SOLAR WATER PUMP DURABILITY RESEARCH MEMO

MAY 2020
EFFICIENCY FOR ACCESS COALITION

Photo: Arne Jacobson

CONTEXT

The Schatz Energy Research Center (Schatz Center) conducted performance and durability testing on solar water pumps in support of the 2019 Global Lighting and Energy Access Partnership (Global LEAP) Awards Solar Water Pump (SWP) Competition – a program implemented through the Efficiency for Access Coalition.

SWP durability is a key issue identified by market actors; however, there is limited information and data available to provide insights on durability and quality concerns. This memo identifies common SWP failure modes through the following sources: a review of relevant, researched literature, evaluations through laboratory testing, as well as qualitative data obtained through stakeholder interviews. This memo also includes recommendations for and potential improvements to the current SWP test methods to enable better evaluation of pump durability.

This memo was developed by Nathaniel Faith and Kaileigh Vincent-Welling, Tyler Bernard, and Arne Jacobson- of the Schatz Center. In the development of this memo, the Schatz Center worked in close collaboration with CLASP as part of the Low Energy Inclusive Appliances (LEIA) program, which is a flagship program of the Efficiency for Access Coalition. Efficiency for Access is a global coalition that promotes energy efficiency as a potent catalyst in clean energy access efforts. Currently, Efficiency for Access Coalition members lead 12 programs and initiatives spanning three continents, 44 countries, and for 22 key technologies.

The Efficiency for Access Coalition is jointly coordinated by both CLASP, which is an international appliance energy efficiency and market development specialist, non-profit organization, and the UK's Energy Saving Trust, which specializes in energy efficient product verification, data and insight, advice, and research.

The authors acknowledge the following people/ companies that provided significant support and input into this memo:

Cai Williams (Impact Pumps); Adrian Honey, David Lemke, Hendrik Hansen (Lorentz); David Katz (Simusolar); Max Garnick (Sunculture); Alan Spybey (Kickstart); Martina Groenemeijer (Futurepump)

Scott Toyama, Meg Harper, Elizabeth Van Skike, Chih-Wei Hsu, Eli Wallach (Schatz Energy Research Center); Michael Spiak, Elisa Lai, Wendy Hado, & Riley Macdonald (CLASP).

Cover photo by Arne Jacobson, Schatz Energy Research Center

This memo has been funded by UK aid from the UK government. The views expressed do not necessarily reflect the UK government's official policies.

Schatz Energy Research Center | clasp | energy saving trust | UKaid from the British people

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ACRONYMS & ABBREVIATIONS

AC	Alternating Current
DC	Direct Current
GLOBAL LEAP	Global Lighting and Energy Access Partnership
IEC	International Electrotechnical Commission
kW	Kilowatt
LEIA	Low Energy Inclusive Appliances Programme
MPPT	Maximum Power Point Tracking
OCP	Overcurrent Protection
OVP	Overvoltage Protection
PWM	Pulse-Width Modulation
ROI	Return on Investment
SWP	Solar Water Pump
SWP TWG	Solar Water Pump Technical Working Group
W	Watt
Wh	Watt-Hour

EXECUTIVE SUMMARY

The Schatz Energy Research Center (Schatz Center) conducted performance and durability testing on solar water pumps (SWPs) as part of the 2019 Global Lighting and Energy Access Partnership (Global LEAP) Solar Water Pump Awards competition. During this time, information regarding SWP durability was compiled through testing, interviews with various SWP experts, and a review of relevant, available literature. The information assembled from this work is intended to inform next steps for possible development of test methods for assessing the quality and durability of SWPs used in small-scale agricultural settings (less than 2kW in size) in areas such as in rural Africa and Asia.

SWP durability is a key issue identified by market actors for numerous reasons: high upfront system costs for customers; relatively higher manufacturing costs incurred by companies that use more durable materials and component technologies in their systems; and the variability of success of installed SWP systems due to an array factors discussed in this memo. The most significant challenges related to SWP durability, as identified by industry experts and literature, are: designing systems that can function effectively over time in "dirty water" (i.e., high levels of sand, clay, or salinity); designing systems that can be effectively used in highly variable, site-specific, geographic conditions; and difficulties in providing adequate user training/education. Additionally, user issues, such as improper handling and maintenance, were cited as being among the top reasons for system failure in the field. Another set of challenges are related to the limitations of laboratory testing for quickly and inexpensively assessing SWP system durability due to the nature of pump failure mechanisms and the wide variety of conditions experienced in a field setting.

Limited literature is available that describes test methods, standards, and durability expectations for SWPs for the size range and applications considered in this paper. The literature that is available demonstrates a lack of consensus regarding basic concepts, test methods, metrics, and applicable standards. For example, there is no clear formal definition of "failure" for SWPs, and there are no accepted standard estimations for the life expectancy of SWP systems. Literature and industry expert interviews suggest that SWP systems (including surface and submersible pumps) may have expected lifetimes ranging anywhere from two to 25 years. Further, this research noted that "failures" due to user misuse differ from "failures" due to a mechanical or component deficiency or issue, and that these respective types should be defined.

The Schatz Center tested the performance of 37 SWPs using a custom laboratory setup in a controlled environment, with simulated using a pressure-sustaining device and variable pressure valves as described in the companion document, Global LEAP SWP Test Method Version 1 (Schatz 2019), summarized in Appendix B. The sample included more submersible pumps (81% of tested pumps) than surface pumps (19% of tested pumps). Pumps were assessed for durability using a visual screening and an internal inspection to determine the quality of materials and workmanship, pump condition, and functional durability (i.e., repetitive operating of controls and dry-run protection testing). Findings from these assessments indicated that pumps used a variety of materials and designs and exhibited good workmanship. Rust and corrosion were cited as the most common issues during assessment. Additionally, most tested SWPs had dry run protection (68% of pumps) and some type of known voltage control (81% of pumps).

Based on the analysis described above, the Schatz Center team makes the following recommendations:

- Develop a set of definitions for failure conditions for use in test methods and standards development
- Include the following in any durability test method:
    - Visual screening, intake, and functional durability tests, such as those conducted during this project and described in this memo
    - Recommended tests for which existing methods have already been developed (miswiring, mechanical durability, and battery durability and safety)
- Conduct additional research to adapt the following existing test methods from IEC/TS 62257-9-5 to SWP technology: overvoltage protection (OVP) and overcurrent protection (OCP)
- Conduct additional research to develop test methods to assess SWP durability in "dirty water" conditions. Expert interviewees and the existing literature cited sand, clay, and salinity as significant concerns.
- Assess return on investment (ROI) so that maintenance costs are taken into account when estimating the real lifecycle cost of a SWP system; this can then be used to calculate comparative metrics such as dollar per watt-hour ($/Wh).
- Determine which existing standards can be incorporated into a SWP quality standard. Existing standards for materials, bearings, seals, operating temperatures, and other topics have been developed for water pumps and other technologies that could be applied to SWPs. Selected applicable standards are listed in Appendix A.

INTRODUCTION

The purpose of this memo is to provide insights into the design and implementation of durable solar water pump (SWP) systems; replicable test methods to assess SWP durability in a lab setting; and quality standards related to SWP durability. This document provides useful information for the development of test methods and quality standards for the emerging global SWP industry, specifically SWPs used in small-scale agricultural settings (less than 2kW in size) in areas such as rural Africa and Asia.

Highly variable, site-specific geographic conditions and infrastructure create technical challenges for developing test methods and programs for SWPs. In the marketplace, one significant challenge is the trade-off between supplying more durable products at a higher initial cost, versus solutions with lower initial cost that may require more maintenance and operational expenditures over time. Additional challenges include the limitations inherent in laboratory test facilities, lack of accessible research using large sample sizes, undefined quality assurance objectives, and market conditions and barriers—particularly in developing economies.

This memo reviews relevant literature and summarizes SWP research findings from product testing conducted for the 2019 Global Lighting and Energy Access Partnership (Global LEAP) Awards Solar Water Pump competition and qualitative data obtained through stakeholder interviews. These summaries are followed by a description of potential test methods for SWP durability and recommended next steps for future test method development.

LITERATURE REVIEW

A review of relevant literature suggests that limited studies of small-scale agricultural SWP applications (less than 2kW) are available. Research has emphasized larger-scale systems, or individual components such as photovoltaic (PV) modules (Aliyua et al. 2018, Shinde and Wandre 2015). Due to the challenges of replicating diverse geographic and environmental conditions and longitudinal observations in a laboratory setting, existing research on small-scale applications consists primarily of field case studies, demonstration projects, and monitoring of installed systems (Shinde and Wandre 2015).

Field research typically finds that solar technologies are a viable solution for remote areas, particularly in comparison with fossil-fuel-powered pumping system common throughout rural Africa and Asia. Solar systems have become more affordable over the years, can be configured for specific conditions and installed on-site with little supporting infrastructure and required maintenance (Singh 2019, Malik and Vagh 2018, Shinde and Wandre 2015, Carrêlo 2014, Narale et al. 2013).

