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ORIGINAL PAPER

Quantifying the energetic cost tradeoffs of photovoltaic pumping systems for Sub-Saharan African smallholder farms

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Abstract

As solar technology has matured, irrigation using photovoltaic pumping systems (PVPSs) has gained popularity in developing markets as an effective means to alleviate poverty and increase food security. Yet, there remains a barrier to adoption; the upfront costs of PVPSs pose a financial burden for many low-income farmers. In a PVPS, the capital cost of the solar array contributes a large portion of upfront system costs. The solar pump is the largest energy consumer in the system, thus its efficiency directly impacts the size and cost of the solar array. There is a limited quantitative understanding of how solar pump efficiency affects the capital cost of the solar array. This study presents a technoeconomic framework to directly quantify the impact of solar pump efficiency on the cost of the solar array in a PVPS, for a range of hydraulic operating conditions. New empirical efficiency scaling laws were created by characterizing the efficiencies of 4-inch multistage centrifugal borehole pumps and induction motors. The utility of the technoeconomic framework is demonstrated through a case study comparing solar pump architectures with motors of different efficiencies. Results indicate that, despite the increased motor cost, the use of high-efficiency motors in solar pumps may lead to an overall cost reduction in a PVPS. Counter to the conventional capital cost-driven process, this work demonstrates that an efficiency-driven design process could improve low-cost, solar-powered system design. Engineers and system designers can leverage the presented framework during the design process to make informed decisions to achieve more cost-effective PVPSs.

Introduction

There has been a growing interest in providing low-cost photovoltaic pumping systems (PVPSs) to increase reliable water access to smallholder farmers in Sub-Saharan Africa (SSA) (Schmitter et al. 2018). In SSA alone, there are an estimated 50 million smallholder farmers who collectively produce more than 80% of the food for the region (Lowder et al. 2016; IFAD 2013). Studies have shown that increasing reliable water access to smallholder farmers is an effective tool to alleviate poverty and strengthen food security (Burney and Naylor 2012; Giordano and de Fraiture 2014). With the abundance of groundwater at shallow depths, SSA is suitable for installing electric groundwater pumps to provide reliable water access and improve the livelihood of rural households (MacDonald et al. 2012; Pavelic et al. 2013). However, many of the smallholder farmers are off-grid, forcing them to rely on inefficient diesel-powered pumps with high recurring fuel costs (Closas and Rap 2017). Solar panel prices have declined rapidly in recent years, falling from 21 $USD \cdot W_p^{-1}$ in 1992 to 0.81 $USD \cdot W_p^{-1}$ as of 2019 (Karekezi and Kithyoma 2002; Coalition Energy for Access 2019). The drop in solar panel prices makes solar-electric systems more cost-competitive with diesel-powered systems because the lifetime cost of diesel fuel has started to outweigh the high upfront cost of the solar array (Closas and Rap 2017). A recent techno-ethnographic study has elucidated 4 farmer profiles in East Africa with farm sizes ranging from 0.125 Ha to 5 Ha. It evaluated the energy source that is most promising for irrigation practices of each profile and has found that solar-powered irrigation systems are the most desirable options for all profiles (Van De Zande et al. 2020; Van De Zande et al. 2022). However, many smallholders remain

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financially hesitant to purchase PVPSs since they are more sensitive to the high upfront costs of PVPSs than the high lifetime cost of diesel fuel, creating a barrier to wide-scale adoption of PVPSs in the region (Pavelic et al. 2013).

In a PVPS, the solar array is often the dominating upfront cost, and the size of the solar array is directly related to the overall efficiency of the system (Muhsen et al. 2017). To increase the affordability of PVPSs, numerous efforts have been made in the past decade to provide efficiency improvements to existing PVPSs. These advancements include improving solar cell efficiency, developing more efficient power management algorithms, and designing more efficient mechanical hardware (Abdolzadeh and Ameri 2009; Corrêa et al. 2012; Karami et al. 2017; Caracas et al. 2014; Sokol et al. 2018; Sashidhar and Fernandes 2014). While these efforts have provided multiple avenues to improve PVPS efficiency and increase affordability, it remains unclear what the quantitative impacts of improving solar pump efficiency are on the overall upfront cost of a PVPS. The efficiencies of solar pump hydraulics and motors used in the small irrigation space are also not well characterized. The solar pump is the primary energy consumer in a PVPS and improving its efficiency can reduce the size of the solar array. Therefore, it is essential to quantify the relationship between solar pump efficiencies and capital costs of the solar array in order to understand how to effectively reduce the overall cost of a PVPS.

