Adoption of Solar Water Pumps in Tanzania: The Farmers' Perspectives

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***Abstract*— In Tanzania, solar water pumps experience sparse uptake by smallholder horticulture farmers. Thus, there is a need to surface information about the conditions on-site and provide an improved understanding of early-state challenges as well as of the farmers' situations and expectations. Moreover, expected benefits require validation. In order to assess the potential impact of solar water pumps, a logical model is developed according to the theory of change leading to a results staircase, which links the desired impact with required interventions. Field surveys based on participatory rural appraisal, during which 12 farmers are repeatedly visited during 13 weeks, deliver in-depth information on farmer level. Thus, farmer profiles are created encompassing among others farming details and water supply information. It is found that what farmers value most in a water supply system is reliability, followed by low operational costs and simple handling – all characteristics of solar water pumps and drawbacks of fuel pumps. However, most farmers require financial service, which indicates the initial investment barrier. Logistic troubles due to Tanzania's vast area result in unsatisfactory quality of service and increased costs constituting additional challenges. Moreover, assessing the farmers' needs and providing a properly designed system proves to be particularly difficult. Insufficient quality of water sources and deficient briefing of customers complete the early-state barriers encountered. The severity of the barriers is highlighted by the limited progress experienced by the farmers on the results staircase. Nevertheless, the logical model is partly verified, indicating solar water pumps' aptitude to enable rural prosperity.**

Keywords— Solar water pumps, solar irrigation, smallholder farmers, horticulture, theory of change, participatory rural appraisal

I. Introduction

Solar energy is by far the largest energy resource on this planet estimated up to approximately 50,000 EJ/year [1]. Tanzania itself receives an average daily global horizontal irradiation of between 1,700-2,400 kWh/m², higher than the irradiation experienced in South Europe [2]. At the same time, 80% of the labour force is employed in agriculture in Tanzania [3]. Nevertheless, the country's potential in the agriculture sector is still not being exploited and is mainly set up by subsistence and smallholder farmers [3]. Despite the potential to improve harvest yields and increase farmers' resilience, a vast majority of the food crops are not irrigated and suffer from the climate's unpredictability [3], [4]. Utilizing the country's solar resources to provide reliable and sustainable energy for irrigation purposes is considered promising with expected benefits in farm yields and thus progressing rural prosperity contributing to the Sustainable Development Goals [5]. However, the spread of solar water pumps for irrigation is extremely small with studies being unable to detect solar water pump users in Tanzania, which highlights the need of action to enhance the market [6], [7], [8].

Thus, CLASP and Simusolar Ltd. conducted research activities for the LEIA programme from the Efficiency for Access Coalition, yielding the report "Tanzania Market Snapshot: Horticulture Value Chains and Potential for Solar Water Pump Technology" [6], which delivers market intelligence on Tanzania's horticulture sector. Aiming to validate the findings and surface additional information on farmer level about consumers, market challenges, and impacts of solar water pumps, additional field surveys were scheduled. This paper constitutes a summary of the report of the field research.

II. Solar Water Pump Systems

Today's market is dominated by PV water pumping systems – solar thermal systems require more research to realize their latent potential [9], [10]. A water pump system powered by a solar PV system usually encompasses the standard components PV array, controller (e.g. MPPT controllers), electric motor (if an AC motor is used, an inverter is additionally required), pump, water storage tank, and BOS (e.g. wiring and piping) as shown in Fig. 1. Taking into account the high variety of water usage (e.g. crop irrigation, livestock watering, and domestic use) and the changing conditions on-site with varying water sources, distances, and elevations as well as irrigation technologies (manual, flooding, sprinkler, trickle, and their respective versions [11]), designing a solar water pump system is a highly customer-dependent activity [12].

Hand in hand with the technological progress, costs for PV modules have decreased in the past decades and are still decreasing, making solar water pumps an increasingly attractive solution [13], [14]. Compared with fuel-powered pumps, solar water pump systems are assessed as economically favourable [15], [16], [17], [18], and are generically found to be profitable with payback periods of less than six years [10], [15], [19], [20], [21], [22]. However, the high initial investment of solar water pumps caused mainly by the PV sub-system constitutes a high obstacle for smallholder farmers and the importance of access to credit for the rural population is repeatedly highlighted [15], [16], [17], [21], [18].

Solar water pumps are often deployed in place of fuel-powered or grid-connected pumps preventing CO_2 emissions [10], [20], [23], [24]. However, the exploitation of groundwater is a critical aspect to consider taking into account that groundwater use is expected to increase along with the

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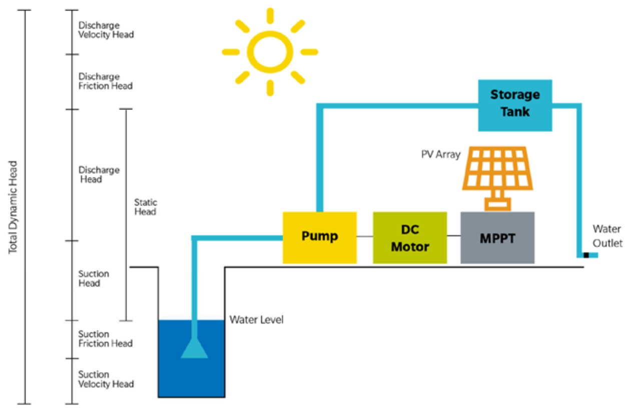

Fig. 1. Set-up of a solar water pump system [20].

spread of solar water pumps. In contrast to the case with fuel-powered pumps, the extractable amount of water is not limited by concomitant fuel costs in the case of solar water pumps [16]. Moreover, farmers using solar water pumps potentially expand their irrigated farmland and cultivate higher-value crops, which have often higher water demands, or they even provide water to neighbouring communities for domestic use and livestock watering [16], [25].