However, the life span of a SWP system depends not only on the technology used in the system, but also upon local geographic, environmental, cultural and water conditions for specific applications (i.e., type of crop or livestock irrigated), as well as proper installation, operation, and maintenance (Hipoldina dos Santos Isaías 2019, Singh 2019, Hadwan and Alkholidi 2018, Shinde and Wandre 2015, Corrêlo 2014, Hjalmarsdottir 2012). while PV modules are often warrantied for 20-25 years, the literature posits that submersible SWPs and controllers have expected life spans of 5-10 years or more, particularly if systems are well-maintained, are located in areas with relatively clear water, and are designed to be repaired in the field (Shinde and Wandre 2015, Hjalmarsdottir 2012). Information obtained through Schatz Energy Research Center (Schatz Center) interviews provided similar insights, supporting the literature. Little information appears to be available for surface pumps.

Field experience does not consistently support the expectations regarding sustainable system durability described in the literature. While advocates of SWPs often cite minimal maintenance requirements as an advantage, field research commonly finds evidence of adverse effects of improper maintenance, and cites that sustainable operation and maintenance of SWPs is an ongoing challenge (Thomson et al. 2012). Hadwan and Alkholidi (2018) found that performance can reduce to less than one-half of the original level over time. This reduction in performance level could also contribute to reduced life-span if the system requires replacing, because it cannot meet customer needs. Hjalmarsdottir (2012) reported that, while no major repairs were needed over a three-year field study of 39 water points served by submersible pumps in Namibia, installation issues were common. The water points mentioned served agriculture and other community needs, with livestock watering being a primary use; and the pumps were most likely installed by technicians. At the start of the project, 57% of pumping systems had technical problems that required correction. Almost all of these technical problems were described as "issues pertaining to initial equipment settings". Hjalmarsdottir (2012) also stated oversized systems too powerful for their application and faulty settings led to well exhaustion.

Additional studies cite user perspectives that solar technology can be deemed too expensive, with unproven durability; that SWPs are vulnerable to lightning, are difficult to repair, and repair services are not always available locally; and that theft and vandalism are common problems (Shinde and Wandre 2015, Hjalmasdottir 2012, Thomson et al. 2012). These findings suggest that adequate user education and support are as important to successful, long-term SWP operation as sound technological design and construction of the product (Malik and Vagh 2018, Hjalmarsdottir 2012).

From a technological perspective, Singh (2019) identifies the use of certified components from credible manufacturers as a factor in minimizing replacement and maintenance costs, and notes the importance of proper PV module sizing to ensure the desired level of system performance. In this research, no universal standards pertaining to SWP systems were found, but standards for individual components such as motors and bearings are available. Selected applicable standards are described in Appendix A.

Taken together, the above points demonstrate that additional research into small-scale (less than 2kW) SWP system durability in an agricultural setting would benefit the development of more comprehensive test methods, as well as applicable quality standards. The research presented in this report is intended to provide additional data to inform the development of each of these.

SWP QUALITY AND DURABILITY TESTING IN A LABORATORY SETTING

In support of the Global LEAP Awards competition, the Schatz Center conducted testing on 37 SWPs based on Global LEAP SWP Test Method to evaluate these products' performance, quality, and durability. Prior to being tested operationally at the Schatz Center as described in Appendix B, pumps were screened for general characteristics, ports, connections, cables, and recommended operating parameters using the following steps:

- Photographing all components, including any labels (both product specification and hazard labeling)
- Measuring component dimensions
- Reviewing the manufacturer's website, product packaging, user and installation manuals, and warranty information for ratings and consistency with product features and labeling. These materials are reviewed specifically for the following types of information:
    - Information provided in multiple languages, including English and common regional language
    - Information conveyed in images rather than text
    - Information presented in multiple sources for accessibility: labels on product components, in printed manuals, online, etc.
    - A warranty that is consumer-facing, provided with the product, and which contains clear instructions about how to access the warranty
    - Ratings information for physical ingress and water protection (IPXX ratings) and performance
    - Component specifications (i.e., maximum input voltage, maximum input current, etc.)
    - Instructions for installing, operating, and maintaining the system, including: (a) making pre-use connections, charging the battery, and positioning the PV panel, (b) keeping the panel clean and avoiding sediment buildup, (c) avoiding operating the system in extreme temperatures (if applicable)
    - Safety warnings to prevent injury
    - Cautions to prevent equipment damage (i.e., do not allow the pump to run dry)
    - Hazardous material disposal instructions
    - Any other useful information

When performance tests were complete, the following additional assessments were conducted:

- **Mechanical durability**: switches, buttons, ports, and controls were assessed by repeated operation to simulate use over time.
- **Dry-run protection**—including sensors versus integrated controls—was assessed by attempting to operate the pump without a source of intake water. This test simulates the water source level dropping, which exposes the pump's motor to dry running. This can occur in droughts or if a well isn't sized properly for SWP system (or vice versa). Running dry can cause damage to seals, and increase the operating temperature, which can damage the motor or other system components.
- **Internal inspection**, conducted by opening the pump and motor enclosures, discharging fluids if applicable, and examining the individual components to assess quality and internal conditions:
    - Bearings: type (sealed, shielded, open or combination), material, rating, number, and placement
    - Impellers: type (i.e., open, closed, semi-closed), materials, and configuration
    - Motor: type, general condition, appropriate power to operate the pump, proper securing of components, insulation
    - Connections and wiring (internal): assessing the conditions, including worn insulation, loose connections, pinched or twisted cables, sufficient gauge, and workmanship quality
    - Water in motor enclosure (unless the pump is water-cooled): including in and around bearings
    - Type of lubricant in enclosure, such as oil: including in and around bearings

- Rust, corrosion or wear: including pinching of wires or worn insulation, loose connections, or other signs of loss of integrity

- Charge controllers, when provided: integrity of materials, solder joints, and use and condition of adhesives and fasteners

The mechanical durability test simulates button, switch, and port use overtime to assess the quality of these components in relation to SWP functionality. Should a switch fail during this test, it could prevent proper functioning of the SWP and therefore reduce durability. Testing for dry run protection involves simulating a water source level falling—due to drought, because the well isn't sized properly for the SWP, or because the SWP is removed from the water source during operation. Dry running can lead to overheating of the motor and result in SWP failure. Further, the visual and internal inspections were conducted because SWP characteristics, such as the type of pump and materials used in construction, affect durability. Inspecting the interior of a pump can reveal rust, corrosion, wear, leaks, or other damage. Damage, poor construction, or inferior materials make pump failure more likely. Images presented in Figure 1 show some of the types of wear that can be identified during an internal screening, which is conducted immediately after a pump undergoes short-term performance tests. In addition, due to the importance of bearings to pump functionality, bearings were inspected and photographed as shown in Figure 2. These tests can provide an indication of general SWP quality and help identify potential durability issues. However, they cannot directly indicate how durable a SWP will be when being used in the field by a customer over a longer period of time.

System durability can also be affected by proper installation, use, and maintenance, so the quality and accessibility of information about the product and its use were included in durability testing.

Figure 1, left to right: A submersible pump impeller end cap, closed metal impeller, and the hydraulic oil reservoir located between the impeller and stator casing. Significant rust and discoloration are visible on the internal end cap and the impeller, while the reservoir shows rust and discoloration around edges.

