. The high number of respondents who had a grid connection before they purchased a SWP may indicate that most respondents prefer buying a SWP to using electricity from the main grid due to the high energy cost of using the utility grid. Respondents in Kenya using the battery-enabled solar pump (SWP 2) would also use the battery as a backup option to the grid for lighting and powering other domestic appliances or to reduce the cost of their monthly electricity bills.

Figure 9: Respondents Connected to the Grid



Water Source, Storage and Sufficiency: The primary water source for most respondents were wells and boreholes. The depth of these varies significantly between countries and locations within the countries. Wells were most common in Senegal and Kenya. The average depth of these wells was 15.4m in Kenya, 16.6m in Senegal and 8.3m in Tanzania. The deepest well in Kenya was reported at 50m, while in Senegal and Tanzania, the deepest wells were 30m and 14m, respectively. Tanzania had the highest number of boreholes, with 64% of the respondents using this as their primary water source. The average depth of these boreholes was 102m, with the shallowest borehole at a depth of 70m while the deepest borehole stood at 14m. Other water sources included rivers, canals, and water ponds at 19%, while piped water and rainwater harvesting users stood at 1%, respectively (Figure 10).

Most respondents in Kenya and Tanzania mentioned that their water source is sufficient for their water needs, while most respondents in Senegal found their water sources insufficient. The Senegalese farmers primarily relied on wells in the country's arid areas, often requiring a recharge[2] after pumping.

Across all countries, most respondents who indicated water source insufficiency used wells and boreholes. Only two respondents sourced water from a river or water pan in Kenya (Figure 10. In Tanzania and Senegal, the respondents sourcing water from wells and boreholes all have high-powered pumps (SWP 3 and 4), while those in Kenya use the low-power battery-enabled SWP 2. These three pumps (SWP 2, 3, and 4) yielded the most amount of water daily primarily due to their high pumping capacity for SWP 3 and 4, as well as through longer pumping durations/hours of operation, as observed in SWP 2.

2. Well recharge is the process through which water enters an aquifer primarily from a more saturated area of the ground to a less saturated area of the ground.

Figure 10: Primary Water Sources for SWP Users

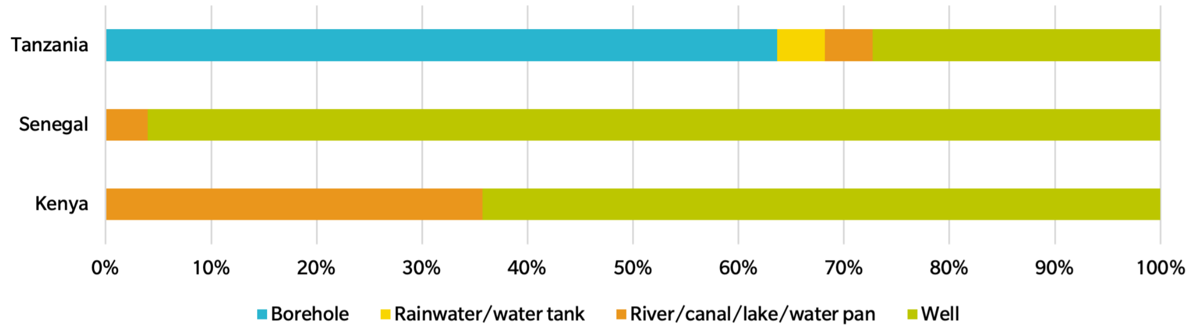
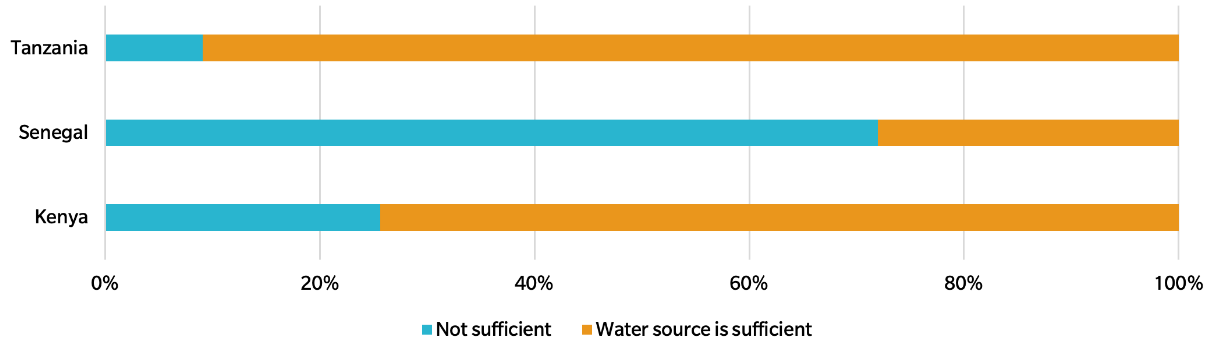


Figure 11: Water Source Sufficiency



Storage: Almost half (48%) of respondents across the three countries store their water. Tanzania has the highest share (73%), followed by Kenya (47%), then Senegal (28%) (Figure 12). 75% of respondents who store their water did so in elevated tanks. All respondents who stored water in Senegal did so in open reservoirs. There was an observed correlation between water sufficiency and water storage whereby 71% of respondents who did not store water indicated that their water was insufficient. In comparison, 58% of those who stored water indicated that their water source was sufficient (Figure 13). Given the reported water insufficiency in Senegal, increased awareness and use of water storage should be encouraged as an adaptation solution.

Figure 12: Water Storage Practices

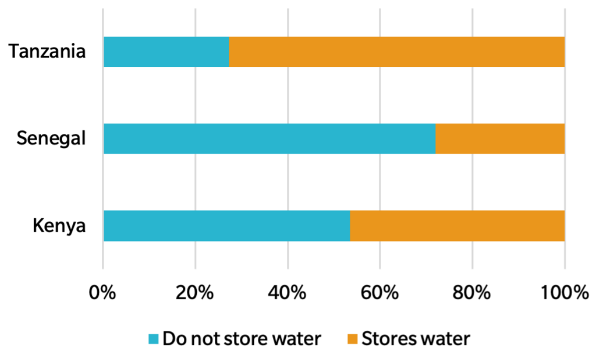
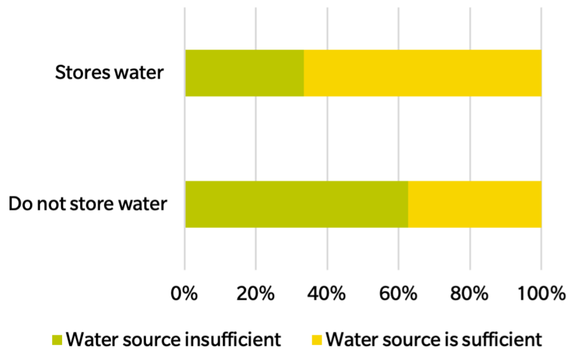
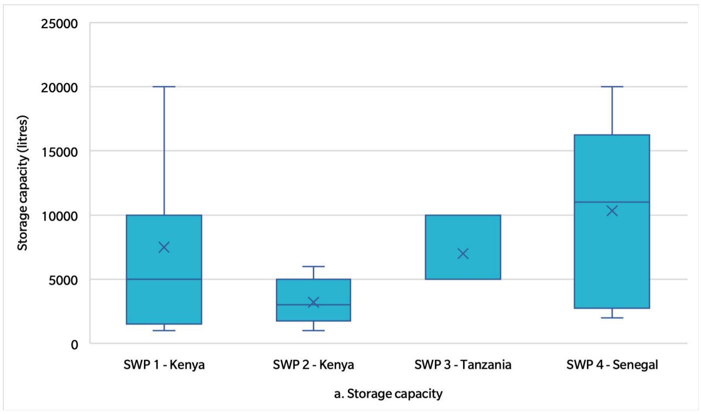


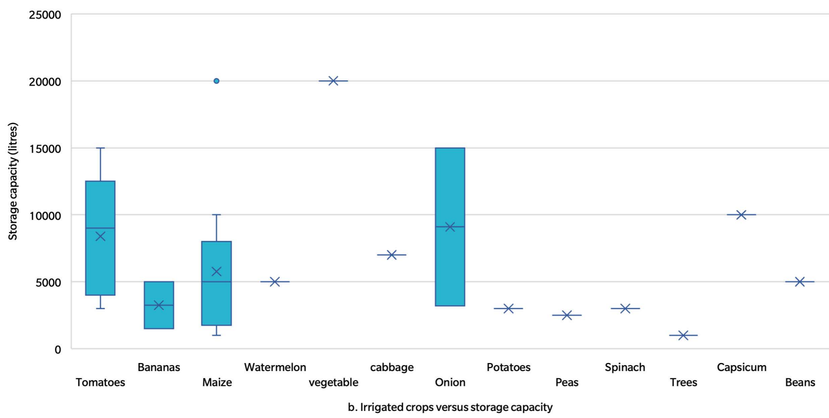
Figure 13: Water Storage vs Water Sufficiency



The water storage capacities varied considerably. The largest water storage capacity reported was 140,000 litres (140 m3) by a respondent in Tanzania who stores water in a groundwater and an elevated tank. The largest elevated tank was reported in Senegal, with a tank capacity of 20,000 litres (20 m3). Figure 13 indicates the storage capacities of the respondents across the three countries, excluding the one outlier of 140,000 litres. It is noted that respondents with the battery-enabled SWP (SWP 2) had the least storage capacity, perhaps hinting at the reduced need to store water when pumping is available for an extended duration due to the inclusion of batteries. Although it is easier to store water than energy, battery-enabled pumps do offer flexible pumping hours compared to their direct drive counterparts in addition to serving as an energy source for other household appliances. Further, respondents that grow maize were found to store water for irrigation the most, with 36% of the 33 maize farmers having water storage. Their storage capacities ranged from 2,000 to 20,000 litres (Figure 14).