During the design process of a PVPS, the impact of solar pump efficiency on the costs of the solar array is often overlooked since solar pumps are typically designed as standalone units by manufacturers. When a new solar pump is designed, pump engineers improve upon existing hydraulic designs, then source a submersible motor from a third-party supplier. Based on interviews with manufacturers such as Xylem, these motors are selected with a proper power rating and to be sufficiently low cost, but their efficiencies are not necessarily considered a high priority during the design of the pump. When a PVPS is designed, local system designers such as Davis and Shirtliff do not influence the design of the solar pump, rather they often use off-the-shelf solar pumps in conjunction with solar sizing software provided by pump manufacturers in order to produce a system-level package for the customers. These types of sizing software are formulated with the intent to provide an estimate of the overall panel size based on the manufacturer's existing product portfolio. Therefore the system designers have no control over the solar pump efficiency determined by the pump engineers. This demonstrates a disconnect in design considerations between the system designers who incorporate the costs of the solar panels, and the pump engineers who dictate the efficiency of the solar pump. This is especially problematic since most solar pumps are designed with an emphasis on capital cost reduction over efficiency improvement due to the capital cost of the product directly impacting sales competitiveness and profit margins. However, for a solar-powered application, the solar pump efficiency has a more significant implication on the capital cost of the overall PVPS than the cost of the solar pump itself due to the relatively high cost of the solar panels.

This work proposes a unique technoeconomic framework that enables solar pump engineers to directly quantify the cost implications arising from the solar pump efficiency on the solar array cost in a PVPS. Using a higher efficiency solar pump, a system designer can effectively reduce the costs of a PVPS for a smallholder farmer. However, the quantitative economic incentive of using a more efficient solar pump remains unclear during the design process. The knowledge contribution of this work is to provide the engineering community with a quantified, broad view on when to choose more efficient solar pumps and understand how their energetics affect the overall costs of PVPSs. Moreover, it introduces an efficiency-focused design mindset that can help achieve more cost-effective, integrated PVPS designs. This technoeconomic framework can be valuable to the solar pump industry by allowing solar pump engineers to evaluate the design implications of the decisions they make when designing a new pump. The framework can also inform local irrigation system designers about the downstream system-level impacts in the integrated PVPS design when choosing solar pumps of various efficiencies. The specific objectives of this study are:

- Propose a quantitative framework to connect solar pump energetics to the costs of the solar array.
- Quantify the efficiency of solar pump hydraulics and motors in the small irrigation space.
- Illustrate the advantageous design space for the development and use of high-efficiency solar pumps to achieve cost and energy savings.
- Demonstrate the value of an efficiency-focused design mindset to achieve a low-cost solar pumping system design using a specific case study.

Framework to quantify the impacts of efficiency on system costs

In the typical power flow structure of a PVPS, the electricity generated from the solar array powers the electric motor of the solar pump. The electric motor then delivers shaft power to the rotor shaft of the pump hydraulics, where the rotating pump hydraulics convert the shaft power into hydraulic power, achieving the flow rate and pressure head needed for the required hydraulic operating conditions.

Since the flow rate and pressure head are typically given functional requirements of PVPSs, they are often designed