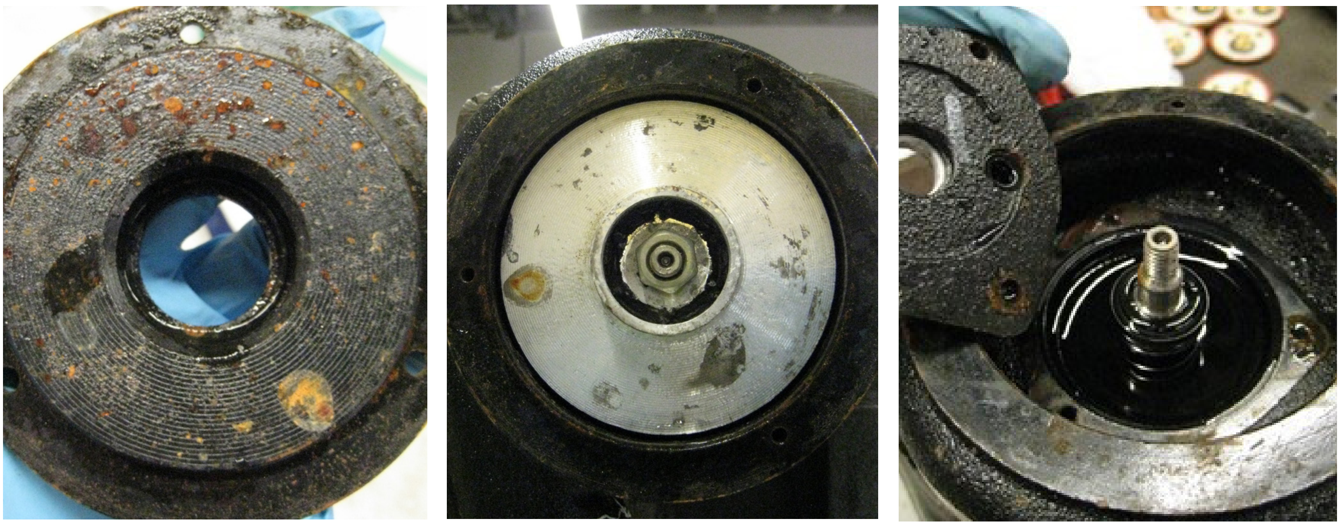
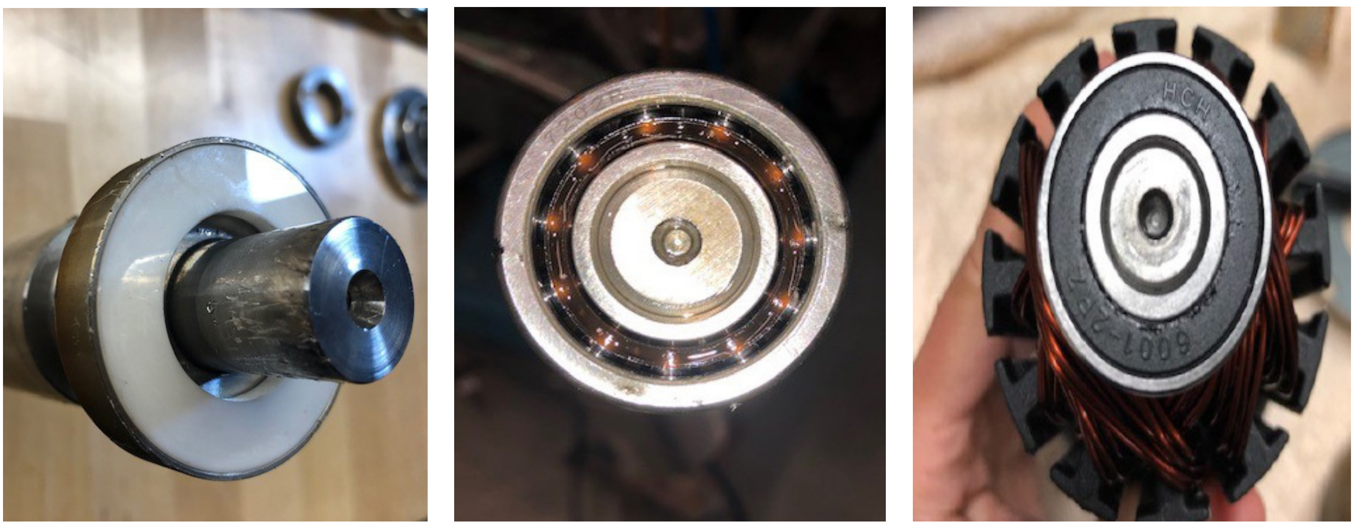


Figure 2. Bearings were photographed and assessed during the internal visual screening since they are often a limiting component for SWP system durability. Left to right: ceramic plate to allow the pump rotor to spin, an open, metal ball bearing, and a motor-end, sealed, metal ball bearing



Characteristics of the 37 Tested SWPs

In total, 37 pumps were submitted for testing by 17 manufacturers/distributors, 14 of whom submitted products that competed in the awards contest. The section below summarizes the characteristics and observations of all 37 pumps tested.

Overview of SWP Characteristics

As shown in Table 1, the majority of pumps tested (81%) were submersible. Over one-half of the tested pumps (54%) were centrifugal, over one-third were helical rotor; positive displacement pumps were less common (8%). A majority of the pumps tested (68%) included dry run protection; however, it was not possible to assess all pumps for this feature. There were two main reasons for not being able to assess dry run protection on a pump: either the pump was submitted without any information or specifications with which to determine appropriate test parameters, or a necessary component was not provided. For example, a water level sensor may have been advertised but not provided.

Maximum Power Point Tracking (MPPT) was far more common (76%) than Pulse-Width Modulation (PWM) (5%) for voltage control. For the samples that were not assessed, this was because no information about the voltage control algorithm was provided.

Over one-half of the devices tested (57%) were pumps with a direct current (DC) motor and a controller, compared to 16% of pumps that used an alternating current (AC) motor with an inverter.

Plug and socket connections were the most common, followed by screw terminal connections, with fewer pumps using screw ring/spade connections or clamps.

Input Power

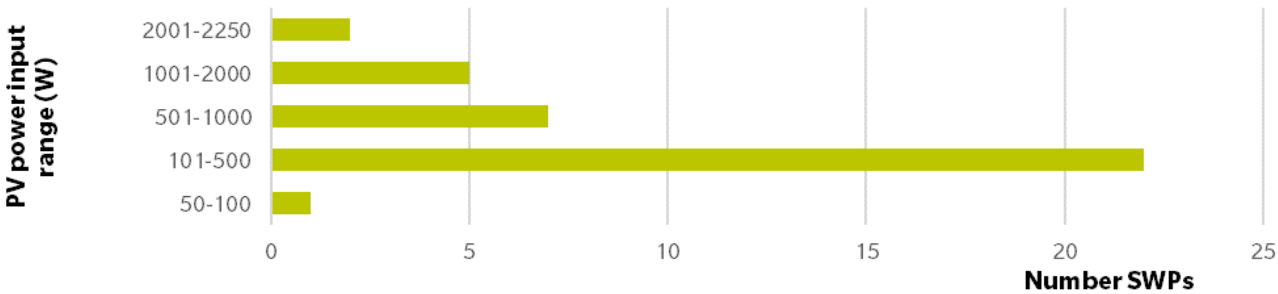
Figure 3 displays the various sizes of the PV arrays simulated during testing and how many SWPs fall into each range of input power. Note, one SWP tested was tested using two different PV array sizes and was tested twice for performance using these two different inputs. As shown, the largest bin

Table 1. Characteristics of SWPs submitted for testing at Schatz Center, May 2019- March 2020

Pump Characteristics				
Category	**Submersible**	**Surface**		
	30 (81%)	7 (19%)		
Type	**Centrifugal**	**Helical Rotor**	**Positive Displacement***	
	20 (54%)	14 (38%)	3 (8%)	
Dry Run Protection	**Included**	**Not included**	**Information Not Provided**	
	25 (68%)	5 (14%)	7 (19%)	
Voltage Control	**MPPT**	**PWM**	**Information Not Provided**	
	28 (76%)	2 (5%)	7 (19%)	
Pump type and Control	**DC pump with a Controller**	**AC pump with an Inverter**	**DC without Controller****	
	21 (57%)	6 (16%)	10 (27%)	
Connections***	**Plug and Socket**	**Clamps**	**Screw Terminals**	**Screw Ring/Spade**
	8 (22%)	2 (5%)	6 (16%)	4 (11%)

* Two used pistons, one used a screw.
** Not all pumps were submitted with accompanying voltage controllers. Some pumps are designed to operate without such components.
*** Some results involve correlation with particular manufacturers. For example, the four pumps that used screw ring and spade connectors were all produced by the same manufacturer.

Figure 3. Number of SWPs tested in different ranges of PV power input



includes 22 SWPs (59.5%) that were tested with a PV power input between 101 and 500 W.

Bearing Materials and Types

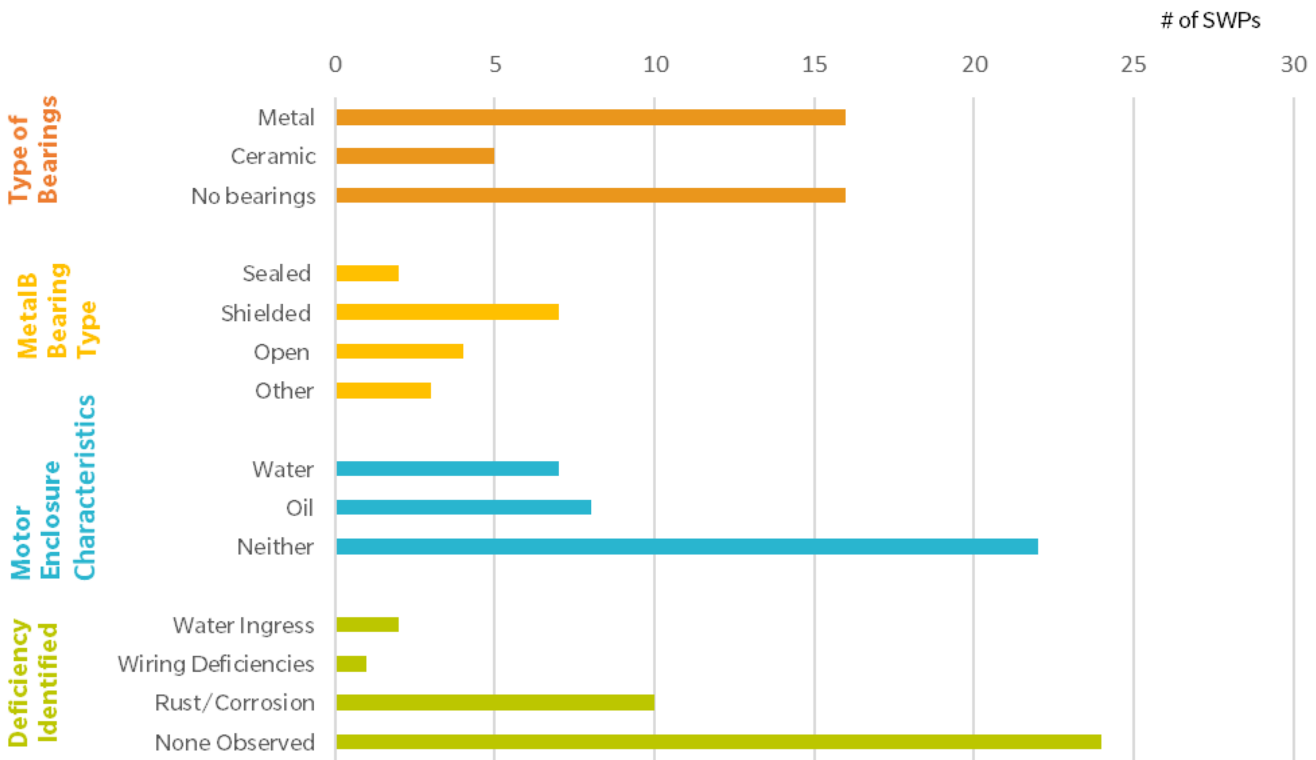
Over one-half of tested pumps (57%) incorporated either metal or ceramic plate bearings into the design. Forty-three percent of the SWPs tested included metal bearings, while 13.5% included ceramic bearings. Another 43% did not include bearings, shown in Figure 4 below. Metal bearings were observed as being either shielded, sealed, open, or "other" (meaning there wasn't enough information to determine). Shielded metal bearings were the most commonly observed (Figure 4). According to industry association information, sealed bearings are typically considered more durable; however, bearing selection depends on the application (PRS 2020, AST 2010).