Figure 14: Storage Capacity and Irrigated Crops





2.1.1 Customer Experience

Solar water pump functionality and reliability: Most respondents (79%) indicated that their SWP was meeting their water needs at the time of the survey. The reasons given for SWPs failing to meet water needs include insufficient water from the source (44%), large farm sizes (17%), pump breakdown, and low water pressure (6%). In Kenya, the most cited reason the SWP did not meet their needs was insufficient water for irrigation needs (Figure 15). The only respondent in Senegal mentioned a large farm size for the pump not meeting their needs. It is also worth noting that some respondents had increased their area under farming after owning the pump, which may contribute to the pump failing to meet their needs.

Respondents in Tanzania indicated that they would prefer a battery-enabled pump as it would provide flexibility in terms of pumping start time and duration. Table 3 highlights how various factors may have affected customers' perception towards the pump's reliability.

Warranty and aftersales services: All respondents across the three countries indicated that they received a consumer-facing warranty at the point of purchase. This is expected as all the pumps were either purchased on a pay-as-you-go model or from an authorised distributor for SWP 1 users in Kenya who purchased their pumps on a cash basis. 61% of the respondents still had an active warranty at the time of the survey. 43% of respondents had claimed their warranty since the baseline survey (Figure 16).

Respondents experienced pump breakdowns since the baseline survey as indicated in Figure 17. SWP 2 was seen to have had the most breakdowns since the baseline. SWP 2 users who sourced their water from wells indicated that the pump was susceptible to impurities in water clogging the small water passages of the pump inlet. While the reasons for increased water turbidity may vary from increased rainfall to siltation, larger sized filter screens may reduce clogging instances.

Figure 15: Reasons for SWPs Not Meeting End-User Needs

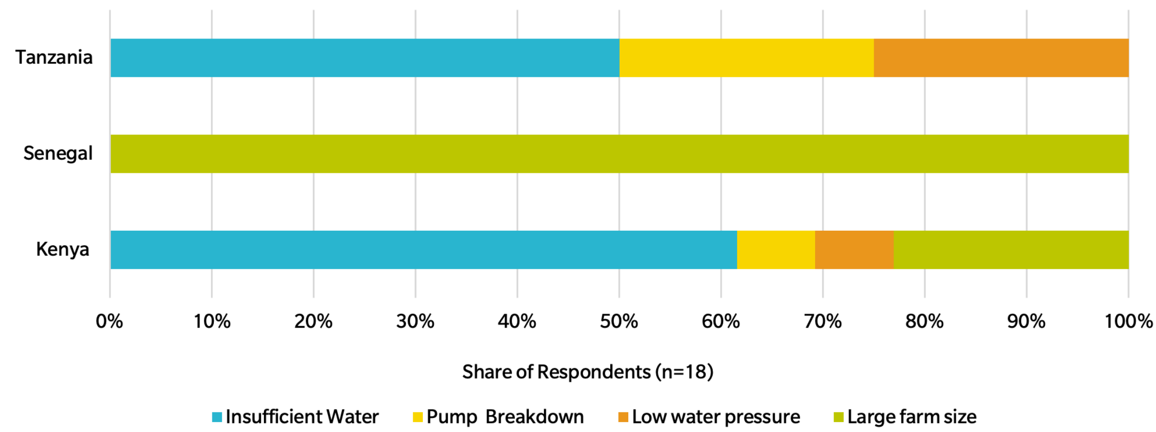
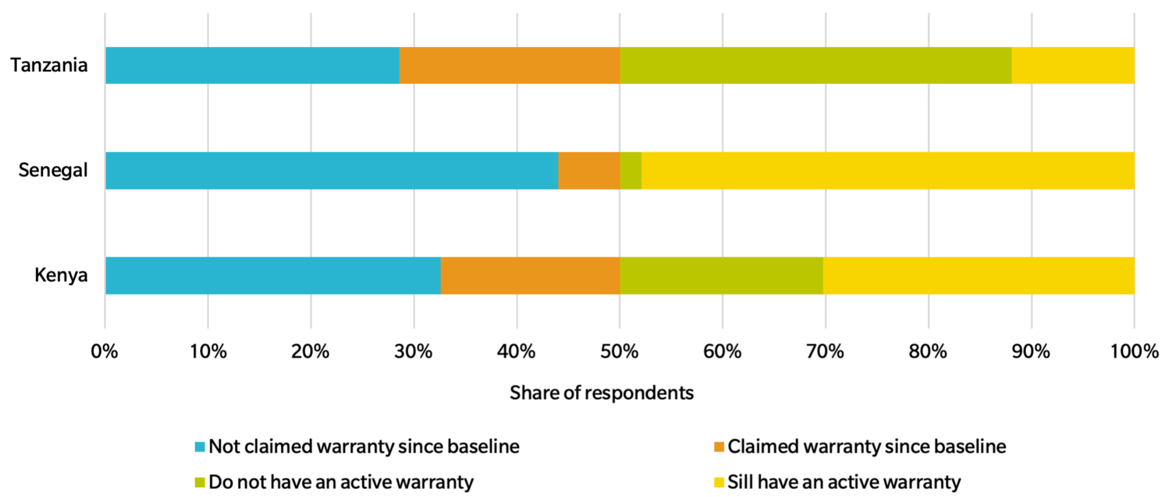


Table 3: Factors Affecting the SWP Meeting the Respondent's Water Needs

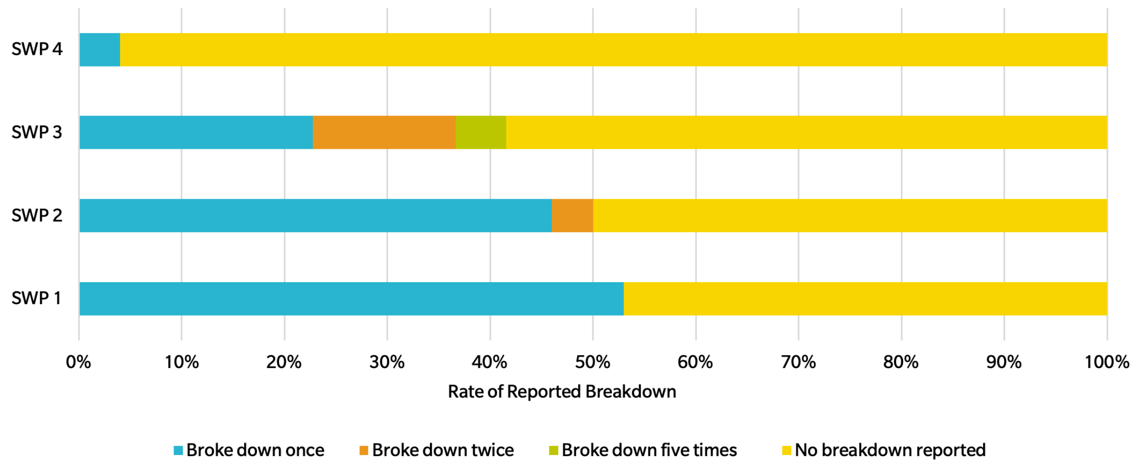
	SWP meeting the respondent's water needs	
	No	**Yes**
	Number of respondents	*Number of respondents*
SWP model		
SWP 1	5	12
SWP 2	8	18
SWP 3	5	17
SWP 4	1	24
Water Storage		
No	7	40
Yes	12	31
SWP breaking down since baseline		
No	7	51
Yes	12	20
Number of times the SWP has broken down		
Once	11	16
Twice	1	3
Five times	0	1
Is the warranty still active?		
No	9	25
Yes	10	45
Has the warranty been claimed since the baseline?		
No	10	52
Yes	9	18

Figure 16: Warranty Status



Training and Demonstration: 98% of all respondents mentioned that a training/demonstration on pump usage, farming practices and SWP maintenance was conducted at the time of purchase. Respondents who were trained mentioned that the training was useful. Regarding maintenance, 45% of the respondents said they do not maintain the SWP in any way. Those who maintain their SWPs either clean the panels, unblock the pump, lubricate parts, or conduct general cleaning. Respondents were further queried about the cleaning of the solar panel. 26% of respondents mentioned never cleaning the panel or relying on the rain. Of those who clean their panels, 43% clean them once a day, 25% clean them once a week, and the rest more infrequently.