III. Methodology

A. *Theory of Change*

"Theory of change is […] a comprehensive description and illustration of how and why a desired change is expected to happen in a particular context" [26]. When applying the theory of change, a logical model is created encompassing the four levels Activities, Outputs, Purpose (i.e. desired outcomes that motivate the outputs pursued), and Objective (i.e. generic impact targeted, to which external occurrences may also contribute) [27]. In order to monitor and evaluate the progress and success of an intervention, multiple indicators are assigned to each level (the number of indicators required in each level varying from case to case) [27]. This work follows the approach outlined by PHINEO in the Social Impact Navigator [28], which sub-classifies the main levels Outputs and Purpose into three sublevels each generating a so-called results staircase as presented in Table II [28]. In terms of impact assessment, a more graduated logical chain is of great advantage since it allows a more detailed assessment of the level of impact reached after an arbitrary time period.

B. *Participatory Rural Appraisal*

The aim of this research of obtaining on-site information on farmers' level can best be reached when an actual engagement with the farmers is sought. Participatory rural appraisal was found to fit best to these requirements ensuring an equitable interaction with the participants.

Field research with PRA is characterised by elementary principles. First of all, learning is reversed as to learn directly and on-site from local people appreciating their knowhow and experience, empowering them to conduct the research activities themselves analysing and ranking, and changing the researchers' role to that of a facilitator. Moreover, a PRA researcher listens instead of lectures, is unimposing instead of intimidating, and seeks diversity including the marginalized and looking for variability and possible ranges in order to learn from exceptions. Therefore, PRA is conducted with a great consideration of improvisation, being flexible to adapt on-site and pursuing to optimize the cost-benefit trade-off in terms of quantity, accuracy, and relevance of the information obtained. On the same time, iterations and cross-checking are indispensable to triangulate and thus verify and validate the findings. [29]

The PRA methodology was applied during this research with help of Drei Wellen's "Toolbox for Exploration and Evaluation" [30], which was made available by the co-author S. L. Brugger and presents specific methods with a guideline of when and how to apply them. For this work, activities based on daily routine schemes, flowcharts, mental mapping, pair-ranking, seasonal calendars, transect walking, and timelines were developed. Moreover, the best-practices for conducting each activity as well as for good-interviewing presented in the toolbox were followed.

IV. The Field Trials

The field visits were separated into three rounds – an initial, a mid-line, and an end-line round – in order to obtain the desired information. Thus, it is possible to gain insights into the different stages of the adoption of solar water pumps, to develop a better understanding of the farmers' situations, and to provide a baseline analysis for a follow-up impact evaluation in future research. Moreover, visiting the same farmers up to three times throughout a period of three months allows to create rapport. Thanks to the cooperation with the Tanzanian start-up Simusolar Ltd., it was possible to get access to Simusolar's customer base and select 10-15 farmers based on the following criteria:

i. The installation of the solar water pump system happened not more than three weeks prior to the initial visit;

ii. The customer is using or planning to use the solar water pump for horticulture farming;

iii. The area used for horticulture is estimated to be less than 4 ha prior to the first visit;

iv. The customer is located within the following areas: Morogoro region, Central region, and the Northern Highlands.

By selecting farmers according to these criteria, the relevance of this research in reference to the Tanzania Market Snapshot [6] is assured. Taking into account the limited availability of the farmers, 12 farmers were identified to match with above criteria. Two additional farmers located in Pwani region next to Dar es Salaam, but fulfilling the first three criteria, were added as redundancy in case other farmers drop out. Due to the inaccessibility of two famers in the course of the field research (one in the Northern Highlands and one in Pwani), 12 out of the 14 potential farmers were visited – including one in Pwani.

A. *In the Field*

From the very beginning, the field trials were designed with the purpose of being flexible and adapting to the conditions on-site. As a natural consequence, many contingencies happened and multiple changes were implemented on the field last minute.

The initial visits happened before or up to three weeks after the installation of the solar water pump. In a few cases, it was possible to combine the initial visit with the installation of the pump. Making two rounds of the route Dar es Salaam

→ Morogoro → Dodoma → Singida → Moshi → Dar es Salaam, it was possible to complete the initial visits within a period of four weeks. This way, it was possible to include the midline visits in the second round of the route while finalizing the initial visits of the last farmers. This implies that only the farmers, which were visited within the first round of the route, could be included into the midline round. In the end, three farmers participated in the midline round approximately two weeks after their initial visit. It was chosen to follow this procedure and reduce the number of farmers in the midline visits in order to remain within the limited budget and use the scarcely available time optimally. For the end-line visits, all 12 farmers were included again. Between the initial and the end-line visit of each farmer was a break of 7.5 up to 11 weeks.