Lubrication Types

SWPs are sometimes lubricated with hydraulic oil, or alternatively have a water-cooled motor enclosure. Typical combinations include water-cooling with ceramic bearings, and oil lubrication with metal bearings, although variations do occur. Figure 4 shows that an approximately equal number of pumps used oil or water within the motor enclosure, respectively, while most SWPs used neither water or oil in the motor enclosure as a design feature.

Three types of issues that may affect pump durability, as well as performance and safety, were identified in the samples tested, as shown in Figure 4, below. Most common were signs of rust or corrosion, with 10 pumps exhibiting slight to severe rust, or wear accompanied by the presence of loose shavings. Two pumps that were not designed with water-cooling were observed to have water in the enclosure. It was considered to be a potential durability flaw to observe water within the enclosure when metal bearings were present, due to the likelihood of bearing failure over time because of rust. While water was found in the enclosure of only two pumps, the presence of rust on other samples suggests leakage may be an issue for those samples. Wiring was assessed according to the following criteria: all electrical connections were sound (no loose connections or poor solder joints, etc.), all of the wires had proper insulation (with no signs of wear or ruptures), and wiring was neatly and securely organized within the motor and controller, if applicable. Wiring deficiencies were not common, with only one pump exhibiting such deficiencies.

Figure 4. Additional Characteristics of 37 tested SWPs



INTERVIEWS

As part of this research, Schatz Center staff interviewed industry experts to obtain valuable perspectives on the most current trends and field conditions. Interview feedback also provided an informal means of validating test results by providing a perspective based on field experience regarding expectations for pump performance and durability. Finally, interview responses complemented the literature survey, which was limited by the lack of published research pertaining to SWPs of this scale.

A total of 10 individuals representing seven SWP manufacturers and distributors participated in seven scheduled interviews. The majority of interviews were conducted in-person and over the phone. One was conducted via email. Most of the interview candidates were selected from a list of members of the Solar Water Pump Technical Working Group (SWP TWG) who had attended a meeting in November, 2019. The SWP TWG is a group formed under the UKaid-funded Low Energy Inclusive Appliances (LEIA) Programme. A few of these respondents referred additional experts to this research project who agreed to participate. Information was also gathered through informal conversations during the Schatz Center team's visit to Nairobi, Kenya for the Global Off-Grid Solar Forum & Expo in February 2020. The individuals who provided feedback included researchers who have experience testing SWPs in the field, SWP product engineers and designers, and professionals with expertise in the SWP market.

Each interview consisted of 12 questions developed by the Schatz Center team, as shown in Appendix C. Questions were intended to collect information regarding the most common types of SWP failures, mitigation of these failures, and approaches for testing SWP durability in relation to these common failures. A failure can be defined as a condition that causes the SWP to stop working. However, one key finding of this research is that there are different types of failures which need to be defined in order to develop test methods and quality assurance programs. Failing conditions can could include degraded performance, as opposed to system shutdown. Failures also have different causes, and there is value in categorizing failure types when establishing definitions of failure. Component failure, issues resulting from improper system sizing and configuration, installation issues, and improper use can all contribute to a system failure. This research reveals that additional research is needed to define different failure parameters.

To help understand these issues, interview questions were designed to elicit responses in key topic areas pertaining to pump failure and durability. These questions were developed during SWP testing and while conducting supplemental research. Six researchers and testers from Schatz Center developed the questions over the course of two months, drawing from previous hands-on experience with pump testing and the associated test results. Table 2 summarizes some of these key topics, which include: environmental factors, product design, user/technician behaviors, and limiting SWP components. These are issues currently observed in the field, some requiring additional research and testing, and where standards development could be useful. Other key topics, which include current problem-solving practices, durability testing needs for both stakeholder interests and standards development, and manufacturer abilities to address these issues, are discussed further below.

The current SWP test methods address some of these issues. Environmental conditions currently are not being addressed. Some of the topics related to product design are being addressed, such as dry run protection and water ingress. Dry run protection is tested and mechanisms are documented for each SWP, and functionality is confirmed after this test to ensure the SWP was not broken in the time it took for the SWP to stop dry running. Water ingress is noted during the internal screening of the SWP after conducting all tests; this is when signs of rust, bearing conditions, and any internal deficiencies are noted. The battery quality and durability are currently not being assessed. User/ technician behavior are briefly being assessed by conducting visual screenings on all included SWP documentation aimed at providing information to the customer to assess whether or not there is sufficient information on: installation, operation, maintenance, and warranty. In terms of limiting SWP components, the only component being currently assessed is a pump's bearing(s). Bearing type, condition, and number in each SWP is documented.

According to current general design and testing practices, respondents emphasized the prevalence of field testing. According to two respondents, field testing is quite common in Kenya. The country has numerous demonstration sites, and manufacturers field test installations regularly. Another respondent stated that every product they manufacture undergoes field trials, with some installations supplemented by lifetime monitoring. Another interviewee described a two-phase testing process at their company where pumps are first tested in semi-controlled conditions, and then installed at no or low cost to users who agree to allow their systems to serve as test cases.

Various respondents reported that the emphasis on field testing over laboratory testing is due to the high cost and difficulty involved in replicating variable environmental conditions in a controlled environment.

Table 2. Failures discussed during Schatz Center SWP durability research interviews

Issue Causing Failure	Description of Potential Failure
Environmental Conditions	
Water Quality ("Dirty" Water)	• Sand causes abrasion and wear; different types of sand cause different types of damage to various types of materials • Clay causes blockages and clogging • Salinity causes corrosion
Product Design	
DryRun Protection	• No protection feature • Protection mechanism fails • The protection mechanism is inadequate in its response time when dry running occurs
Water Ingress (other than water-cooled pumps)	• Seal failure lead to potential motor damage, often due to rusted metal ball bearings failing
**Battery	• Battery failures can lead to electrical damage • Batteries may need to be replaced more frequently in order to have the SWP output expected by the user
User/Technician Behavior	
Installation Issues	• Users do not understand the instructions provided • Users are not knowledgeable about system requirements such as proper well depth to allow sufficient water buffers for submersible pumps (i.e. hand-dug wells are common in sub-Saharan Africa at places of installation- this could lead to increased particles in the water ("dirty water") and improper depth and width of the well.) • Damage occurs during installation, such as nicked wires, which lead to electrical shorts or other damage • PV Systems are not sized properly • Systems are not positioned properly • Damage occurs during transportation to installation site (i.e. SWPs transported on the back of motorbikes and getting dropped accidentally in-transit and breaking)
Operation and Maintenance Issues	• Users may lack understanding of the product, leading to inappropriate customer service complaints, such as reporting a failure when the pump doesn't operate in overcast conditions • Equipment is subject to rough handling and is not properly maintained. This may be affected in part by the water source; users who rely on shared sources such as rivers may have to transport the pump back and forth each day • Users do not always understand warranties: if there is a warranty, how to access the warranty, or what is covered • Warranties may terminate before financing (e.g., PAYG) is complete (e.g., 1-2 year warranties are common; financing may be 3 or more years) • Manufacturers may go out of business before warranty periods expire • Replacement parts may not be available near the location of the customer • User manuals may not provide enough information, present information simply, or present information in the correct local language(s). Additionally, a user manual may not be included at all.
SWP Limiting Components	
Limiting SWP Components (vary by pump)	• Brushed DC motors: brushes fail • Helical rotor: steel wears in dirty water • Centrifugal design: water ingress into motor compartment • Piston pumps: seals on rods fail • Pumps with batteries: batteries fail • All pumps; bearings fail; however, they can be replaceable • Dry run protection mechanism fails

*Note: Water ingress is not necessarily considered an issue in all cases. Some technologies are meant to use water as a cooling lubricant instead of oil to mitigate the issue of inevitable water ingress. The pumps tested that had this design feature did not use metal ball bearings but rather ceramic plate bearings for smooth rotation.
**Note: Most SWPs tested at Schatz Center did not include a battery.