Figure 17: Rate of Breakdown by SWP Brand



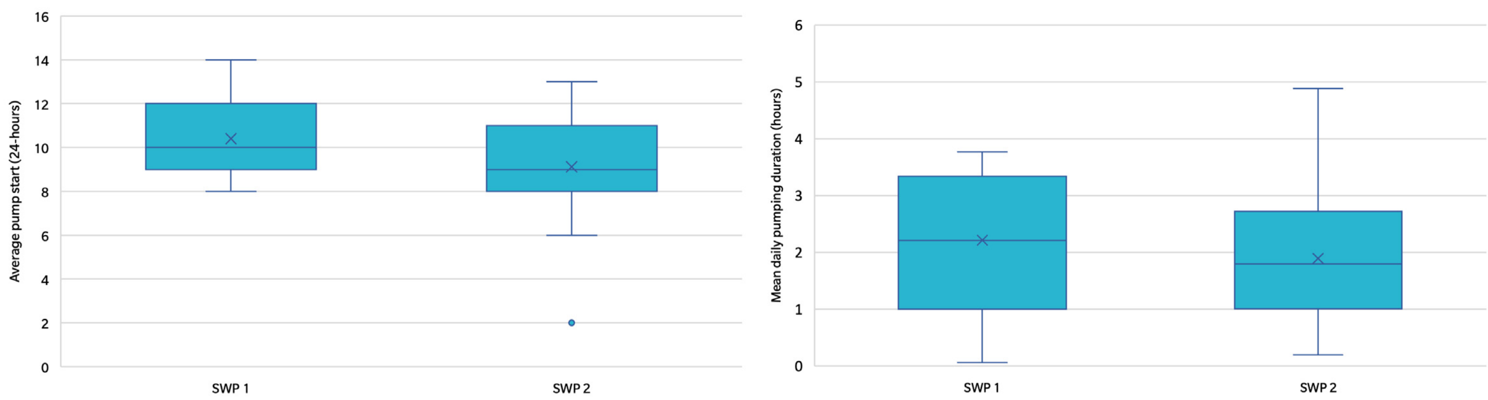
2.1.2 SWP Pump Usage

On average, respondents across the three countries use their pumps for an average of 3.9 hours each day. The low-power pumps in Kenya average about two hours of pumping hours each day, while the high-power pumps in Tanzania and Senegal pump for an average of six hours each day. 50% of pumps in Senegal began operating at 6 AM, with the rest pumping from 7 AM. This was similar in Tanzania, where the average start time was 6 AM, with 68% of the pumps recording this start time. These early start times may be influenced by the automatic start-stop set-up of these pumps based on the amount of current coming in from the solar PV modules. On the other hand, pumps in Kenya did not have automatic power set-ups but instead relied on the users to switch the pumps on and off for the case of SWP 2 or manually set up the pump for the case of the portable SWP 1.

Low Power Pumps in Kenya (SWP 1 and SWP 2)

The time of day when pumping occurs varies; however, we noted that the battery-powered SWP 2 allowed for flexible pumping patterns, with the earliest pumping session starting at 2 AM and the most common starting time being 9 AM, as indicated in Figure 18. SWP 1, as a direct drive solar pump, would only operate once there is sufficient solar power. The earliest time recorded for SWP 1 is 8 AM, with the most common start time being 10 AM.

Figure 18: Average Pumping Start Time and Mean Daily Pumping Duration (Kenya)



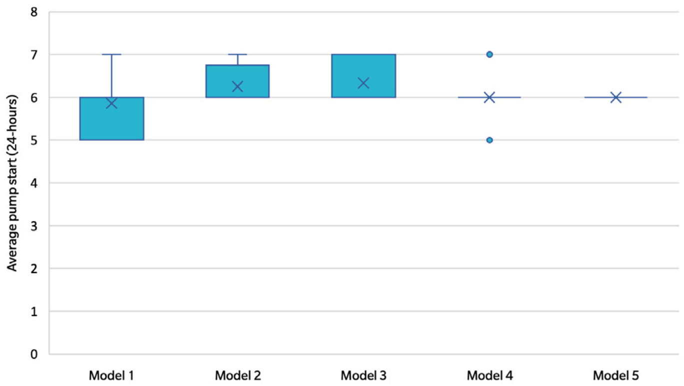
The battery-powered pump (SWP 2) was used on average for shorter periods daily relative to the direct-drive solar water pump (SWP 1) (Figure 18). SWP 1 had a mean daily usage of 2.1 hours, while SWP 2 had a mean daily usage of 1.8 hours. Using other appliances on the battery and battery health may contribute to shorter pumping durations.

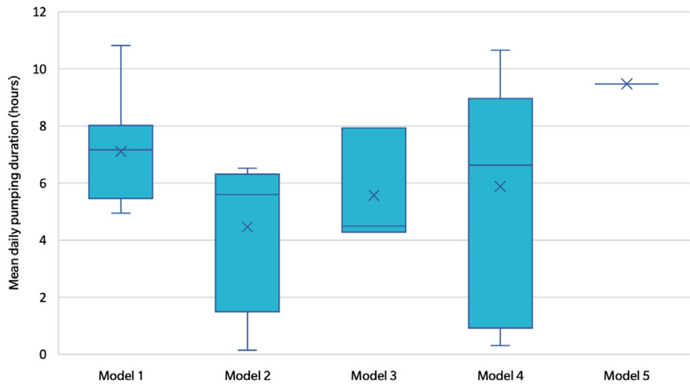
Further, the respondents in Uasin Gishu county and Siaya county in Kenya recorded longer pumping times for SWP 2 and SWP 1, respectively.

High Power Pump in Tanzania (SWP 3)

The average time of day to start pumping across the SWP 3 respondents was 6 AM, with two outliers starting earlier at 5 AM and five starting later at 7 AM (Figure 19).

Figure 19: Average Pumping Start Time and Mean Daily Pumping Duration (Tanzania)





Further, we found that all the SWP 3 pump models are operated on average for more than 4 hours daily. Pump models 1 and 4 were used on average for 7 and 6 hours, respectively and recorded the highest pumping durations at 10 hours a piece, see Figure 19. All models of SWP 3 were direct-drive solar-powered pumps without a battery; therefore, pumping would start from dawn until the respondents switched it off or continuously until dusk in the outlier scenarios. During the baseline, several respondents commented on the desire to have a battery pack addition to the SWP system to enhance their pumping flexibility; however, it was noted that no battery pack is available from the pump manufacturer, which we assume is due to the cost of setting up a pack large enough to power the high-powered water pumps.

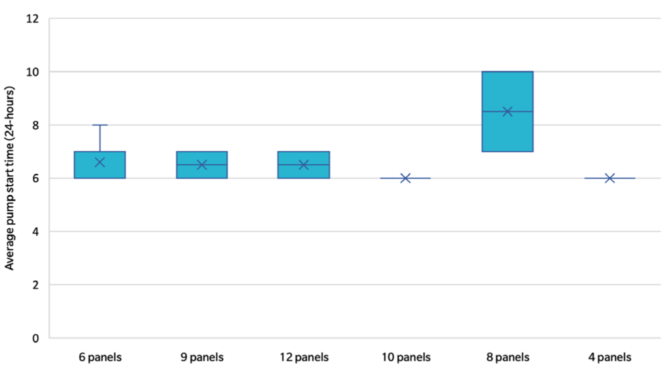
In the six months between the baseline and midline surveys, drought affected most respondents, which prompted respondents to either pump for longer where the water source could sustain the required flow or reduce the size of the cultivated area where the water source experienced reduced yield.

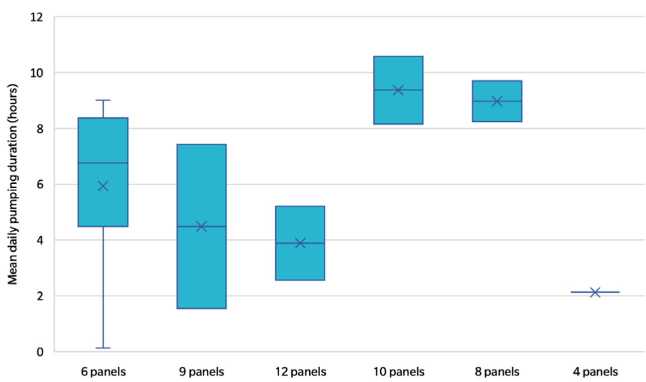
High Power Pump in Senegal (SWP 4)

Like the pumps in Tanzania, the pumps in Senegal are solar direct drive pumps whose use followed the diurnal rhythm. Over 90% of water pumps would, on average, start operating between 6 AM and 7 AM, with the only outliers beginning to operate between 8 AM and 10 AM (Figure 20).

The average pumping duration for users in Senegal was six hours, excluding one 4 solar panel-powered pump, which averaged two hours. Pumps fitted with eight and ten panels averaged the highest pumping durations of eight and nine hours, respectively. These outlier pumps were all located in Louga, Senegal.

Figure 20: Average Pumping Start Time and Mean Daily Pumping Duration (Senegal)





2.2 Technical Performance Analysis

Of the 89 sites set up to record field testing data, 59 have been used in the general analysis seen throughout this report, and 29 sites (33% of the original 89) are used in the efficiency analysis in section 2.3.2. The decrease is attributed to various reasons, including pump failure and tampering, RMM equipment failure and tampering, and poor or insufficient data. Section four of this report highlights the challenges, lessons learned and causes for site data loss/omission from the analysis.

As mentioned in Section 1.2.1, the SWPs included in this field-testing exercise have been anonymised and coded as SWPs 1-4. Table 5 summarises the sites included in the overall performance and efficiency analyses based on data availability and comparability. As indicated in Table 4, 16 sites were included for SWP 1, while SWP 2 had 26 sites. Both these SWP brands had one pump model each, while in Tanzania, four brands of the SWP 3 were included depending on customer availability and willingness to participate in the project. The 25 respondents in Senegal were all using the same brand and model of the SWP, but these were powered using varying combinations of solar PV modules from 4 to 12 panels. In a direct drive configuration, voltages ranged from 270 to 395 V.