Once on the ground, compromises had to be made on how to conduct the field research. With respect to the proposed PRA activities, the optimal procedure would include the involvement of all farm members in almost every activity. However, the amount of persons participating in the activities reflects on the required time to complete the respective activity. With the proposed scope of work, there is a high level of active participation required from the farmers over an extensive period of time. To take up this amount of time was not possible with every farmer, and thus the number of participants for each activity had to be reduced. Moreover, the available number of participants was restricted since the farmers often don't live at the farm, and thus only a few of the farm members were at disposal during the field research. At some farms, the farm members would divide up between the activities (e.g. one farm member doing the transect walk and the mental map and another completing the seasonal calendar) so that each of them would remain with sufficient time to conduct their daily work. Despite the time constrains and thanks to the efforts taken as well as thanks to the farmers' hospitality, all farmers devoted at least half of their day to participate in the field research during each visit.

The order in which the different activities were conducted during the initial round of field visits varied from farmer to farmer. In most cases however, the visit started with a guided tour through the farm similar to a transect walk, during which the farmers introduced their farming activities. When thereafter continuing with the mental map, it was possible to recognise the different parts of the farm, ask specific questions and unveil information, which seemed irrelevant to the farmer as for example the extent of the unexploited farmland. This way, it was possible to gain a holistic overview and minimize the risk of missing information. Next, either the pair-ranking or the seasonal calendar activity followed. In many cases, it turned out to be better to close with the seasonal calendar and do the pair-ranking activity first since it became apparent that it required a lot of energy to fill out the seasonal calendar due to the level of detail required. The pair-ranking activity on the other hand was more straightforward and thus received positively. During completion of the seasonal calendar, the atmosphere usually decayed and motivating the farmers for another activity was challenging. Generally, it has to be pointed out that farmers usually alternate the cultivated crops from year to year without a fix scheme trying out new crops and farming methods aiming to improve their yield. Only a few basic crops are cultivated every year in the same way by the individual farmer. Comparing different years is challenging due to the varying cultivation and potentially different climate conditions thus limiting the comparison's validity. Obtaining information on the yield, income and expenses was challenging since not all the farmers were experienced and almost none kept records. Here, it was necessary to rely on approximate and – in case the farmer had just started – expected values. Regarding the employment situation, it varies on daily basis since most of the work is done by day-workers that are hired according to the present workload. The availability of the water source was in all cases except one constant throughout the year, so that only for one farmer it was included in the seasonal calendar.

There were also some difficulties in terms of the activities and measurements that the field researcher himself was meant to conduct. While the measurement of the cultivated area was easily done with the mobile phone application "GPS Tools" (in addition to the obtained GPS location, the satellite picture helped reaching a higher accuracy), measuring the entire area was at times only possible via satellite picture since parts of the farms were not cleared and therefore couldn't be reached to obtain the GPS location data. The water source, the water supply system, and the irrigation technology were inspected in all cases. However, the water level of the water source was not possible to determinate, since most of the boreholes were closed and/or too narrow to use measuring tools. Since the exact depth is only of importance when the water level is documented over a long period of e.g. one year, it was decided to skip the depth measurements and rely on approximate statements by the farmers and technicians. For the installation of water meters, which help measuring the usage of the solar water pumps, Simusolar agreed to take over and deploy its technicians for the installation. However, the customers' concerns that the chosen meters would limit the performance of their pump combined with unclear responsibilities and therewith unclear path of communication as well as logistic challenges resulted in four out of eight water meters installed – four farmers had no pump installed at the end of the field trials due to challenges with muddy boreholes, floods, and delayed payments by funders. The installed water meters were operating for 2.5 up to 9.5 weeks when read during the end-line round of visits.

The mid-line round of field visits was conducted as planned. Since many initial visits happened one to three weeks after the installation of the solar water pump, many challenges in adopting the new technology were already observed during the initial visit of the farmers. Thus, the aim of the midline visits was partly already covered by the initial visits. Nevertheless, the midline visits helped to gain an improved understanding of the diverse challenges for solar water pump adoption in smallholder horticulture farming in Tanzania and yielded additional insights.