Discussion

One of the primary goals of this research is to inform the development of test methods and quality standards for SWP durability. According to respondents, there are no known standards specific to SWP durability, and that due to the variety of pump types, the development of a single comprehensive standard that applies to all products may not be feasible. As the results presented above show, there is significant variance of pump performance and sustainability depending on multiple factors. The development of a suite of standards that apply to categories or types of pumps may be more appropriate than a single standard. These factors include: the different vulnerabilities and limiting components inherent to different pump types; environmental conditions, such as water quality, that are highly variable and specific to any one location; the different pump types and materials that may perform differently in varying conditions; and user information and support, which may be as important as any other criteria affecting product durability.

Additionally, variable environmental conditions and existing infrastructure may be more compatible with specific types of pumps. For example, some respondents noted that with the lack of drilled wells and high water salinity common in Kenya, centrifugal surface pumps may be more suitable for small-scale installations, depending on the use, because these pumps have been observed to perform better in high saline conditions.

Another general observation is that common terms may need to be defined. In literature and interviews, terms such as “type” were used to refer to submersible versus surface pumps, as well as centrifugal, helical rotor, and positive displacement. As further commentary on the term “failure”, one respondent also noted that users often confuse normal functioning with failure due to general misunderstanding of the product. Users may contact customer service to report that the pump is not operating on a cloudy day, for example. In general, respondents cited user behavior as an important factor in pump system durability, with one respondent attributing an estimated one-half of failures to user error. Installation issues were identified as the greatest source of SWP failures outside of technical issues, although installation is sometimes performed by a qualified professional, so these issues are not easily classified as solely user issues.

When asked what customers want, respondents cited that the most common requests are for lower cost and higher flow rate. Interestingly, customers were not reported to have commented on product lifespan, which is a common concept in regards to durability. It is possible that this was not commonly mentioned because it is understood to be inherent that users want a product that lasts. However, determining expected lifespan is uncertain. In general, interview respondents report that SWPs may reasonably be expected to last anywhere from 2-5 years, with some products observed to operate for 20 years after installation. One respondent estimated that it is reasonable to expect 8,000 hours of operation for a quality pump operating in reasonably clear water, with performance diminishing for steel pumps operating in sandy water. Regarding motors, some respondents estimated that brushless DC motors can last up to ten years if the user is well-informed about proper maintenance and source water is either clear or appropriately filtered, but they also acknowledged that this not consistently the case with installed systems. Literature does not tend to distinguish between surface and submersible pumps with respect to lifespan estimates. The two pump types may be subject to different stresses, in that surface pumps may be transported from place to place, while submersible pumps may be subject to water pressure and quality in different ways than a surface pump. As yet, there appears to be little literature exploring the difference in lifespans for the different pump types. It would be useful to distinguish this feature of pumps in the literature.

In terms of current practice, in the absence of quality standards specifically applicable to SWP systems, a few respondents noted that they refer to existing standards for motors when assessing components. Appendix A contains a list of applicable standards that may be relevant to SWP test methods and a quality assurance program.

Respondents noted, though, that while standards would be beneficial for assessing product quality, there are many factors beyond manufacturer control, which may require infrastructure support or other programmatic cooperation, such as financing schemes, to ensure that products perform as expected in the field. Based on findings in the literature and respondents, issues include:

- The lack of drilled wells
- The fact that many wells are not sufficiently sized to allow adequate water around submersible pumps
- Some users must use community or shared water sources, such as rivers, which require users to transport the pumps to and from these shared water sources each day. This type of use increases wear and tear on pumps.
- Vandalism and theft may be common

Clearly, pump and system durability are affected by proper installation and use. Therefore, a comprehensive quality standard, or suite of standards, would include the assessment of the quality of user information on installation, operation, and warranties and service.

POTENTIAL TEST METHODS FOR SWP DURABILITY AND RECOMMENDED NEXT STEPS

After gaining experience from testing, conducting a literature review on SWP durability, and receiving feedback from interview respondents, the Schatz center research team presents the following in this section:

- Recommendations from respondents for actions that manufacturers could take that do not require the development of additional testing or standards
- Additional durability metrics for consideration in test method development (Table 3).
- Durability metrics that require more research before consideration in test method development (Table 4).

Respondent Recommendations

One concept expressed by some of the interview respondents is to focus less on avoiding failures, and instead devote efforts to minimizing the adverse effects of failure. Many respondents agreed that components will fail due to factors beyond their control, such as environmental conditions, or improper use (even when training is provided). To address this, these manufacturers design their systems so that when a component fails, it does as little damage to the system as possible, and they ensure that parts and service are readily available to restore the system to operation as quickly as possible.

Respondents further recommended the following as measures manufacturers can take under current conditions to improve pump system durability, even as testing methods and standards remain under development:

- Product design modifications
- Incorporate quick-response dry-run protection
- Use quality materials, including:
    - Quality seals on switches and ports (lip seals and mechanical seals)
    - Higher quality batteries (or, omit batteries from the design)
    - Sealed ball bearings or ceramic plate bearings
- Incorporate adequate screening and filtration
- Incorporate proper bracing against vibrations
- Use coatings on wiring and more protection for electronics
- Consider designs using brushless DC motors
- Design systems so that parts are easily replaceable
- Employ connectors to prevent miswiring
- System implementation modifications
- Properly size systems for the application
- Implement remote monitoring to provide companies with more data from SWPs installed in various conditions and to enable them to receive immediate feedback on failure that they can troubleshoot in real time. In some cases, monitoring can help detect problems before they lead to failure, thereby providing an opportunity to address issues and increase system durability.
- Provide instructions and training in multiple languages and using images; the images could even be presented on the pump or controller itself
- Identify capable, local partners to provide installation services
- Make parts and services readily available and ensure that customers understand how to access them

Testing Recommendations

The Schatz Center team recommends using an enhanced version of the visual screening, intake, and functional durability tests described in "SWP Quality and Durability Testing in a Laboratory Setting" on page 7 as the first phase of durability testing. The visual screening conducted for the Global LEAP testing could be expanded to incorporate assessing SWP system components according to various available standards applicable to the specific component, such as materials, bearings, motors, and other standards. SWP components can be verified against rating scales or standards during visual screening to determine whether components meet recommendations. Applicable standards are described in Appendix A.

Recommendations for laboratory durability testing must consider the requirements for testing pump performance with varying water quality within an idealized test set up with limited space and time. Test benches can simulate PV module power and head, as described in Appendix B and in the companion document Global LEAP SWP test method version 1 (Schatz Center 2019); however, comprehensive testing for some of the recommended metrics may need to be phased in over time, to allow for test method development and equipment acquisition.

Table 3 describes durability tests found most relevant in this research for assessing a SWP's durability in a test lab setting along with our recommendations for each. The tests listed could potentially be added to the durability assessment already included in the Global LEAP SWP test methods. Table 4 describes durability tests that are recommended, but which require additional research to develop appropriate methodology. The information in the tables has been organized by priority (higher or lower) and level of difficulty to implement (easier or more challenging). Higher priority test methods are those which assess safety issues (i.e.., miswiring), acute system failure (i.e., seal failure), or the most commonly reported problems (i.e., dirty water). Lower priority test methods are those which assess more gradual failure or performance degradation (i.e., UV or heat degradation) or which may not apply to the majority of SWPs (i.e, battery durability). The test methods that would be relatively simple to implement are those tests that have already been developed for other technologies, and could be adapted to SWPs, while the more challenging tests may require extensive development of metrics and methods.

Additional considerations, including the life cycle cost of a pump and the required sample size for testing are discussed below the tables.

Table 3. Recommendations for durability test methods-existing

Test: Bearings and Seals	**Priority: Higher**	**Implementation: Easier**
Description	Challenges	Recommendations
It is generally acknowledged that seals on a SWP system will fail eventually, but it is most important to determine the impact that failure will have on the system and if it is significant. One way to assess this could be to observe upon internal screening if a pump has water in the encasement, and, if so, if there are any moving parts or sensitive electronics exposed that are vulnerable to corrosion/ rust/ water damage. Another possibility is to assess bearings and seals against standards and ratings.	Determining: • What the most vulnerable parts are to water internal to the pump (which would vary by pump) • How vulnerable the parts are (for example will exposure to water cause failure or minor reduction in performance, etc.) • Which standards to apply, and how to record the assessment information	Add this to the internal screening section of the current test report to note if there are any components (e.g., moving parts, sensitive electronics) that would be exposed in the case of water ingress to the motor enclosure. There could be an associated, defined severity score given.

Test: Reverse Polarity	**Priority: Higher**	**Implementation: Easier**
Description	Challenges	Recommendations
If possible, feed the positive power lead for the simulated PV power to the negative pump lead (or charge controller lead if applicable) and the negative input power lead to the positive pump lead (so to mismatch the power leads when wiring up the pump). This would simulate one miswiring scenario that could occur during installation. The pump should not be damaged or cause a safety hazard when wired incorrectly.	• Defining the potential safety hazard • Determining the appropriate length of time for the miswiring event during the test	Take safety precautions during this test. Knowing more about the typical end user and/or installer would be valuable when determining specific parameters for the test. An assessment of the user safety when re-wiring after miswiring should also be done by looking at manufacturer-provided information. If connectors are unique and cannot be interconnected incorrectly, this can be assessed during visual screening and functionality testing.