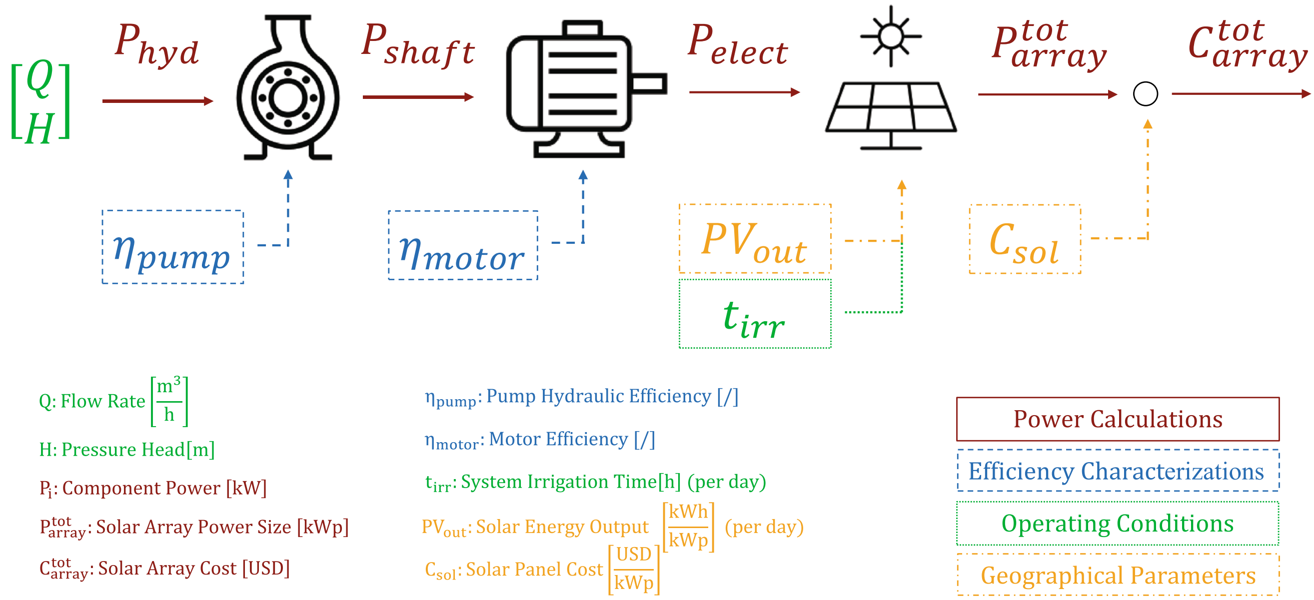


Fig. 1 Proposed technoeconomic framework structure to quantify the impact of solar pump efficiencies on the capital cost of the solar array in a photovoltaic pumping system (PVPS). The framework calculates power flow (solid red) throughout the PVPS based on the component efficiencies (dashed blue), the operating conditions (dotted green) of the system, and the geographical-specific parameters (dot-dashed orange)

in a backward power flow manner. The solar array is sized based on the hydraulic power needed, the efficiencies of the pump hydraulics, and the efficiencies of the electric motor. Our technoeconomic framework (Fig. 1) is presented in this backward power flow structure, where the power flow through each component (solid red) is back-calculated based on the operating conditions (dotted green) and the efficiencies of the pump hydraulics and electric motor (dashed blue). The efficiencies of the pump hydraulics and electric motors are needed to back-calculate motor power and panel size respectively (considering geographical factors). By formulating the framework in this manner we are able to quantify the impacts of solar pump efficiency on the size and cost of the associated solar array, while adhering to the customary design flow path in the solar pump industry.

Framework formulation

When selecting different solar pump hydraulics and motors, components with lower efficiencies will draw additional power from the power system, attributing to a larger solar array size. The energetic costs associated with the inefficiencies can be quantified by correlating them to the capital costs of the solar array, where the capital cost of the solar array is directly proportional to the power requirement of the system, and therefore the efficiency of the system.

Quantification of the efficiency-related costs in the solar array can be done using the backward power flow structure of Fig. 1. The flow rate (Q) and pressure head (H) define the operating condition of the solar pump hydraulics, and its hydraulic power output (P_{hyd}) can be calculated using Eq. 1. The shaft power (P_{shaft}) required for the solar pump hydraulics can be back-calculated using Eq. 2, given the hydraulic efficiency of the pump (η_{pump}). The electrical power requirement (P_{elect}) can be calculated similarly using Eq. 3 with the motor efficiency (η_{motor}). The solar array power (P_{array}) is sized based on the electrical power, the daily run time (t_{irr}), and location-specific photovoltaic electricity output (PV_{out}) using Eq. 4. Since this study focuses on solar irrigation as an application of PVPSs, the system runtime will simply be the daily irrigation time of the farm. Photovoltaic electricity output, PV_{out}, which has units of $kWh \cdot kW_p^{-1}$, represents the daily average electrical energy generated for a given installed solar capacity in a target region. It is modeled by Global Solar Atlas (GSA) using Ground Horizontal Irradiance (GHI) and Direct Normal Irradiance (DNI) based on SolarGIS algorithm, which has an uncertainty of up to ± 8% for GHI and ± 14% for DNI (ESMAP 2019). Lastly, the capital cost of the solar array can be calculated using Eq. 5, which includes the solar panel retail price (C_{sol}). For this study, C_{sol} of 810 $USD \cdot kW_p^{-1}$ is estimated, based on reports by local NGOs in SSA (Coalition Energy for Access 2019):