The end-line visits were again more extensive and included, similarly to the initial survey, activities of the PRA methodology. They began with a transect walk through the farm. In-between, it was possible to include the readings of the water meters and – in case there was any change – measure the different areas. The order of the remaining activities varied, but most of the matrix of crops followed. After the experience with the seasonal calendar, it was surprising to see what level of detail the farmers were able to recall. It turned out that it was easier for the farmers to give information on more specific matters rather than estimating overall costs or yields. Combining both the seasonal calendar and the matrix of crops gives a good overview on the initial situation of the farm resulting in a solid baseline for an impact evaluation. Information about the usage of the new solar water pump and irrigation practices was not available in a high level of detail since the farmers were only able to provide average numbers. In order to provide a higher level of detail, it is recommended for future research to use smart meters, which not only measure accumulatively the water flow but also the time periods of usage. For the research at hand, these meters were not available due to their higher costs and their lack of availability in Tanzania. Usually, the end-line visit ended with the creation of a flowchart of the farmers' goals and needs. Most of the farmers flourished when narrating about their aims and how they intend to reach them – the only challenge being catching the essence of their explanations in the flowchart. Only one farmer didn't see any point in the activity and was short in explaining his visions. After concluding the end-line visit with each farmer, the neighbours were sought in order to learn about their perception of solar water pumps. Often, the farmers joined in visiting their neighbours and supported by introducing one to another. In many cases though, the visit of the neighbours was skipped, since some of the farmers had no pump at the time of the end-line visit or had been barely able to use it, leaving the neighbours with no chance to experience the pump working and form an own opinion on solar water pumps. In other cases, there were simply no neighbours in the direct surroundings, making the activity obsolete.

B. *Limitations*

The available budget and the given time frame combined with the distances to overcome to visit the farmers in the different regions constitute limitations to the research realized. Most importantly, they limited the extent of the field trials in terms of available time for each visit and the total amount of farmers visited. It was decided to keep the total number of visited farmers low in order to maximize the time available witch each one for the PRA activities conducted during the visits. Thus, the results obtained in this research cannot be generalized for the entire Tanzanian horticulture market due to the low number of smallholder farmers visited and are therefore not representative. Moreover, some of the farmers included in the field research don't entirely fit to the predefined typology of smallholder farmers. Due to the limited available information about the farmers prior to the visits and its poor quality, six farmers turned out to cultivate a larger area with non-horticulture crops or to possess secondary farms. However, the solar water pump was purchased to provide irrigation predominantly to horticulture areas of typical smallholder size in all cases. Thus, the obtained results can be used to validate to a certain extent the findings of prior research studies. Moreover, they yield new insights from the challenges in the field, which can be subject of future research for validation of their relevance for the overall market.

Regarding the information obtained, the level of detail reached is outstanding despite the difficulties faced. Nonetheless, the information collected includes the farmers' individual views as well as their objectives and their subjective perceptions of the challenges in the field. Thus the farmers' level is reached, which facilitates an improved understanding of the market. This implies that most of the information presented in this work represents the farmers' personal view and might fail to correspond with the overall situation or in extreme cases even the reality. The accuracy of the individual information – especially regarding finances and water needs – cannot be guaranteed, but the overall picture serves nevertheless to understand the approximate situation on the field. Also, a farm's conditions can vary greatly from case to case reducing the relevance of single values and increasing the interest in potential ranges, which can be used to enhance the promotion of solar water pumps in Tanzania's horticulture sector.

In closing, it is important to point out that there are gaps in the information obtained. Apart from the already mentioned limitations, obtaining information on finances was in some cases not possible due to the taboo-like perception of financial issues as long as a certain level of confidence is not reached. This level of confidence was not always achievable, and in these cases it was decided to renounce from querying in order to sustain the rapport and not affect the remaining research. Moreover, language and culture barriers might have interfered with the information obtained despite the efforts taken, the use of PRA methodology, and the support of a local interpreter. Also, this work does not address the sustainability of solar water pumps, which especially in terms of groundwater depletion risk is of particular importance.

V. Results

The insights obtained in the field can be allocated to four different areas. On the one side, there is detailed information about the farmers' initial situation before obtaining a solar water pump, which improves the understanding of the farmers' needs. Furthermore, the farmers' prioritization of a water supply system's characteristics is analysed and purchase drivers assessed. Thirdly, the close interaction in the field with the farmers as well as with Simusolar allowed to identify early-state barriers to the adoption of solar water pumps in Tanzania's smallholder horticulture market. Last but not least, the farmers' progress on the theory of change model is assessed to provide insights into the potential of solar water pumps.

A. *Farmer characteristics*

In order to provide a deeper understanding of the situation on-site as encountered during the field trials, a range of selected farmer characteristics are presented in this section. A short overview is presented in Table I. More detailed farmer profiles are included in the report of the field research.

The participants of the field surveys were all new Simusolar customers and were either farming as main or secondary source of income, or started farming as a retirement plan. Their farming experience and their level of education varied highly from primary school to university. All participants had at least one additional source of income and reached overall a mean income of 23 million TZS per year – corresponding to approximately 10,000 USD [31] – while facing average expenditures of nearly 22 million TZS. The operation costs of the farmers' former water supply system (mostly fuel-powered pumps were used) reached an average of 36% of their total expenditures. On the other hand, the acquisition costs of the solar water pump systems in question amounted to an average of 42% of the farmers' yearly income. Consequently, only two farmers opted to purchase the system with one single payment, while the remaining made use of Simusolar's financial service and are paying by instalments.

All visited farmers acquired solar water pumps due to struggles to properly irrigate their farmland with their former system. Moreover, the visited farmers encountered further significant challenges. Besides expectable struggles (pests and wild animals degrading the harvest; extreme weather conditions; generally unreliable climate), the market constituted a major limitation in terms of yielding proper

TABLE I. OVERVIEW OF SURVEYED FARMERS.