Table 4: A Breakdown of the SWP Sites Included in the Technical Performance Analysis

Code	Pump Type	Country Site	Number of Sites	Sites in Overall Technical Performance Analysis	Sites in Efficiency Analysis	Dates w/ Data for Efficiency Analysis
SWP 1	Surface	Kenya	16	8	2	9
SWP 2	Submersible with Battery	Kenya	26	16	2	34
SUBTOTAL:			42	24	4	43
SWP 3.1	Submersible direct drive	Tanzania	7	5	4	558
SWP 3.2	Submersible direct drive	Tanzania	4	2	2	273
SWP 3.3	Submersible direct drive	Tanzania	3	1	0	0
SWP 3.4	Submersible direct drive	Tanzania	7	1	1	213
SWP 3.5	Submersible direct drive	Tanzania	1	0	0	0
SUBTOTAL:			22	9	7	1,044
SWP 4.1	Submersible direct drive	Senegal	2	2	2	186
SWP 4.2	Submersible direct drive	Senegal	2	2	2	155
SWP 4.3	Submersible direct drive	Senegal	1	1	1	2
SWP 4.4	Submersible direct drive	Senegal	16	16	9	441
SWP 4.5	Submersible direct drive	Senegal	2	2	2	157
SWP 4.6	Submersible direct drive	Senegal	2	2	2	85
SUBTOTAL:			25	25	18	1,026
OVERALL TOTAL:			**89**	**58**	**29 (33%)**	**2,113**

2.2.1 Energy Dynamics

SWP 1 and SWP 2 (Kenya)

The minimum and maximum steady-state power consumption were recorded for both pumps. The steady-state figures are considered the condition the pump motor reaches after startup torque is attained, where power consumption depends on pump load and available input power from the solar PV panels or battery pack. The mean minimum and maximum instantaneous power consumption for the direct drive SWP 1 was 7.8 W and 98 W, respectively. The battery enabled SWP 2 was 19 W and 120 W, respectively (Figure 20). These readings align with the rated power by the manufacturer and readings from lab testing. Maximum and minimum instantaneous are good indicators of the operating range of a solar water pump and a helpful indicator of how much power the SWP draws from a solar panel or a battery.

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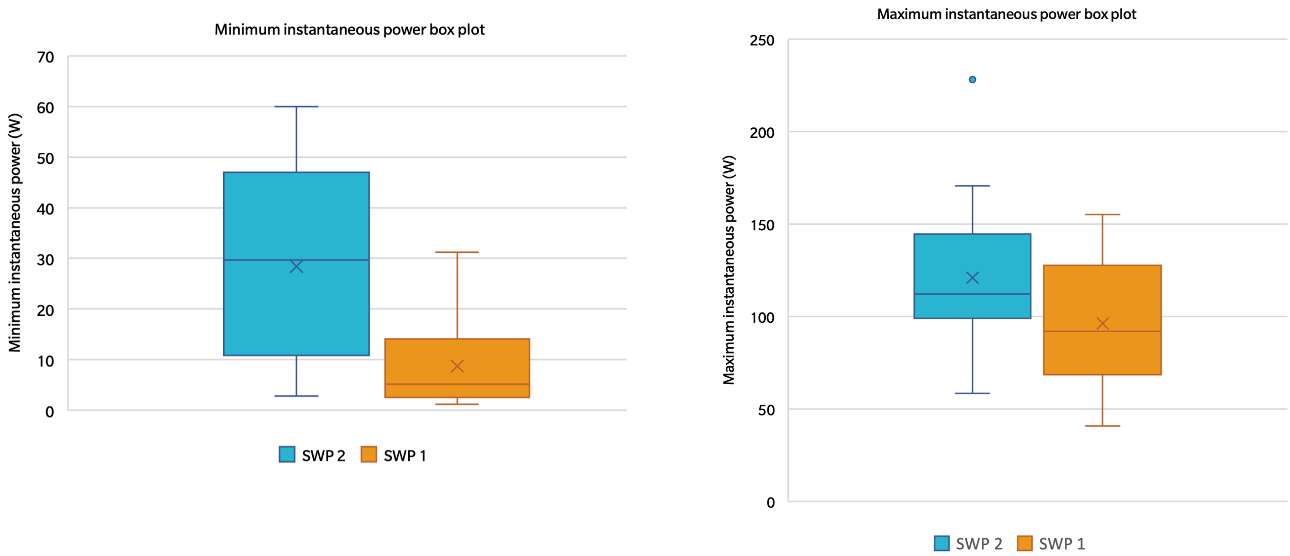
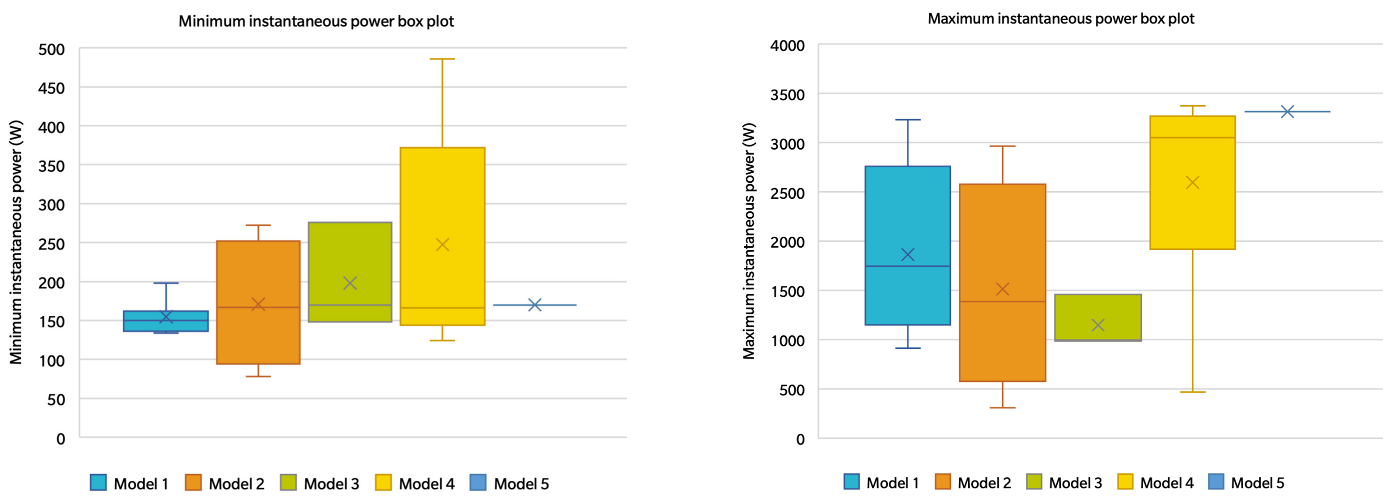
Figure 21: Maximum and Minimum Instantaneous Power for SWPs 1 and 2



SWP 3 (Tanzania)

In Tanzania, the mean minimum instantaneous power consumption across the five models of pumps was 193.8 W, while the mean maximum instantaneous power was 1,972 W (Figure 22). It was noted that the highest maximum instantaneous power recorded was 3,374 W for pump model 4, which was higher than the simulated PV output in the lab test setting.

Figure 22: Maximum and Minimum Instantaneous Power for SWP 3

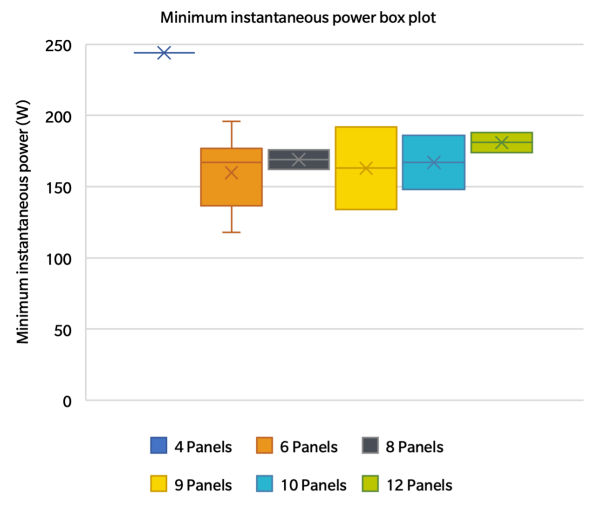


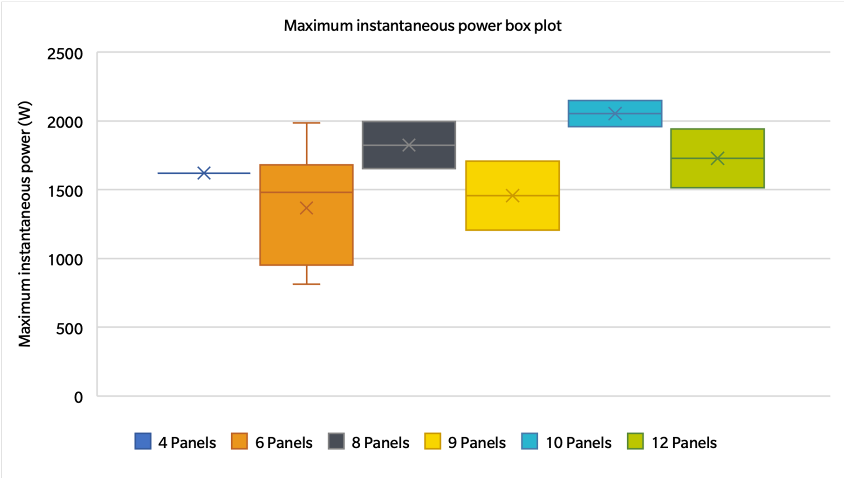
SWP 4 (Senegal)

In Senegal, the mean minimum instantaneous power consumption across the pumps with the five different PV panel configurations was found to be 159.8 W, while the maximum was 1,510 W (Figure 23).

The large capacities of the pumps in Tanzania and Senegal were evident in the significant power consumption recorded across the pump models. It was, however, noted that the power consumption across the pumps in Tanzania was higher than those of the pumps in Senegal. This may result from the water source in Tanzania being deeper boreholes than the wells in Senegal.

Figure 23: Maximum and Minimum Instantaneous Power for SWP 4





2.2.2 Wire to Water Efficiency

In addition to sourcing water, pumps must divert water often vertically to their destination, such as storage tanks. Together, the depth of the water source plus the height water is pumped to get to its destination determine the total vertical rise. Pumps must be powerful enough to overcome the total vertical rise, and every site may have different depths and heights to pump. Most of the users of SWP 1 in Kenya sourced their water from surface sources and directly irrigated their farms without having to store the water, except for three sites which sourced their water from shallow wells (Figure 24).