Test: Cable Strain Relief	**Priority: Lower**	**Implementation: Easier**
Description	Challenges	Recommendations
Applying force in various angles to all of the cables to assess a product's strain relief, or lack thereof	Defining the following parameters: • Testing time • Angles to test • Force to use	Follow the test procedure described in the IEC 62257-9-5, Annex W test methods to assess the strain relief of a SWP system's cables. In addition, it could be valuable to gather more information through field testing / monitoring to determine what force(s) / angle(s) to assess for a system's cables.

Test: Battery Durability	Priority: Lower	Implementation: Easier
Description	Challenges	Recommendations
Assesses a battery's durability over time. Note: In the sample tested, batteries were not commonly used. This test is rated lower priority due to the low number of pumps tested that included batteries.	Assessing and acquiring the additional equipment needed	Follow the test procedure in the IEC 62257-9-5, Annex BB test methods to simulate aging of the battery to assess durability.
Require safety documentation for the battery used in the SWP system and review it prior to testing. Overvoltage on a pack-level and individual cell-level would be assessed in this procedure. Note: As with battery durability, above, In the sample tested, this test is rated lower priority due to the low number of pumps tested that included batteries.	• Obtaining battery safety documentation • Assessing the battery safety documentation and determining whether it is acceptable or not.	Require lithium battery safety requirements, included in IEC 62257-9-8 for lithium batteries.

Test: Drop Test	Priority: Lower	Implementation: Easier
Description	Challenges	Recommendations
Assess the SWP and/or product's controller / inverter (not the PV module) for robustness against rough handling by the user (more applicable to surface pumps; less so for submersible pumps)	• Safeguarding against hazards: if wires come loose during this test and short circuit during testing, it could be a safety hazard • Determining which pumps and pump components undergo this test—surface pumps are more likely to be transported; submersible pumps are not	Follow the test procedure in the IEC 62257-9-5, Annex W test methods to perform this test on the pump and other included components (excluding the PV modules). It may make sense, so as to not become a safety hazard, to conduct an internal inspection of the components dropped after the drop test takes place instead of checking for functionality. More field research would be needed to determine whether to subject submersible pumps to this test.

Table 4. Recommendations for durability test methods-to be researched

Test: Overvoltage Protection	Priority: Higher	Implementation: Easier
Description	Challenges	Recommendations
Supply the pump with a voltage higher than the maximum rated input voltage. After exposure to the higher voltage, the pump should not be damaged and once powered at the rated voltage, should function normally.	• Identifying how to determine the input voltage to use during this test for each pump: appropriate voltage to use for this test will vary according to the electrical characteristics of pumps • Ensuring that sufficient information is provided with the sample in order to determine test voltages • Specifying the passing criteria	Before implementing a test method, conduct field testing to determine the appropriate percentage to be used to exceed the maximum rated voltage, or Vmp, specified for the pump. For example, the pump could be powered at a set voltage that is 15% higher than the maximum rated voltage, or another given percentage.

Test: Overvoltage Protection	**Priority: Higher**	**Implementation: Easier**
Description	Challenges	Recommendations
Supply the pump with a voltage higher than the maximum rated input voltage. After exposure to the higher voltage, the pump should not be damaged and once powered at the rated voltage, should function normally.	• Identifying how to determine the input voltage to use during this test for each pump: appropriate voltage to use for this test will vary according to the electrical characteristics of pumps • Ensuring that sufficient information is provided with the sample in order to determine test voltages • Specifying the passing criteria	Before implementing a test method, conduct field testing to determine the appropriate percentage to be used to exceed the maximum rated voltage, or Vmp, specified for the pump. For example, the pump could be powered at a set voltage that is 15% higher than the maximum rated voltage, or another given percentage.

Test: Overcurrent	**Priority: Higher**	**Implementation: Easier**
Description	Challenges	Recommendations
Supply the pump with a current higher than the maximum rated input current.	• Determining how to establish the input current to use during this test • Specifying the passing criteria	Similar to overvoltage protection above.

Test: Dirty Water (sand)	**Priority: Higher**	**Implementation: Challenging**
Description	**Challenges**	**Recommendations**
A specified concentration of sand is evenly mixed in the source water in a tank while the pump is running for a standard length of time. Sand can be very abrasive on pump components and wear them down over time.	• Identifying what concentration of sand to use for the best general representation of real conditions (acknowledging that all real life conditions will be different) • Determining the appropriate length of testing for an appropriate assessment • Choosing what type and size of sand to use • Specifying testing equipment (for instance, flow meters) that can handle significant particles flowing through them	Conduct additional research and lab testing to explore development of this potential test method. Information gathered could include the assessment of the types of sand and the concentrations in specific cases, as well as the wear pumps show. Using this information, it might be appropriate to use a specific type of sand at a concentration that is beyond what is expected to be seen in the field. (note this is different from testing using water with a lower concentration of sand over a longer time period). The results from this test could be assessed based upon a comparison of like-pumps after testing multiple pumps under the same conditions and for the same length in time. We also recommend that the component that failed first (that caused the pump failure) be noted. Determining both the most vulnerable point in a system, as well as overall wear, would be useful.

Test: Dirty Water (clay)	**Priority: Higher**	**Implementation: Challenging**
Description	Challenges	Recommendations
Running the pump in a specified very high concentration of clay. This test assesses if the pump would get clogged and if it would cause failure. This would simulate the SWP being installed too close to the bottom of the well and intaking clay-dense water.	• Similar to challenges above (sand)	Similar as sand above.

Test: High Salinity in Water	Priority: Higher	Implementation: Challenging
Description	Challenges	Recommendations
A specified concentration of salt in the water that is evenly-mixed throughout the whole test. High salts in the water can be very corrosive to the pumps depending on the pump materials.	Determining: • Which concentration of salt to use in the source water for best general representation of field conditions for locations that are highly variable from one another • Maximum length of test • What testing equipment could handle long-term testing	Similar to the two dirty water conditions (sand and clay) above. One test method that could be implemented without additional research would be to include an assessment of materials during visual screening and intake. Specific materials that have known susceptibility to damage from salinity can be identified during these processes (refer to Appendix A.)

Test: UV or Heat Degradation	Priority: Lower	Implementation: Challenging
Description	Challenges	Recommendations
This would check to see if UV or heat would damage a SWP system over time. This may be specifically aimed at surface pumps and pump controllers, which may be exposed to the sun during the day.	• Locating a test site or configuration offering consistent environmental conditions could be complex • Specifying length of testing time to capture long-term UV or heat exposure; for example, will months or years be simulated? • Identifying how to conduct this test to simulate a long length of exposure time without testing for a long time and spending significant amounts of money on testing equipment (solar simulator/ artificial sun)	Obtain more information during field testing and monitoring to understand whether users generally place surface pumps and controllers in direct sunlight. When sufficient data is available to determine the value of such a test, we recommend conducting the test in a controlled environment, whether it be tested in certain weather conditions or inside using a solar simulator (which would increase the overall cost for equipment significantly for the test lab).

Test: Dry Run Protection- Increased Repetition	Priority: Lower	Implementation: Easier
Description	Challenges	Recommendations
This would amend the current dry run protection test specified in the SWP test methods to increase the number of times this metric is tested. Repeating the dry run protection test for each SWP multiple times may be a more realistic durability assessment for this metric. The reason why this may be more realistic is because the source water level may change over time. It may drop and rise seasonally, which would expose the pump to potentially occasional dry running (more than a one-time occurrence).	• Determining what would be a representative number of times to conduct / repeat this test	Obtain more information through field testing / monitoring to determine how frequently pumps dry run within some given time frame. If the proportion of number of dry runs to time frame observed can be translated to the number of dry runs over the course of the given pump warranty, this could be an appropriate metric for developing a test method.

Additional considerations not summarized in Table 3 include financial analysis and sample size.

One respondent suggested that a cost-benefit or life-cycle cost analysis be included in durability testing, because a system's Freight-on-board (FOB) or retail price at purchase does not include other costs predicted over the pump's lifetime, such as maintenance costs. Life cycle cost isn't generally considered as a metric of durability; however, it is a cost metric often used to assess the applicability of a SWP for certain applications. To include life-cycle costs, however, such an assessment would need to account for the type of pump, materials used, overall design (specifically if the user is expected to maintenance their SWP system or a technician), accessibility and cost of spare parts and, if applicable, customer support for maintenance, and possibly additional assumptions. Some manufacturers and researchers are providing this type of information, so it may also be possible to reference manufacturer analyses for specific products undergoing testing, if information is available for that pump (Hjalmarsdottir 2012; DRFN 2008).

As a final consideration, enough samples must be submitted for testing to enable completion of all the specified tests. Competitors in the Global LEAP Awards Competition were required to submit two samples for testing. Samples undergoing durability tests may be subject to damage, so sample size is an important consideration. It can be beneficial to use a sample size larger than one for each test for at least two reasons. First, if a sample fails or is damaged during a durability test, it may not be possible to complete all tests, and therefore, not all potential failures would be assessed. Second, a larger sample size helps to ensure that the results observed represent the product itself, not just the sample chosen, when tests are conducted on multiple samples. The benefits of increased sample size must, of course, be weighed against the cost of providing the samples and carrying out the testing. An additional consideration is requiring SWP samples to be selected according to a methodology that ensures random sampling, such as random product sampling methods described in IEC 62257-9-5, Annex E.