Farm	Region	Farming Objective (regarding income)	Farm Area [ha] tot. / cult. / hort.	Cultivated Crops hort. / non-hort.	Water Source	Formerly Used Technology
1	Morogoro	Primary	2.0/1.6/1.6	5/1	Borehole	Grid-connected electric pump
2	Morogoro	Secondary	3.2/1.2/1.1	0/1	Hand-dug well	None
3	Morogoro	Primary	4.0/2.0/2.0	4/1	River	Petrol pump
4	Central	Secondary	4.0/0.8/0.8	2/0	Borehole	Diesel pump
5	Central	Retirement plan	20.2/2.8/1.6	0/1	Borehole	None
6	Central	Secondary (farming group)	8.1/1.2/1.2	1/1	Borehole	None
7	Central	Secondary	20.2/8.1/1.4	6/3	Borehole	Diesel pump
8	Northern Highlands	Retirement plan	1.2/0.8/0.8	2/0	Hand-dug well	Petrol pump
9	Northern Highlands	Retirement plan / primary	8.1/1.6/1.6	4/1	Hand-dug well	Petrol pump
10	Northern Highlands	Primary	1.6/0.0/0.0	0/0	River	Petrol pump
11	Northern Highlands	Primary	8.7/8.1/4.0	6/1	River	Diesel pump
12	Pwani	Secondary	4.0/0.8/0.8	2/0	Borehole + river	Diesel pump

revenue and in terms of acquiring quality inputs. The farmers identified value-adding processing of their produce (e.g. by milling or packaging) as a possibility to yield higher prices, and reported the need of adequate mobility in order to be able to reach an increased market and hold greater flexibility.

Furthermore, it was observed that farmers struggle obtaining information on best practices, reliable suppliers, or new agriculture methods. Interestingly, their preferred source of information were the local governmental agriculture offices, while the media was almost irrelevant as source of information for the surveyed farmers. Furthermore, only four of the visited farmers knew any additional solar water pump supplier besides Simusolar, which highlights the low awareness of the sector regarding solar water pumps and indicates the relevance of word-of-mouth recommendation. In fact, most of the farmers' neighbours only learned about the possibility of using solar power for water supply due to their neighbours' new systems – and two eventually purchased a solar water pump system for themselves. Generally, the experience obtained in this work suggests that it is easier to reach well-educated and wealthier farmers as of now.

In terms of water supply, almost half of the farmers were limited by their prior water supply systems on the area they were able to irrigate and thus to cultivate. Seven farmers struggled to finance operation and maintenance expenditures for their fuel or electric pump and were thus facing temporary or long-term water shortages. Maintenance of the fuel pumps was named specifically and described as challenging due to the costs involved but also due to the need of a technician and the struggles because of their limited availability and the often remote location of the farms. Fuel and grid-connected, electric pumps faced breakdowns at least once a month – in case of the electric pump mostly due to the grids' unreliability.

B. *Farmers' Perspectives*

In PRA pair-ranking activity, the farmers prioritize individually a predefined set of factors, which describe potentially important characteristics of a water supply system, delivering insights into the farmers' expectations and properties important for them. Looking on the final results, the reliability of a water supply system is by far the most important factor identified by the surveyed farmers. Seven of the twelve farms ranked the reliability of the system into the first position, reaching a mean position of 1.79. Comparing the reliability of the system with the next-ranked factor, the overall score is nearly double as high. Such a clear outcome indicates that the reliability of the water supply system is a characteristic that could help promoting solar water pumps, and it should therefore be granted proper attention. However, it is recommended to validate the outcomes of this work with further research with representative groups of participants. In second place, low operational costs reach a tie with the simplicity of use. Both are factors that are characteristic for solar water pumps and can therefore help increase the interest in them if advertised effectively. However, the reached score by the second-placed factors is only one point higher than the forth-placed and less than two points above the fifth-placed. Thus, the ranking of the factors apart from the system reliability is equivocal and likely to change with a different set of participants.

While the PRA pair-ranking activity yields a good overview of how farmers envision their optimal water supply system, there might be differences between the farmers' requirements on a system and the factors they actually consider when it comes to make a purchase decision. In case of the surveyed farmers, all of them had already purchased a solar water pump at the point of the initial visit. Therefore, the presented ranking constitutes the farmers' requirements on a water supply system rather than the purchase decision drivers. This is can be clearly recognised when looking closer on the financial factors. The operational costs are ranked high in the PRA pair-ranking outcome, but the initial investment is on the last position. This doesn't fit to the fact that nine of the visited farmers opted for payment by instalments. Moreover, in the PRA flowchart activity, nine participants explicitly named capital as a requirement for reaching their objectives, which is indicative of the importance and the limiting potential of financial factors. Taking all of this into account, it becomes apparent that the initial investment is a major factor for the purchase decision process. The height of the initial investment required will likely determine if a farmer opts to purchase a solar water pump, while other factors such as the reliability of the system, simplicity of use, or operational costs will attract the farmer's interest in the first place.