Calculated metrics used throughout this analysis include:

Total vertical rise of water [meters] = Vertical depth + vertical height
Wire to water efficiency = pgHL / IV[t1−t0]

p = the density of the water
g = gravity
H = head; total vertical rise was used for this value because information about piping was not captured and fluid frictional energy loss in the system cannot be determined
L = the volume of water moved per day
$IV[t_1-t_0]$ = the energy consumed by the SWP per day

Given the varying site setups– in particular, the total vertical rise (the depth to the water source + the height water is pumped to the destination), which has a substantial impact on the volume of water – daily wire to water efficiency was selected as the only relevant comparative performance metric. The following analyses rely on this metric exclusively.

To calculate wire-to-water efficiency, water yield and energy consumption data were aggregated to a daily resolution (24 hours). Therefore, we had to modify the standard wire-to-water efficiency or pump efficiency calculation to incorporate water yield per day rather than flow in litres per second and summarise the instantaneous power to daily energy recordings. The resultant equation is:

Pump efficiency [%] = *p**g*H*L / IV[t1−t0]
where:

p is the density of the water
g is gravity
H is the head
L is the quantity of water recorded by the flowmeter per day
I is PV current (I).
V is PV voltage (V).
t_1-t_0 is time duration
$IV[t_1-t_0]$ is the energy consumed per day in watt-hours

Another way of writing this is energy outputted (as water weight raised on a vertical distance, i.e., kinetic energy) divided by energy consumed by the pump.

The site factors that affect efficiency include:
- weather conditions, primarily the solar irradiance
- size of the PV array
- electrical losses in the system
- sediment and obstructions in the water
- depth of the water source and the vertical height the water is ultimately pumped (combined to form the total vertical rise)
- piping features, especially the diameter, material, and shape (such as smooth bore vs corrugated

Figure 24: Combined Vertical Distance for Surface Pumps (SWP 1 in Kenya)

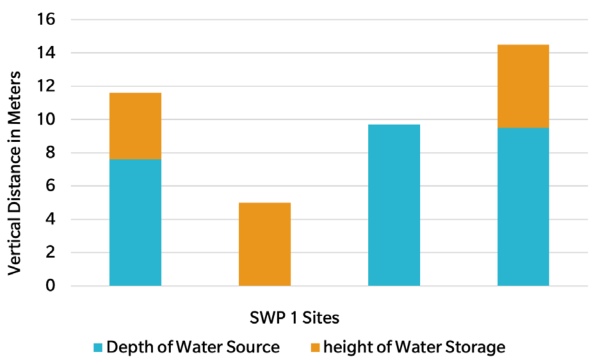


Figure 25: Combined Vertical Distance for Submersible Pumps (SWP 2, 3 and 4)

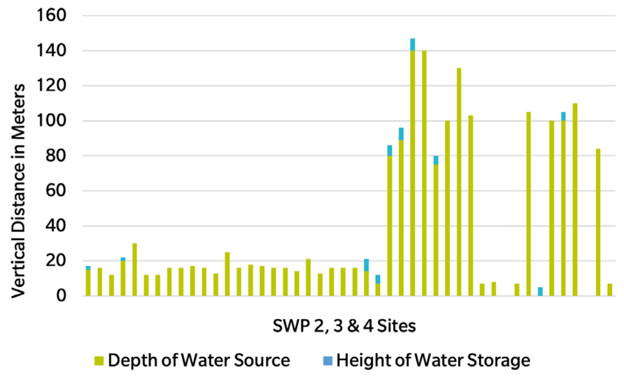
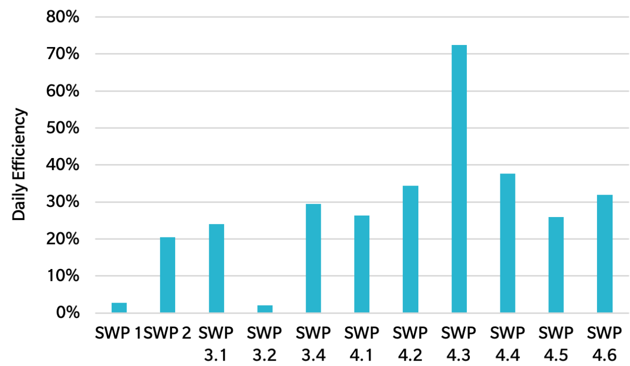


Figure 26: Average Daily Efficiency by Pump Model



This project attempted to control for as many of these variables as possible, but in a field setting, there are limits to what's possible. In particular, the total vertical rise was only recorded at the beginning, not daily, and therefore subject to change by users who moved the pumps, especially the surface pumps. Piping information was not collected in this project, and therefore it is excluded from these calculations.

Daily Efficiency Performance

Figure 26 shows the average daily efficiency performance of each pump model, aggregated across all the sites where it was tested. Some variability is evident and ultimately reflects errors in the data, but the general pattern is clear. Most pumps, on average, are performing at efficiencies between 20-40%.

Figure 27 shows the average daily efficiency performance of each site (included in the analysis) n=18. From this, we can see that efficiency performance is likely more variable than the 20-40% range seen by the pump model above and may indicate that the pump system setup is partly responsible for the difference (as well as weather and usage patterns) – which may suggest that optimising pump setups present an opportunity for improving pump performance and subsequent impact.

Figure 28 shows the daily efficiency over time of four different pumps of the same model operating at four different sites.

Interesting patterns were revealed that warrant further analysis to understand:

- The two downward-sloping patterns are broken apart by an abrupt increase (in November 2021) of site 13F6
- The upward sloping and much worse overall efficiency of sites 13EA and 140B.

A variety of factors could explain the 13F6 pattern, including user behaviour (such as extending the pipe length or gradual vertical inclination as farmers irrigate fields farther away or higher from the pump source before returning to irrigate sections near the pump and repeating the pattern), seasonal weather patterns, or other environmental factors (such as residue buildup in the pump that slowly worsens performance which is then removed by the user causing the dramatic uptick in performance), among others. In contrast, site 141D was steady in its efficiency and the highest performing of the four sites (all of which used the same pump model). This suggests that 141D was most likely set up more optimally (via vertical rise, piping, environmental factors, etc.) or that the user used the pump more optimally. It could also be a combination of both.

Figure 27: Average Daily Efficiency by Site

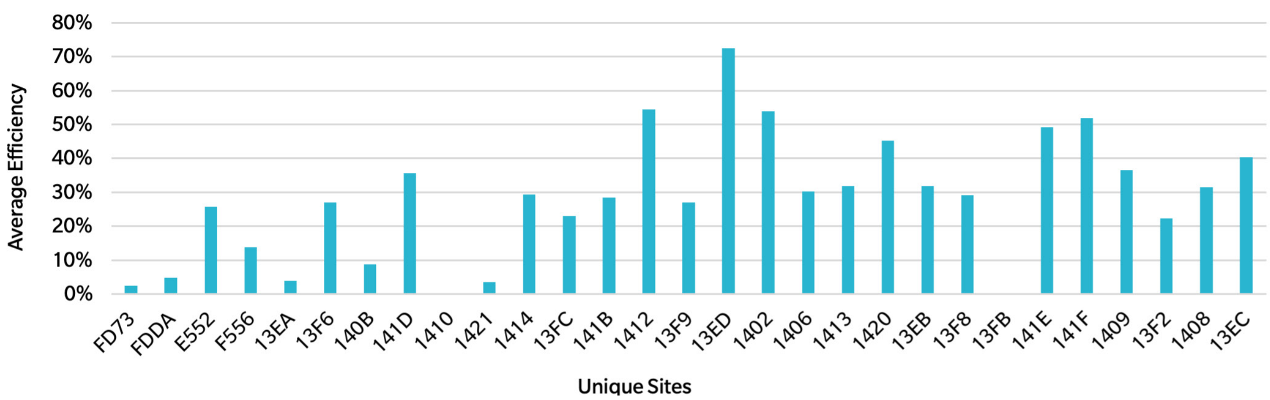
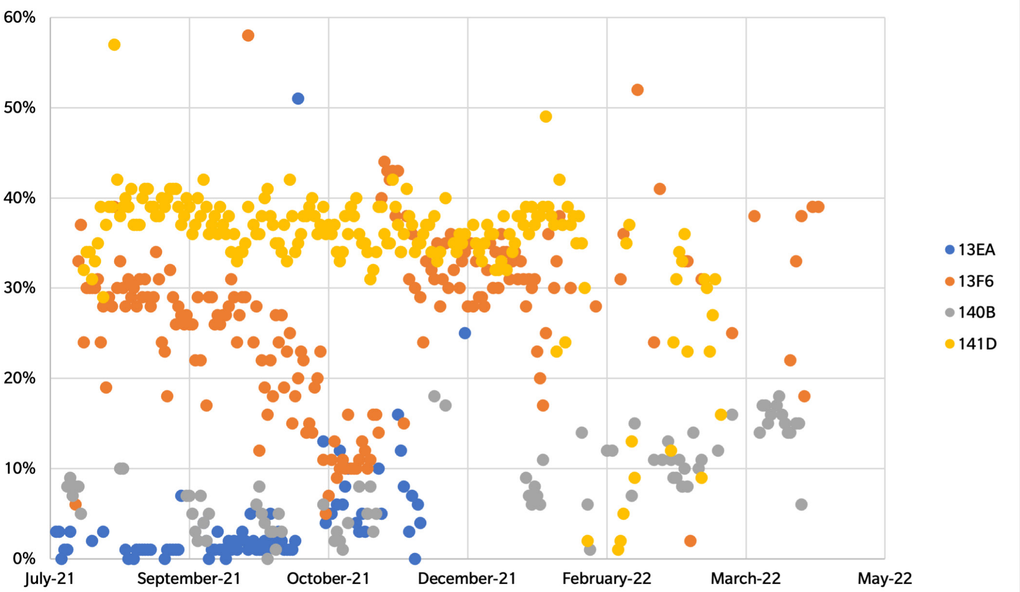


Figure 28: Daily Efficiency Over Time at Four SWP 3.1 Sites



Daily Efficiency Distributions

In addition to evaluating the averages of efficiency performance, we studied the distribution of daily efficiency for each site and pump model. The distributions vary widely by dates at individual sites and between sites. Additionally, we noted variations in distributions between sites with the same pump model and those with varying pump models. The latter is unsurprising, given that product models are built differently and are likely to perform differently. However, the distribution at each site by date is high, as seen in Figure 27, where the lower and upper quartile boxes (within which 50% of values fall) span a range greater than 15% in nearly a quarter of all sites. The variability of these distributions across sites is also high.