CONCLUSIONS

Based on a survey of relevant literature, product testing, and interviews with industry experts, this research describes useful methods for assessing SWP product durability, while also identifying opportunities for further development of test methods and quality assurance requirements for SWPs.

Literature and respondent feedback suggest that all of the above measures that manufacturers and distributors can take require additional programmatic support to develop the SWP market. One important aspect of market research is the assessment of return on investment (ROI), particularly over expected product lifespans and typical loan periods. Such assessment helps develop appropriate financing mechanisms.

Finally, to reiterate a concept described by interview respondents, it may be useful to develop test methods and standards that emphasize minimizing the adverse effects of failure, rather than avoiding failure altogether. It is taken as a given among industry experts that components will fail. But, although it is not possible to avoid all failures, there are many ways to ensure that failures do as little damage as possible to systems, and that systems can be restored to full operation quickly. This concept could form the foundation for the types of pass or fail parameters determined for both testing and quality standards.

Photo: Simusolar

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STANDARDS AND GUIDANCE DOCUMENTS

Schatz Center staff reviewed either the abstracts or complete text of a number of standards that may be applicable to the development of a quality assurance program and durability test methods for SWPs. There appear to be few, if any, standards that apply specifically to SWPs, and most existing standards for other pump types apply to pumps that serve industry rather than agriculture. A variety of standards are available to ensure uniformity in design of pumps for petroleum extraction, chemical manufacturing, and related industries. Those standards were deemed more stringent than may be necessary for small agricultural applications and were not reviewed comprehensively. However, some standards that may be worth considering further have been briefly described here.

Two considerations regarding standards are:

1. Because there are currently no known requirements to design SWPs to a particular standard, one way to evaluate a product's durability is to assess whether the components used in the system are designed to specific component standards.
2. Much component information is produced by component manufacturers, so information quality and applicability will be a consideration for any test method development or quality assurance program development.

With the one exception noted, the following International Electrotechnical Commission (IEC) standards have been reviewed in their entirety.

International Electrotechnical Commission (IEC)

https://www.iec.ch/ The IEC develops international standards and manages conformity assessment systems in a wide variety of electrotechnology fields.

IEC 60034-18-31

This subpart of IEC 60034 was recommended by a participant in this research. The multi-part standard covers rotating electrical machines. Part 18-31 describes thermal endurance test procedures to evaluate function, windings, and insulation used in indirectly cooled AC or DC electric motors with form-wound windings. Assessing a product to this standard determines whether the motor is appropriate for the expected heat conditions in the application. This was not reviewed in its entirety.

IEC 60335-1 Household and similar electrical appliances – Safety – Part 1: General requirements

This subpart of IEC 60335 Household and similar electrical appliances – Safety, is extensively referenced in IEC 60335-2-41, described below. Both of these standards are recommended resources for the development of SWP durability testing methods and quality assurance standards.

Testing parameters include comprehensive guidance for visual screening and intake, including assessing materials, labeling, and proper sample preparation to protect against safety hazards. The standard prescribes comprehensive safety measures and methods for operational testing, including power and current, voltage tolerances for motorized systems, moisture resistance testing according to ingress protection rating, and many more. Annex P in these standards includes test parameters for systems intended to be used in warm, damp, equitable (WDaE), climates, and may be applicable to surface pumps designed for Asian and other tropical markets. A quality assurance program for SWPs could potentially include a recommendation that manufacturers consider designing products for such climates and complying with relevant standards, including labeling products with the WDaE marking.

IEC 60335-2-41 Household and similar electrical appliances – Safety – Part 2-42: Particular requirements for pumps

This subpart of IEC 60335 Household and similar electrical appliances – Safety, is directed at assessing pump safety, including pumps used in agriculture, so this standard applies directly to SWP durability assessment. Testing parameters include comprehensive guidance for visual screening and intake, including assessing materials, labeling, installation documentation, and proper sample preparation to protect against safety hazards. The standard prescribes comprehensive safety measures and methods for operational testing. These parameters include moisture resistance testing according to ingress protection rating for submersible and other pump types, static pressure testing, leakage test metrics, and more. Other safety standards are included by reference to IEC 60335-1 Household and similar electrical appliances – Safety – Part 1: General requirements, described above.

IEC 62253 Photovoltaic pumping systems – Design qualification and performance measurements

IEC 62253 covers the design and performance of PV pumping systems. That standards address testing either outdoors with a PV module, or indoors with a PV simulator. The standard specifies requirements for power versus flow rate, pumping head versus flow rate, system design parameters and requirements, specification, design verification, and documentation requirements. Pumping systems are categorized by motor type, i.e., brushless DC, DC/AC inverter, etc. Schatz Center performance test methods were developed in accordance with this standard; however, there are no requirements specific to durability. This standard incorporates several other standards by reference, which cover lighting protection, damp-heat suitability, and other requirements. This standard is recommended for incorporation into SWP durability test method development and quality assurance program design, which includes additional durability parameters.

With the one exception noted, the full texts for the following standards have not been reviewed. The recommendations below are derived from a review of the abstracts for the standards as well as recommendations from participants in this research and Schatz Center staff.

American Bearing Manufacturers Association (ABMA)

https://www.americanbearings.org/

ANSI/ABMA Standard 20 and the ABEC Bearing Rating Scale

Standards are ANSI-approved and apply to tolerances, precision levels, rolling elements, and more. For example, the ABMA's Annular Bearing Engineering Committee (ABEC) developed a scale ABEC rating ball bearing tolerances, ANSI/ABMA Standard 20, which correlates to ISO 492. The ABEC scale specifies standards of precision bearings in a specified class. Although the rating does not specify certain factors such as load handling, ball previous, or materials, a higher rating indicates that the bearing should provide better precision, efficiency, and potentially greater speed capability. These bearings are expected to perform well in applications requiring very high RPM and smooth operation. Bearings that do not conform to at least the lowest rating cannot be classified as precision bearings as their tolerances are too loose. Due to the importance of bearings in pump design and function, it may be useful to include bearings standards in testing and quality assessment.

A recommended starting point for durability testing intake and visual screening would be to ensure that testers can identify bearings by type, and to include this information in test results. Two useful sources of information are:

- AMBA puts out a primer on bearings at: https://www.americanbearings.org/page/what_are_bearings.
- AST Bearings, a manufacturer of bearings and related products, publishes descriptive information and guidance on choosing the right bearings for various applications, including agriculture. Selected resources are:
    - Bearings for Off Highway Industry & Applications (including agriculture) web page with links to further descriptive information: https://www.astbearings.com/off-highway-bearings.html
    - White paper, "Bearing Closures – Shields and Seals": https://www.astbearings.com/assets/files/ENB-04-0556-Rev-B-Bearing-Closures.pdf

After the bearings have been identified, it could be useful to determine the ABEC rating described above for bearings in pumps under test during visual screening or intake. The ABEC rating is not a comprehensive measure of bearing durability, and should be used in conjunction with information on bearing clearance, accuracy, lubrication and more. However, evaluating a bearing's tolerance against this rating scale can be a useful preliminary assessment.

Note: Although ANSI/ABMA Standard 20 was not reviewed in full, the ABEC rating scale is widely available, and has been reviewed in full. One source which lists the scale and describes the tolerances for each rating class is published by AST Bearings: https://www.astbearings.com/bearing-tolerances-precision-levels.html. A search for the terms "bearing rating scale" will return a number of additional results describing the scale.

American National Standards Institute

https://www.ansi.org/

ANSI supports voluntary standards and conformity assessment both in the US and abroad. Their standards encompass the majority of industries. A thorough review of all standards accessible through ANSI that may be applicable to developing a SWP durability quality assurance program is beyond the scope of this research. However, a few notable resources are described here.

ANSI/HI 9.1.9.5 – 2015 Pumps – General Guidelines

This guide is described as a comprehensive overview of positive displacement and rotodynamic industrial and commercial pumps, and is published by the Hydraulic Institute (HI, pumps.org). The guide is described as depicting a classification of pump types, standard materials used in the construction of pumps, and relative resistance of different materials to cavitation erosion. However, this guide includes extensive information on measuring sound, which is typically more applicable to indoor installations, so it is unclear how well this guide would apply to SWPs. It is recommended here as a possible accessible source on materials.

ANSI/HI 9.6.9 – 2018 Rotary Pumps- Guidelines for Condition Monitoring

This is a guideline, not a standard, published by HI, designed to offer users a tool for monitoring the condition of rotary positive displacement pumps. For this category of SWP, this guide makes recommendations for monitoring indicators of potential failure, such as temperature, leakage, pressure, and other factors. It also describes common methods to measure these indicators.

ANSI/HI 11.6 – 2017 Rotodynamic Submersible Pumps: for Hydrostatic Pressure, Mechanical, and Electrical Acceptance Tests

This guide is designed for test laboratory managers who are setting up pump tests and determining the instrumentation needed for testing and data collection. This guide may not be directly applicable to SWP testing, because it describes three levels of acceptance tests for pumps of at least 10 kW, in applications ranging from municipal water an wastewater, to industries such as chemicals and electric power. However, this standard includes an irrigation category, and default acceptance grades based on specific applications and driver rated power. The guide may offer some useful general guidelines that could be scaled down.