Looking closer on further potential purchase drivers, the categorization approach of smallholder horticulture farmers into six different categories is applied as proposed in the Tanzania Market Snapshot [6]. The different categories (cost-driven, distribution-reliant, water conscious, effortless, unaware, and technical farmer) offer the possibility to address the solar water pump market in diverse, category-specific approaches and correspond to specific purchase drivers. While categorizing a market in order to be able to individually address certain groups can be a helpful approach, fitting the surveyed farmers into one category only turned out to be impracticable. A farmer's answers covered at least three different categories, which renders a clear categorization impossible. However, it is possible to determine a farmer's correlation with the different categories assessing each farmer's characteristics against reference values and using concomitant correlation factors in order increase the accuracy. Interestingly, the classification into the effortless and unaware categories is ambiguous due to the low correlation values of its reference values.

Overall, the technical category is the most frequently featured with a total of 10 out of 12 farmers, which shows that the farmers surveyed have a clear objective of increasing their productivity by switching to a reliable water supply technology. The distribution-reliant category follows with nine farmers but with a greater appearance as main category and with 23% a greater relative difference to the secondary category as compared to the technical category (13%). Thus, the distribution-reliant category is assessed to be of slightly higher relevance as the technical category. Looking on the relative difference between the primary and secondary as well as between the secondary and tertiary correlation, it becomes obvious that the number of relevant categories for each farm varies significantly. While for some farmers the correlation with the primary category is significantly higher than the correlation with the secondary or tertiary category, other farmers show very similar correlation levels with the three main categories. When addressing individual farmers, it might therefore be necessary to consider one, two, or more categories depending on the correlation characteristics of each farmer, combining the strategies proposed in the Tanzania Market Snapshot [6]. Comparing the rankings for the surveyed farmers of the water supply system's most important characteristics and of the purchase drivers according to categorization approach, similar rankings are observed, which indicates that relevant system characteristics are connected to prevalent purchase drivers. However, purchase drivers go beyond a farmer's valued characteristics and might be prioritized slightly different.

During the PRA flowchart activity, the relevance of solar water pumps for the farmers was outlined very clearly. The goal of the PRA flowchart was to retain the farmer's objectives as well as what the farmers assume to require in order to reach them. Solar water pumps were explicitly named in 12 flowcharts as one of the requirements. Five of the farmers went even further and detailed how the solar water pump is supposed to assist them in reaching their aims reducing their expenses. They named the solar water pump the "critical point" and a "multiplier" when aiming to reach community learning and prosperity. This is a direct indicator of the importance that solar water pumps can have within smallholder farmers' undertakings and should be utilized to raise awareness and promote the technology.

Taking into account the characteristics of solar water pumps, the PRA flowcharts also show that many of the solar water pump characteristics are of importance to farmers. For a start, 12 participants stated sufficient water supply as a requirement to achieve their goals. While a satisfactory water supply can also be reached by other means than a solar water pump, potential alternatives face limitations, which don't exist for solar water pumps (e.g. dependency on the manpower or fuel available with manual or fuel-powered pumps). Thus, a properly designed solar water pump is more likely to reliably provide a sufficient water supply. In point of fact, reliability is a challenge mentioned by seven participants in their flowcharts, while another four farmers explicitly aim to reduce costs to reach their goals. The PRA flowcharts are thus verifying the outcome of the PRA pair-ranking activity and indicate the importance solar water pumps can bear for smallholder horticulture farmers.

C. Adoption Barriers

Besides the high potential of solar water pumps, the field trials unveiled many difficulties in satisfying the needs of solar water pump purchasers. By the end of the field trials, only one participant had been using his solar water pump for an extended period of time without facing any challenges. Two other faced minor issues but were also able to operate satisfactorily their solar water pumps for an extended period of time. All the other participants faced diverse challenges in obtaining and operating their solar water pumps as well as in ensuring sufficient irrigation for their farming activities.

Challenges in logistics were the most prominent to be observed. They mainly originate in the immense area of Tanzania and the limited amount of Simusolar branch offices, leading to great areas that each branch office has to cover. Simusolar staff has to travel on average 129.75 km to reach the surveyed customers. Taking into consideration that only three farms are situated directly next to a paved road and that distances of up to 80 km have to be covered on unpaved roads, the accessibility of customers is a big challenge for Tanzania's smallholder farmer market. The fact that two potential farmers were left out of this work due to non-accessibility of the farm highlights the severity of this obstacle (during the rainy season plenty of unpaved roads become impassable even with all-wheel vehicles). The long distances to the customers are reflected on the service delivered. Since the staff tries to optimize the travelling time and distance in order to keep expenses down, they might be urged to carry out tasks fast and under stress as to prevent a second journey to the same customer, which potentially leads to lesser-quality service. However, instalments and repairs of solar water pumps are usually time-critical due to the importance of irrigation for farming. Thus, the customers' happiness and the reputation of solar water pumps is highly dependent on the quickness of response to malfunctions. The speed of response relies furthermore on the availability of the spare parts and the system's components.