Some sites show concentrated efficiency values around their mean and others much broader, again with overlap anywhere between efficiencies of 10% and 50% for most sites. There are also several outliers relative to the total number of site date efficiency recordings within each site. These are likely attributed to the myriad of variables, some controlled and others not, that affect pump performance and efficiency calculations. There is a need for further research and analysis to better understand which variables drive the performance variability and how. This can be achieved by attempting to control more real-world variables during field testing and closely studying unique sites and performance patterns (such as the four sites for SWP 3.1 highlighted in the previous section) to uncover and isolate variables.

Figure 29: Average Daily Efficiency Distributions by Site

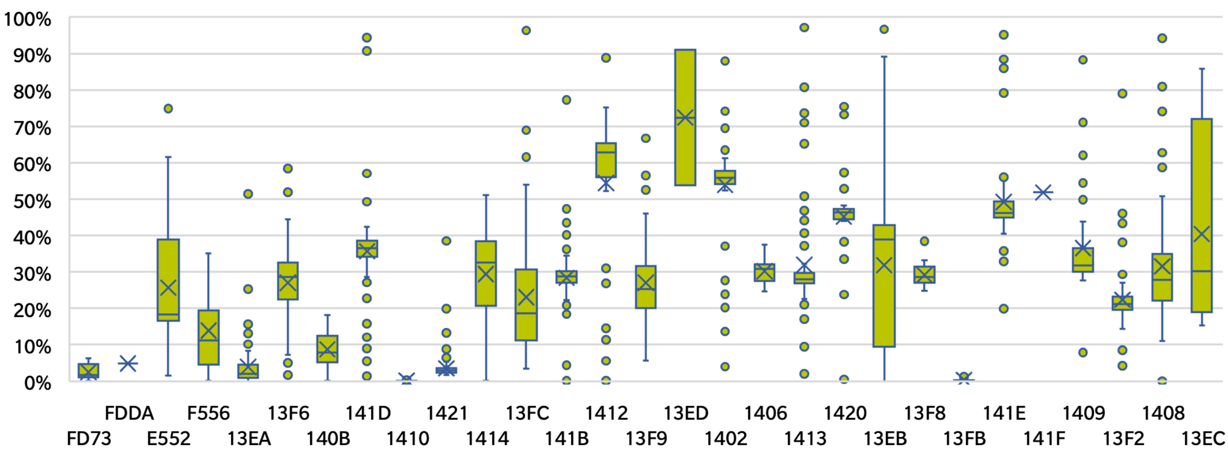


Figure 30 and Figure 31 show the average daily efficiency distributions for SWP 3.1 and SWP 4.4 at each site. Despite the mean result varying significantly across sites, the degree of variability at each site was relatively similar for both pump models. The vertical size of the boxes represents this, except for site 13EB, which has a very low n value, causing the distribution to look large. This indicates that once installed, the two pump models perform relatively consistently day-to-day, reflecting well on the pump's performance replicability. The likely explanation for the difference in the means is a function of the setup and other non-pump factors like the environment and user behaviour.

Figure 30: Average Daily Efficiency Distribution at Four SWP 3.1 Sites

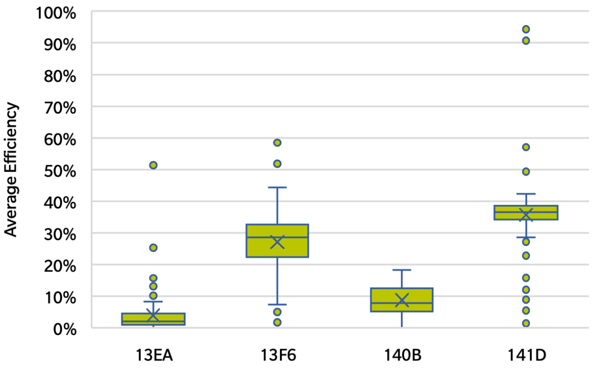


Figure 31: Average Daily Efficiency Distribution at Nine SWP 4.4 Sites

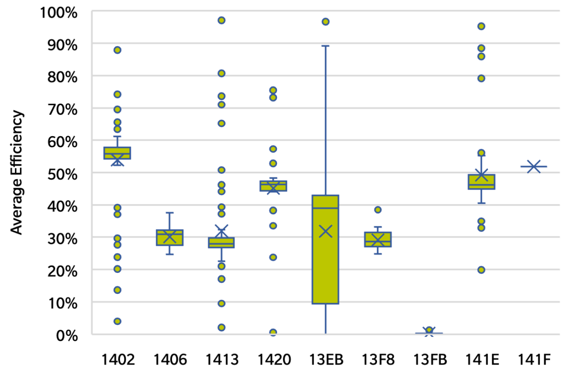
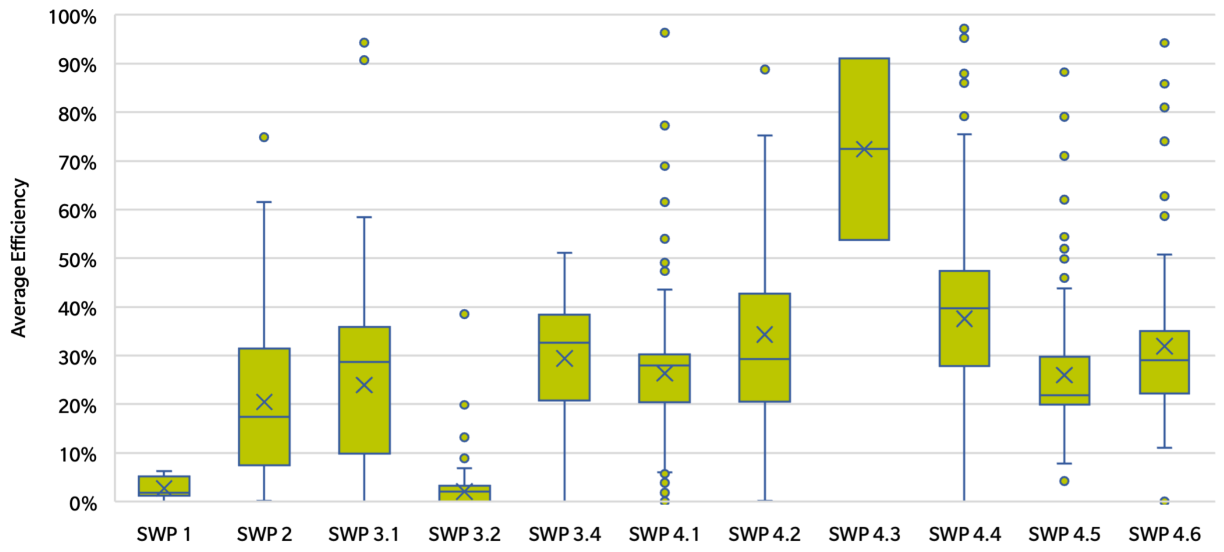


Figure 32 shows the average daily efficiency distribution by pump model. Aside from SWP 1, SWP 3.2, and SWP 4.3, all the other models have similar distribution profiles. Specifically, the 50% of middle data points that fall between the upper and lower quartile (the boxes) for each pump model span a similar range of about 10-20%. This indicates that SWPs (at least those in this project), regardless of brand and model type, appear to perform consistently with respect to efficiency. Half the days the pumps are in use, they operate at their mean, plus or minus 5-10% efficiency. At the same time, this indicates that the pumps operate outside this range for half of the days. For example, for SWP 4.2, a user could expect that every other time they use the pump, the efficiency will be between 20% and 40%, and every other day, the efficiency will be worse than 20% or better than 40%. Overall, this indicates that current SWPs have a relatively wide individual performance range that may make it difficult for users with more performance precision and predictability needs. The smallholder farmer market, however, primarily seeks to add irrigation to unirrigated crops, increase their access to it, or reduce its cost – not necessarily for precision irrigation.

A key takeaway from this finding may be that it highlights the importance of complementary pumping system solutions that minimise the effect of the high variability of SWP daily efficiency performance. For example, storage tanks allow farmers to irrigate crops independently of SWP operating times and flow rates. While battery-integrated solutions also help address performance variability, current models generally do so within a 24-hour period (due to batter sizes), which likely doesn't offer as much potential for reducing multi-day and seasonal performance variability as a storage tank.

This analysis presents an opportunity for future research to compare the ROI for using or developing different solutions that reduce SWP performance variability. For example, from a farmer's perspective, what is the ROI of buying and using a storage tank in conjunction with a SWP, learning and implementing a drip irrigation system, vs buying and using a battery for the SWP, vs buying more precise/high-performing SWPs? From a funder's perspective, what is the ROI of investing in the education/deployment/market transformation/technical development of the same type of solutions?