$$P_{\text{hyd}} = \frac{\rho_{\text{water}} \cdot g \cdot Q \cdot H}{3.6 \cdot 10^6} \quad (1)$$

$$P_{\text{shaft}} = \frac{P_{\text{hyd}}}{\eta_{\text{pump}}} \quad (2)$$

$$P_{\text{elect}} = \frac{P_{\text{shaft}}}{\eta_{\text{motor}}} \quad (3)$$

$$P_{\text{array}} = \frac{P_{\text{elect}} \cdot t_{\text{irr}}}{PV_{\text{out}}} \quad (4)$$

$$C_{\text{array}} = C_{\text{sol}} \cdot P_{\text{array}} \quad (5)$$

Equations 1–5 have the corresponding units P_{hyd} $[kW]$, P_{shaft} $[kW]$, P_{elect} $[kW]$, Q $[m^3 \cdot h^{-1}]$, H $[m]$, t_{irr} $[h]$, PV_{out} $[kWh \cdot kW_p^{-1}]$, P_{array} $[kWp]$, and C_{sol} $[USD \cdot kW_p^{-1}]$.

During the motor selection process, solar pump manufacturers can use this technoeconomic framework to quantify design implications on the overall systems when deciding between higher efficiency motors versus lower efficiency motors. In an example scenario, a designer may consider two solar pump architectures: architecture 1 which consists of a more expensive, highly efficient permanent magnet motor, and architecture 2 with a cheaper, lower efficiency AC induction motor. The difference in efficiency between the two motor architectures will lead to a difference in the costs of the solar array in a PVPS (Eq. 6), which is the absolute difference in energetic costs (ΔC_{array}). The percentage difference in energetic costs ($\%\Delta C_{\text{array}}$) can be calculated with Eq. 7. Designers can compare estimates of solar panel costs to the difference in the capital costs ($\Delta C_{\text{capital}}$) between the two motors (Eq. 8). In this process, designers can quantitatively determine whether the energetic benefits that arise from a more efficient motor can outweigh its additional capital cost:

$$\Delta C_{\text{array}} = C_{\text{array}}^{\text{arch}_1} - C_{\text{array}}^{\text{arch}_2} \quad (6)$$

$$\%\Delta C_{\text{array}} = 100 \cdot \frac{C_{\text{array}}^{\text{arch}_1} - C_{\text{array}}^{\text{arch}_2}}{C_{\text{array}}^{\text{arch}_1}} \quad (7)$$

$$\Delta C_{\text{capital}} = C_{\text{capital}}^{\text{arch}_1} - C_{\text{capital}}^{\text{arch}_2} \quad (8)$$

In Eqs. 6–8, $C_{\text{array}}^{\text{arch}_i}$ and $C_{\text{capital}}^{\text{arch}_i}$ correspond to the capital cost of the solar array and the capital cost of the hardware (excluding solar panels) in architecture i, respectively.

Efficiency characterization of 4-inch multistage centrifugal borewell pumps (MSPs)