Apart from logistics, great challenges were observed in terms of need assessment and the subsequent design of the solar water pump system. First and foremost, assessing the farmers' needs is a highly challenging task since even the farmers themselves often don't know accurately enough what they need. This is most apparent when it comes to the water needs. Five of the visited farmers had no notion about their water demand for irrigation, and one additional farmer only irrigated the seedlings and didn't know how much water irrigating the whole farm would require. For the four experienced farmers with an estimation of their water needs, the theoretical water needs accounts to 220% of the farmers' estimates, while unexperienced farmers estimated their water requirements five times lower than the theoretical values. Moreover, four farmers struggled to irrigate the entire farm with their new solar water pump due to insufficient reach. The pump's power turned out to be insufficient to overcome the total dynamic head increased by the use of a drip irrigation system (which was the case in three farms) or flooding irrigation method (one farm). Four farmers needed to enhance their systems with additional panels, and one farmer is still using his fuel pump to pump the water from a pond he uses as water storage to the drip irrigation system. Summarizing, the initially installed systems of five of the twelve visited farmers did not satisfy the customer's needs. Another five farmers had just started using the solar water pump system or not even received it at the end of the field trials, impeding to draw any conclusion on the suitability of the designed system. Also worth mentioning is that half of the visited farmers didn't own any water storage tanks, which might constitute a challenge if they lack the required knowhow to set up a suitable storage system. Inappropriate storage systems can lead to water supply shortages and discontent with the purchased solar water pump system. Two of the visited farmers expressed their discontent of receiving no support in setting up a suitable water storage system.

Beyond logistic and technical challenges, difficulties in communicating with the customers were encountered throughout the field trials in all surveyed regions. The difficulties can be ascribed to misunderstandings, insufficient information conveyed, or even untruthful statements given. Although the farmers when asked assured to have been informed adequately about their solar water pump system both in terms of operation and maintenance, it was observed that their understanding was at least partly deficient. One customer for instance enclosed his PV arrays with massive frames, which also covered a small stripe of PV cells on all four module edges, in order to secure the PV modules against theft. Combined with significant dirtiness of the modules, the created shade caused the system to fail working. Moreover, misunderstandings between customers and sales officers were observed several times. One farmer was highly frustrated because the installation of his solar water pump system was delayed although he had finished all required preliminary work. In order to proceed with the installation however, TAHA had to pay the deposit, as agreed between farmer, TAHA, and Simusolar. Until the end of the field trial, no payment by TAHA happened, and thus Simusolar was not able to install the system. The farmer on the other hand was not aware of the missing payment. Had he known about the actual reason, he might have been able to contribute in finding a solution, or at least he would have been able to understand and been less discontent.

Last but not least, the security of the system's components is a matter that should not be underrated. Most farmers are aware of the risk of theft and secure the equipment by enclosing the borehole with brickwork and a locked trapdoor. One farmer only deployed a security man to mount guard over the solar water pump, and once the security man was absent for a short while, the pump got stolen – luckily, the farmer managed to recover it. Another farmer was using a submersible solar water pump in a river without any diversion to protect the pump from the river's currents. Instead, the pump was fixed with a rope. During the rainy season, the river level and the current intensity increased that much that the rope broke and the pump got flooded away.

D. Impact Evaluation

The farmers' experience with solar water pumps was very diverse as is evident from the information presented so far. In order to provide a holistic overview and showcase potential benefits of solar water pumps, an impact evaluation following the logical model of the results staircase is conducted (cf. Table II).

Step 1 of the staircase "Farmer has a new water supply system" constitutes that the inputs were actually delivered to the customers. This was not the case for three of the customers visited. While farm nº 10 and farm nº 11 were not yet provided with a solar water pump system by the end of the field trials, farm nº 2 only partially reached step 1 due to the delayed instalment of their solar water pump system. Out of the remaining customers, only two failed to complete Step 2. In Step 2, the customers are supposed to be using the installed systems in a proper way, meaning that they are efficiently using their solar water pump systems, that if applicable they make use of the financial service offered, and that they have a proper understanding of their solar water pump system and are maintaining it correctly. The only encountered obstacle to efficiently use the system was a deficient installation of the system resulting in the two farmers failing to complete Step 2.

Reaching Step 3 goes along with being satisfied with the services provided. Achieving this already proved to be a hurdle for the remaining customers. One farmer was not entirely satisfied since his system was not able to supply the entire farm with water due to the combination of the irrigation method used (flooding) and the system's limited power. Other four customers weren't completely satisfied with their received services by the end of the field trials either. One just got his system upgraded with additional five panels one day after the end-line visit since the initial system didn't match his needs. Similar accounted for two of the other farmers, who were only farming for approximately one week and thus not operating the pumps long enough to be able to evaluate their performance. The remaining of the four farmers on the other hand was using his system for 10 weeks, but failed to be fully satisfied due to the water storage used, which impeded him to get completely rid of his fuel pump since he required it to pump the water from the pond to the farmland. Only customers nº 7 and nº 8 were entirely satisfied with their services received by the end of their field trials. They were both able to supply sufficient water for their current activities, were happy with the payment by instalments and had realistic expectations on their opportunities with the new solar water pump system. Evaluating if these two farmers had managed to reach step 4 was not possible within this field research. In order to assess whether the farmers cultivate more efficiently and reliably, it is necessary to observe an entire season from

TABLE II. FARMERS' PROGRESS ON THE RESULTS STAIRCASE.