Figure 32: Average Daily Efficiency Distribution by Pump Model



Comparison of field and lab daily efficiency performance

A comparison of lab and field technical performance was carried out for SWP models that had sufficient field technical performance data and existing lab performance data (Table 5). SWP 3.1 performs very similarly in the field as in the lab. However, as the site data below and the distribution analysis in the previous sections show, the range of performance in the field is very wide, and the site values are far from the lab value. SWP 4.4 performed much worse in the field than in the lab.

We also note that the total head in the sites 1 and 4 exceeds the maximum stated head but the efficiency performance differs in both cases. Additionally, the low head of 7m reported in site 3 does not translate to better efficiency. While there may be an error in recording the borehole depth, the significant performance differences between the lab and field reflects the need for more research and analysis to understand specific drivers of performance variability better. This is especially important for developing a more relevant and robust lab testing methodology that better mimics the real-world use and performance of SWPs.

Table 5: Comparison of Lab and Field Results for Daily Efficiency

	SWP 3.1					SWP 4.4				
	Field Efficiency	Lab Efficiency (Ave Irradiance Day)	Lab Simulated Head (m)	Max Stated Head (m)	Field Head (m)	Field Efficiency	Lab Efficiency (Ave Irradiance Day)	Lab Simulated Head (m)	Field Head (m)	Max Stated Head (M)
Field Efficiency Overall	21.00%	20.00%				37.6%	63%			
Site 1	3.90%		25	48.9	80	53.90%		80	16	120
Site 2	27.10%		25	48.9	21	30.20%		80	25	120
Site 3	8.70%		25	48.9	7	31.90%		80	12	120
Site 4	27.40*%		25	48.9	66	45.10%		80	30	120
Site 5						31.80%		80	16	120
Site 6						29.10%		80	16	120
Site 7						0.30%		80	13	120
Site 8						49.20%		80	16	120
Site 9						51.90%		80	16	120
Difference Between Field and Lab	1.00%					-25.40%				

A comparison between the manufacturer specifications and field recorded data indicates that there is a slight difference in operational parameters between the stated performance by the pump manufacturers with what is recorded in the field as indicated in Table 6.

Table 6: Field Parameters Versus Lab Specifications

#	Country	Lab specifications			Field measurements		
		Max Voltage (V)	Max Current (A)	Max Power (W)	Max Voltage (V)	Max Current (A)	Max Power (W)
1	Senegal						
	SWP 4	200	14	2,800	185	13.8	2,146
2	Kenya						
	SWP 1 (Direct drive)	60	5	120	62	4.6	155
	SWP 2 (Battery)	34	8	200	43	6.8	228
3	Tanzania						
	SWP 3	380	12	4,560	403	13.8	3,374

In Kenya, few instances were recorded for the two solar water pump models where the stated maximum power from the product's technical sheet was exceeded. The rest of the pump operations were within the stated specifications. In Tanzania and Senegal, which both had high-powered water pumps, our monitoring devices rated to 20 A current readings recorded saturated readings in four instances, i.e., once in Tanzania and three times in Senegal. This analysis excluded these readings as the data suggest monitoring device malfunction. We also noted that the SWPs in Tanzania had several instances where the maximum voltage and current were exceeded. These instances are a concern as this erratic performance may pose a fire hazard and risk to pump operators and their surroundings, in addition to potentially damaging the pump.

3. CONCLUSIONS AND RECOMMENDATIONS

3.1 SWP User Behaviour

This field-testing exercise covered both technical performance data collection using monitoring devices connected in series to the water pumps and user survey data collection from the pump users. Some of the conclusions from the user surveys include:

- **SWP users in three countries operate their pumps for an average of approximately four hours daily, typically beginning at 6 AM**. Our analysis indicates that pumps equipped with automatic start-stop features (SWP 3 and 4) have longer operating times because they begin pumping at dawn and stop at dusk without user intervention. However, most users of these pumps do not store the pumped water, which may lead to unsustainable use of water resources, particularly when pumps operate for extended periods without regulation.
- **Users of battery-powered water pumps exhibited the greatest variability in pump start times**, with some starting as early as 4 AM and others beginning as late as 2 PM. This flexibility, as well as the pump's ability to power other household appliances, was identified as a desirable feature, particularly among direct-drive solar water pump users in Tanzania.
- **Significant correlation between water sufficiency and water storage behaviours exist among SWP users in the three countries**. Specifically, users in Senegal reported the highest incidence of water insufficiency and the lowest levels of water storage. Given that many of the solar water pumps in Senegal are situated in arid regions of the country, raising awareness and promoting the adoption of water storage as a means of adapting to water scarcity and managing water resources sustainably is of utmost importance.
- **Water pumps that draw water from wells are vulnerable to impurities that clog the small water passages of the pump inlet, particularly among SWP 2 users in Kenya**. To address this issue, we recommend fitting submersible pumps with a reverse flow mechanism that can automatically flush out impurities at the end of each pumping session or upon detecting impurities, such as during dry runs. This approach will help maintain clear water passages and prevent impurities from blocking the system. Furthermore, incorporating larger filter screens may also be beneficial.

3.2 Solar Water Pump Daily Efficiency

Based on the energy performance data, we observe that all of the solar water pumps operate within acceptable technical limits, except for those sampled in Tanzania, which have an overshoot of nearly 10% in both voltage and current. The consistent performance of the other metrics indicates that the control electronics are well-designed and function properly. Some of the key takeaways from the technical performance evaluation include:

- **SWP models exhibit an average daily wire-to-water efficiency of between 20-40%**. However, we also found that the daily pump efficiency varies considerably across different models, sites, and dates, indicating that a pump's efficiency is highly dependent on a variety of factors, primarily related to site setup conditions, such as power output, horizontal distance, and vertical lift of water from the source, as well as pumping peripherals, such as pipe types and diameters.
- **The variability in the efficiency of solar water pumps makes it difficult for SWP users to predict their performance when in use and to understand how this variability affects their water yield**. Based on our initial assessment, we recognise an opportunity for future research to leverage the data and insights from this project to identify the specific variables that drive performance variability and to assess whether farmers are affected by it or could benefit from solutions that reduce the impact of SWP performance variability.
- **Tracking the performance of portable SWPs was found to be challenging in the field, as site setup conditions would frequently change.** This was particularly true for SWP 1, where end-users would move the pump around, varying the depth and height at which the water needed to be lifted, as well as the horizontal distance the water had to travel. This highlights how end-user behaviour contributes to performance variability due to varying site setup conditions.
- **The high variability in pump setups and conditions means that comparisons between lab and field efficiency are not very relevant without tightly controlled testing environments.** Comparing the performance of two individual pump models through field testing showed inconsistent results compared to lab performance, with a difference of up to 40% lower or worse. This suggests that lab testing is not a reliable predictor of the project's field-testing outcomes.
- **Based on our analysis, we conclude that the current methodology and reporting of lab testing may not provide sufficient insights into the variability of real-world performance.** This research provides an opportunity to update the current lab testing methodologies by including optimal pump performance ranges that consider the variabilities in the installation set-up.

In the future, researchers can build upon the findings of this project by focusing on specific hypotheses that are relevant to the performance of solar water pumps. One such hypothesis is that farmers have their own ways of dealing with performance variability, which may not necessarily involve the solutions provided by SWP technology providers like storage tanks and drip irrigation techniques. Investigating this hypothesis can provide insights that can help the SWP industry in developing product roadmaps, sales strategies, and prioritising interventions. It can also inform funders on where to allocate resources.

3.3 Recommendations

- Although lab assessments are commonly used to assess the performance of SWPs against the manufacturer's specifications, we observed that lab performance results might not be a reliable comparison for field testing due to the significant variability in pump performance. **To address this, we recommend that proper training of installers should be implemented, and strict adherence to installation and operational guides must be maintained during installation to mitigate the variability in performance over time**. We also suggest that manufacturers provide detailed installation and operational manuals for installation and routine maintenance practices to improve the overall performance of SWPs.

- **We recommend that it is beneficial for SWP users to adopt water storage as a standard practice.** Water storage can allow for flexible irrigation scheduling, including nighttime when evaporation rates are lower, reducing water waste and increasing crop yield. It is recommended to bundle water harvesting and storage facilities with SWPs and educate users on the importance of water storage.

- **We recommend exploring options for using second-life batteries from electric vehicles and other applications to power SWPs.** While current battery technologies are suitable for low-power SWPs, using second-life batteries can lower the cost of batteries and provide SWP users with cleaner energy sources to power productive use and other household appliances. This is particularly important as the majority of SWP users are in off-grid areas and require affordable and sustainable energy sources.

- Based on our analysis, we observed that some SWP users increased their farming acreage, which led to increased irrigation needs. As a result, their pump's performance was affected as it couldn't meet their pumping requirements. **To mitigate this issue, we recommend that SWP manufacturers and distributors should encourage farmers to purchase a larger pump that can accommodate any future changes, such as increased land acreage or a change in the current water source.** These options should be highlighted during purchase, so users understand that altering the recommended pump setup may affect the pump's performance.

4. FIELD TESTING CHALLENGES AND LESSONS LEARNED

4.1 Challenges

Global System for Mobile communication (GSM) Connectivity: All of the solar water pump (SWP) locations had poor GSM connectivity, primarily due to the remote locations and physical barriers, such as corrugated iron sheet roofs, obstructing the signal strength. This limited the transmission of real-time data to the online platform, making it difficult to continuously monitor performance remotely. Despite this challenge, the Remote Monitoring and Management (RMM) system was designed to include local data storage using an industrial-grade Secure Digital (SD) card, ensuring that no data was lost. Some respondents were initially sceptical about the RMM and the field-testing process, as they were unfamiliar with it. We reassured them that the devices would not interfere with the operations of their water pumps.