American Society of Mechanical Engineers (ASME)

https://www.asme.org/

B12.18.6/CSA B125.6 – 2017 Flexible Water Connectors

Although not likely to be directly applicable to the SWPs covered in this research, B12.18.6 provides requirements for flexible water connectors used in potable water systems. Specifically, standards apply to systems under continuous pressure. Physical and performance requirements, test methods, materials, connections, and materials are covered.

ASME/ANSI B73.1

ASME/ANSI B73.1 specifies a horizontal end-suction pump design that allows interchangeability across a variety of centrifugal pump sizes. The standard specifies the location of bracing bolts, the distance between the suction and discharge flange centerlines, the height of the pump centerline and overall dimensions. Impellers on pumps that are designed to this standard are open or semi-open. Designs are typically foot-mounted, because these standards do not specifically apply to agricultural water pumps. This standard may be most applicable for the reference to materials, bearing housings, and impeller styles.

American Society for Testing and Materials (ASTM)

https://www.astm.org

STP1167 Wear Testing of Advanced Materials

This guide was published in 1992, but is still available at the ASTM site. This abstract was taken from a search of the ASTM site (https://www.astm.org/search/fullsite-search.html?query=impeller%20materials&):

> "Erosion wear of centrifugal slurry pumps is traditionally attributed to two different mechanisms, particle impact and scouring, which occurs as a result of a sliding bed of particles scratching against the wear surface. The impact and sliding wear coefficients (energy consumed per unit volume of material removed) are usually determined by separately simulating the two processes of wear in laboratory test equipment. Although such simulations yield acceptable relative wear indexes for ranking wear resistance of materials, they fail to yield reasonable absolute values of wear coefficients when compared with actual measurements of wear on a pump. Possible reasons for this lack of agreement are proposed, and an alternative approach is presented to determine the absolute wear coefficients. This approach involves the finite element analysis of two-phase flow within the pump casing coupled with wear measurements on an actual pump casing. Test results for the simulated laboratory tests and the actual pump test are presented and discussed."

International Organization for Standardization (ISO)

https://www.iso.org/home.html

ISO 14847:1999

This standard covers technical requirements for rotary positive displacement pumps. The standard does not include safety or testing. The standard covers pump design, materials, installation, maintenance, and repairs. ISO 14847:1999 was not reviewed beyond the publicly-available abstract; however, it was recommended by a participant in this research.

Underwriters Laboratories (UL)

https://ulstandards.ul.com/

UL 778 Standard for Motor-Operated Water Pumps

UL 778 covers both submersible and non-submersible pumps that are motor-operated and rated a maximum of 600 volts, using universal motors rated a maximum of 250 volts. This standard specifically applies to pumps that are intended for use with water, in contrast to other standards reviewed in this research.

The standard specifies requirements for power switches (including endurance ratings), safety critical functions- such as a motor running overload protection and dry operation, and a range of other requirements for electrical circuitry.

Because this standard applies to water pumps, and includes at least some standards that apply to component durability, it may merit additional review. However, UL 778 incorporates IEC 60335-1, discussed above, by reference, so it may not provide extensive additional information.

The scope and table of contents can be viewed here: https://standardscatalog.ul.com/standards/en/standard_778

TEST PERFORMANCE CONDITIONS

Testing described in this document was conducted at the Schatz Energy Research Center (Schatz Center), over the period from June 2019 to March 2020. Previous documents have described the test equipment and methodology (Schatz Center 2019), some of which were based on IEC 62253:2011 (Figure B-1). Pump performance was tested using a tank and piped workbench in a controlled environment, out of direct sunlight (Figure B-2). The circulating piping included one meter of head, with remaining head simulated using a pressure-sustaining device and variable pressure valves. Pumps were tested in air temperatures generally within 62-75 degrees F, 17-24 degrees C), using clear, non-saline, water at ambient temperature. Water temperature was not measured. Additional details on the full test bench setup and some of the test procedures are described in the Global LEAP SWP Test Method Version 1 (Schatz Center 2019).

Figure B-1: IEC 62253:2011 test station diagram (Schatz Center 2019)

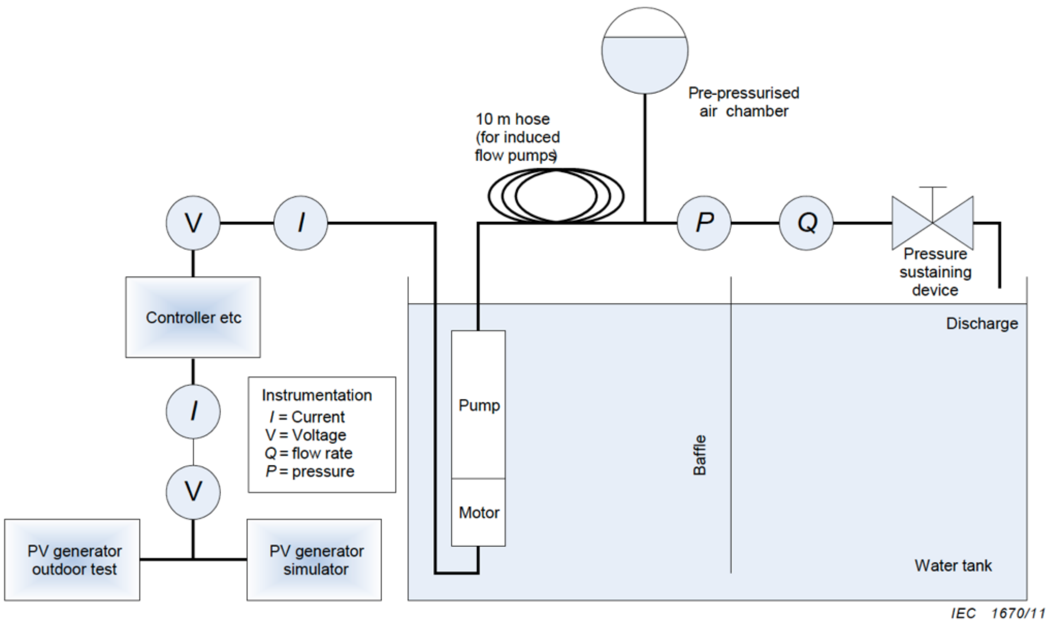

Figure B-2: Schatz Center SWP test station

APPENDIX C

INTERVIEW QUESTIONS

1. In your experience, what are the top three to five causes of pump failure in solar powered pumping systems?
    - For each of the main causes of failure that you have identified, what measures can pump manufacturers take to avoid that type of failure?
    - What measures can be taken by pump buyers to assess whether a pump is more or less susceptible to that type of failure?
2. In your experience, what role do users play in pump failure rates? That is, do their actions contribute observed pump failures all of the time, most of the time, about half of the time, rarely, or never?
    - If applicable, what types of user actions commonly contribute to pump failures? (e.g. improper installation, improper maintenance, improper use, …, etc.).
    - When users contribute to pump failure, does this happen due to lack of access to information (such as information that could be provided in a usual manual) or for other reasons? If it is for other reasons, please specify what they are."
3. Is there an existing durability standard for solar water pumping systems that you know about and/or recommend?
4. What is the typical lifetime of the pumps used in small scale solar water pumping systems (e.g. pumps with power draw < 2 kW)?"
5. What is the limiting component to the lifetime (e.g., the battery, electronic controls, motor, pump bearings, etc.)? Is the limiting component generally replaceable? Are warranties generally long enough to compensate for this
6. Do most SWPs have warranties?
7. What are some new, innovative designs for increasing durability or robustness of SWPs? (e.g., durable materials, different types of bearings and seals, new control strategies, etc.)
8. One common observation when testing pumps this last summer at the Schatz Center was water ingress into the pump motor caused by failed seals. This seems to be a major issue that could affect pump durability. In your view, what types of seals are most effective for preventing water ingress in situations involving rotating parts of the SWP? What types of rotating mechanical seals are used most commonly? Are you aware of designs that allow water to enter the electric motor or other electrical parts of the SWP? If so, what is your view of such designs?
9. During testing at the Schatz Center, we observed some pumps where the stator or other sections of the pumps were not braced well enough for the loads that they would experience. In these cases, significant wear was noted. Can you recommend approaches for assessing whether pumps have adequate internal bracing for relevant components?
10. Out of the pumps we've tested at the Schatz Center, many included dry-run protection. In your experience, how common is dry run protection among small solar water pumping systems (i.e. systems with pumps < 2 kW)? What is your experience with pumps that do not have this design feature with regard to their failure rate
11. Do you think that cheaper pumps made for applications related to small-scale agriculture in areas of Africa, South Asia, and Southeast Asia, that may require more maintenance (maintenance being relatively simple/ cheap) are more advantageous than more expensive pumps that may require less frequent maintenance (maintenance being more specialized)?
12. What are the most common customer complaints about solar water pumping systems? What is the most common positive feedback received?
13. Do you do any field testing of your solar water pumping systems? Are your pump designs based on test results from field testing? If so, what conditions do you test in?

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