Results Staircase Steps	Customer's Progress
-	Farmers nº 2, nº 10, nº 11
STEP 1 Farmer has a new water supply system	Farmers nº 1, nº 3
STEP 2 Farmer uses the installed system in a proper way	Farmers nº 4, nº 5, nº 6, nº 9, nº 12
STEP 3 Farmer is satisfied with the new water supply technology	Farmers nº 7, nº 8
STEP 4 Farmer cultivates more efficiently and reliably	-
STEP 5 Farmer expands his/her activities and generates higher income	-
STEP 6 Farmer's socioeconomic situation improves	-
STEP 7 Rural prosperity at community level	-

sowing to harvesting. The time available proved to not be enough to conduct such an assessment taking into account that the growing period of the crops encountered lasts in average 19 weeks (calculated based on the data available in the Water Requirement Tool [32]).

This short impact assessment showcases how the theory of change can be applied to structurally highlighting the level of impact reached once a coherent logical model is developed. It cannot yield any outlooks on the probability to reach the impact level with the provided input at this early point of the journey, but it validates the logical model itself so far showing that the customers step by step manage to advance on the results staircase.

VI. OUTLOOK

This work represents only one step towards a better understanding of Tanzanian's smallholder horticulture market and its penetration by solar water pumps. In order to progress further, the insights presented in this work have to be verified and validated by research with representative participant pools, and more information has to be acquired e.g. on financial characteristics. Solutions have to be found on how to successfully approach financial limited and less educated farmers. Also, the risks of deploying solar water pumps have to be analysed thoroughly and appropriate measures identified, especially regarding the risk of groundwater depletion. As solar water pumps are increasingly deployed, a greater exploitation of groundwater is to be expected. To understand a region's groundwater aquifer configuration, which is key to determine sustainable groundwater use, extensive studies are needed that lied beyond the scope of this work.

Moreover, the initiated impact evaluation should be completed in order to verify assumptions on the potentials of solar water pumps, to enable better understanding of the logical connections presented in the theory of change model, and add missing interrelations. The farmers' experience was only monitored at most until reaching Step 3 of the results staircase within this work – the available time frame for the field research constituting the main limitation. A continuation of the impact evaluation would show how solar pumps affect a farmer's development on the long term and validate the focus set on progressing their deployment. Thus, solar water pump suppliers would be able to better address the market having an improved understanding of the value of their service and thereby being able to increasingly attract investments. Moreover, the local and national administrations could set appropriate policies according to the revealed relevance of the technology in order to facilitate its wide-ranging adoption among others by enhancing the public awareness. As displayed in this work, the outreach of local governmental agriculture offices is remarkable.

VII. CONCLUSION

Aiming to promote the struggling spread of solar water pumps for irrigation purposes in Tanzania, this work carries on the research initiated by the Tanzania Market Snapshot from the Efficiency for Access Coalition [6]. Information regarding the farmers' needs and their expectations on their water supply system, the relevance of financial factors, potential benefits offered by solar water pumps as well as the barriers for their optimal utilization were assessed within the frame of the conducted field research of approximately three months while accompanying twelve smallholder horticulture farmers spread throughout Tanzania on their experience of adopting solar water pumps.

The field survey delivered highly detailed information of the conditions on-site and the multifaceted challenges faced by smallholder horticulture farmers in Tanzania. This enables an improved understanding of the characteristics of potential customers as well as their expectations and purchase drivers. As shown in this report, the surveyed farmers appreciate most the reliability of a system, followed by low operational costs and simplicity of use, while initial costs were ranked last. This contradicts the experiences of high initial costs as barriers to the adoption of solar water pumps. In fact, when looking closer to the purchase drivers using the categorization approach, it became apparent that although there are correlations between relevant system characteristics and purchase drivers, it is important to differentiate between the two since they are not necessarily prioritized equally and purchase drivers go beyond pure system characteristics.

Moreover, early-state challenges impeding the adoption of solar water pumps were identified including the high initial investment required by solar water pumps, indicated by the high uptake of Simusolar's financial service. Moreover, logistical challenges pose a barrier by decreasing the suppliers' speed of response and thusly lowering the quality of service provided. Assessing the farmers' needs and consequently ensuring an appropriate system design was detected to be particularly challenging. The farmers' own insufficient knowledge of their needs translates to a requirement of adequately qualified staff to assess the customer's needs. Also, the quality of the water source can constitute a hurdle if a minimum water purity is not safeguarded preventing pump breakdowns. Lastly, briefing the customers properly is found to be crucial to prevent mishandling and to ensure customer satisfaction.

The relevance of these challenges is reinforced when looking at the level of progress in adopting solar water pumps. Of all participants of the field trials, only two managed to complete the first section of the logical model, which encompasses the three sections output, outcome, and impact. No farmer managed to progress further and experience benefits in farming efficiency and reliability. However, it was observed that given more time the farmers can potentially progress further, and thus solar water pumps can yield a remarkable impact on the development of rural communities.

Looking forward, the insights surfaced in this work need verification and validation and the initiated impact evaluation should be completed. Beyond that, potential risks of deploying solar water pumps should be analysed, and appropriate counter-measures have to be developed.

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