Respondent Interference and Tampering: In all three countries where the SWP monitoring devices were deployed, some respondents interfered with the devices despite being warned not to do so. Additionally, some water pumps broke down, and the respondents did not reinstall the monitoring devices after repair. One RMM device in Tanzania was reported stolen. Although tampering did not affect instantaneous measurements such as voltage, current, and power, it affected the matching of time series data from the flow meter and RMM energy meter, causing a drift between the two and making them fall out of pace. For instance, removing a water meter causes stagnation in its measurement, while the energy meter continues to measure unabated, resulting in a drift between the two datasets. In such cases, these sites were excluded from the analysis.

Need for more technical specifications data and support during RMM installations: In Tanzania and Senegal, the installation process of solar pumps varied and was not standardised. Some pumps had concrete fixtures built around the control modules, which made it difficult to install monitoring devices. Despite the monitoring devices being designed to be easily installed in series with the wiring and water piping, the concrete fixtures hindered this process. Additionally, Tanzania did not have an accurate registry of the SWPs installed at the respondent's premises. The data collection team consistently found that the pumps installed had different specifications from those provided by the partners, leading to incorrect installation practices. For example, inaccurate pump outlet pipe sizes resulted in purchasing the wrong installation fixtures, which had to be substituted after the initial field visit.

Overall, although the monitoring devices (RMM and water meter) were placed outdoors, we noted that there was no significant damage to the devices nor any water ingress from the rain that affected the electronics.

Data loss and Outliers: Data cleaning was conducted to remove known or potential data errors that fall into the following categories:

- Site, pump, and monitoring equipment issues
  - Damaged pump
  - Pump failure
  - Pump moved/not used
  - RMM failureRMM was stolen/damaged

- Poor and inconsistent data
    - Incomplete/mismatched data readings (e.g., energy consumed reading captured but no water volume reading captured)
    - Calculated efficiency values that aren't possible because they fall outside the domain range (i.e., less than zero per cent and greater than 100 per cent)

Future research could be done to understand better the most common and unclear causes of potential data error, specifically sites where efficiency data points fell outside the theoretical domain range (0>eff>1), pumps failed, and RMM equipment failed.

Figures 33 and 34 in the Annex show the number of field-testing sites and site days (i.e., a specific date and site where at least one performance metric was recorded) that were excluded from the analyses in this report and the reason for the omission.

4.2 Lessons Learned

Valuable lessons were learned from the experience of this novel field testing which we characterise here into the following recommendations for future field-testing campaigns.

- **Plug-and-Play monitoring devices**: The devices used for the quantitative data collection should be plug-and-play to interface with the appliance being monitored. This should be the case for off-the-shelf devices and bespoke monitoring devices designed for a specific field-testing initiative. Plug-and-play monitors allow for easy setup by the testing team and further allow for troubleshooting in case of a device malfunction. Further, plug-and-play devices should ensure that the monitoring device does not impede the normal functioning of the appliance and its operation by the respondent.

- **Respondent consent forms**: All respondents should be briefed on the purpose of the field testing and informed on the level of commitment/involvement required from them to manage their expectations at the point of first communication. The output of this should be a signed consent form, their understanding of how to interact with the monitoring devices and sharing of emergency contact information.

- **Frequent scheduled calls**: It is advised that respondents should receive regular communication throughout the field-testing period. We found this to be a valuable source of information when analysing the quantitative data and triangulating events. For example, from the constant communication with the respondents, we understood that the usage patterns of the solar water pump in Kenya are linked to rainfall patterns as they rely on rain-fed agriculture during rain.

- **Data recording frequency**: We note that the most accurate data that can be obtained from a field-testing exercise should have a sampling rate as high as that of a lab testing scenario. In this regard, sampling of electrical energy parameters should be at the per-second level rather than the per-minute level to capture instances of transient occurrences such as in-rush current/voltage or device failure due to power saturation. This approach is considering the saying that "A second in electrical circuits is an eternity".

- **Data storage redundancy**: It is advised to set up a data storage redundancy chain that allows for the backup of the key monitored data. This should include upload of the data to the cloud in real-time, where it can be further stored offline and local storage of the monitoring device using SD cards or device memory. Though more challenging, the real-time upload of data is the most preferred data acquisition format to ensure constant verification that the monitoring devices are online and operating within the desired operating boundaries. Real-time data collection may involve using GSM, LPWAN, Wi-Fi, or Bluetooth networks, depending on which is the most suitable for the specific field testing.

- **Quick response field team**: Field testing across multiple regions or geographies must ensure that each region or geography has a quick response field team that can address emergent respondent issues and ensure that the monitoring devices can be repaired if damaged. The team should be well-versed in the technical design of the monitoring devices and have a contact list of all respondents in their vicinity.

- **Respondent incentive**: Providing the respondents with an incentive can ensure there is easier reception of the field research compared to where none is provided. This, however, must be judged on an appliance basis so as not to distort the respondent's usage patterns of the appliance.

It is crucial to control or measure as many variables as possible that impact the performance of SWPs due to a large number of such variables and their significant degree of impact. One way to achieve this is to calculate efficiency regularly, either daily or at intervals throughout the day, to obtain more detailed data. However, to calculate efficiency accurately, all variables in the formula must be known, including the vertical lift of water, which may change daily for surface pumps when they are moved around. Future research should emphasise creating complete datasets rather than just collecting a large volume of data to enable in-depth analysis and increase confidence in developing insights.

4.3 Next Steps

The results of this field-testing exercise will be used to prioritise updates to the Global LEAP SWP Test Methods before the Global LEAP Awards competition for SWPs later in the year. These updates will then be used to update the current IEC SWP test methods and develop quality standards for SWPs in collaboration with the Schatz Energy Research Center (SERC).

The findings will also be used to engage in discussions with SWP manufacturers and distributors about improving the design and functionality of SWPs based on feedback from end-users. These discussions will take place during Efficiency for Access' technology working group roundtables, which happen every quarter.

Figure 33: Daily Efficiency vs Energy Consumed

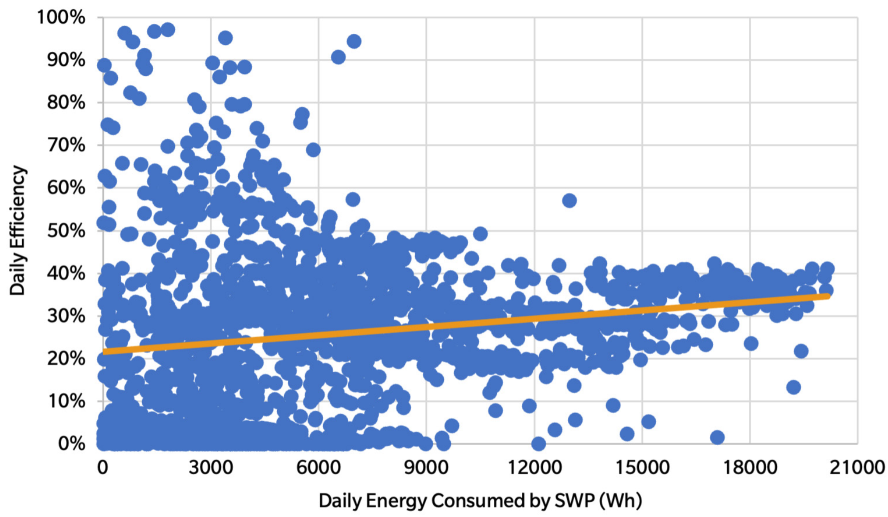
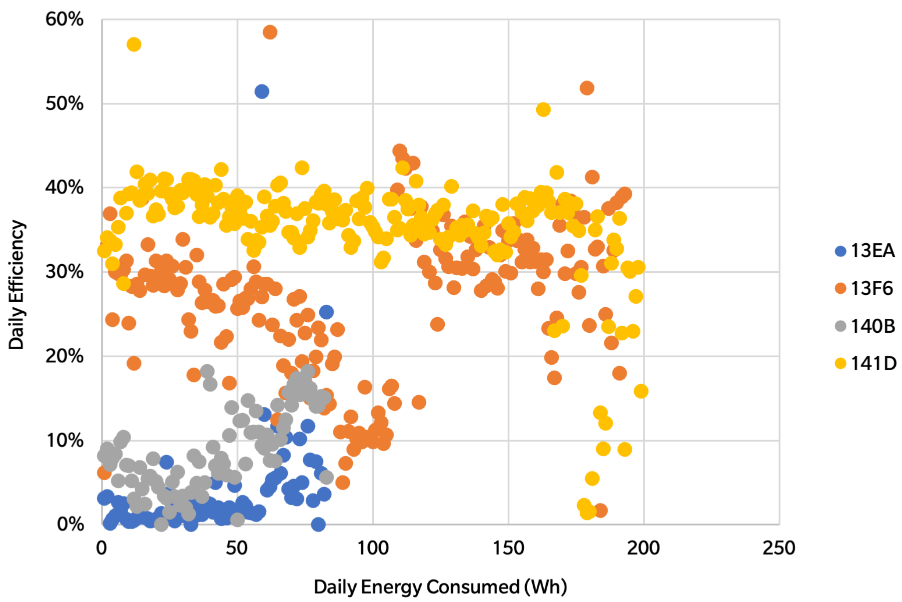


Figure 34: Daily Efficiency vs Energy Consumed at SWP 3.1 Sites



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