In order to implement the technoeconomic framework and calculate pump shaft power (Eq. 2), a means of predicting hydraulic efficiency as a function of the best-efficiency-point (BEP) operating flow rate is needed. While the actual efficiency of pump hydraulics depends on a variety of design parameters and manufacturing tolerances (Gülich 2014), an empirical scaling approach is more practical and straightforward. A prior empirical centrifugal pump efficiency model was initially published by H. H. Anderson and later modified by I. Karassik (Eq. 9). This model predicts centrifugal hydraulic efficiency as a function of flow rate and specific speed (Eq. 10) evaluated at BEP. For multistage pumps, the specific speed is calculated using the head-per-stage of the impeller instead of the total pressure head of the pump (Gülich 2014):

$$\eta_{\text{pump}}^{\text{MSP}} = 0.94 - C_1 \cdot \left(\frac{Q_{\text{BEP}}}{N}\right)^{C_2} - 0.29 \cdot \log_{10}\left(\frac{2286}{N_s}\right)^2 \quad (9)$$

where N is in RPM, Q_{BEP} is in GPM, H_{BEP} is in ft for a single impeller according to the Anderson–Karassik formulation.[1] The specific speed N_s is defined as

$$N_s = N \cdot \frac{\sqrt{Q_{\text{BEP}}}}{(H_{\text{BEP}})^{0.75}}. \quad (10)$$

The Anderson–Karassik model is formulated using pump efficiencies surveyed in 1979 with a large range of pump design flow rates from 1750 GPM to 254,000 GPM (397.5 $m^3 \cdot h^{-1}$ to 57,690 $m^3 \cdot h^{-1}$) (Anderson 1979; Karassik et al. 2008). While it provides a general empirical estimation of efficiencies for a large range of pumps, it may not accurately reflect the low flow rate range that is typical for smallholder farms for SSA (1 $m^3 \cdot h^{-1}$ to 18 $m^3 \cdot h^{-1}$). The pump efficiencies in SSA only correspond to a small subset of the low flow rate pumps surveyed in the Anderson–Karassik model, which is skewed toward pump efficiencies associated with larger design flow rates.

To evaluate the utility of the Anderson–Karassik model in the SSA smallholder market, the BEP hydraulic efficiencies of 4-inch multistage centrifugal borewell pumps (MSPs) were surveyed and characterized. In SSA, 4-in MSPs are commonly used. The operating conditions correlate to a range of specific speeds that are suitable for MSPs (Gülich 2014), and 4-inches is a standard borewell size used

[1] The Q_{BEP} in $m^3 \cdot h^{-1}$ and H_{BEP} in m used by pump manufacturers in SSA and the presented results of this paper have been converted correspondingly prior to substituting into the model.

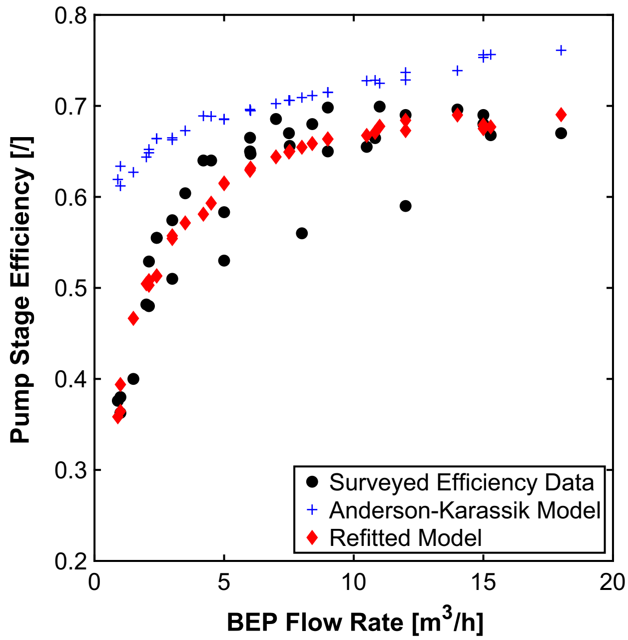


Fig. 2 Surveyed and model-predicted 4-inch multistage centrifugal pump efficiencies for a flow rate range of 1 $m^3 \cdot h^{-1}$ to 18 $m^3 \cdot h^{-1}$. Surveyed efficiencies from the Sub-Saharan Africa (SSA) borehole market are denoted by black dots. Efficiency predictions from the prior Anderson–Karassik model (blue crosses) deviate from surveyed data, especially at low flow rates. Efficiency predictions from the updated model presented in this work (red diamonds) provide a more accurate prediction for the low and refitted flow rate pumps used in the SSA market

by SSA drillers (Van De Zande et al. 2020; Van De Zande et al. 2022). Therefore, efficiencies of 37 independent impeller designs used in 453 different 4-inch MSPs sold in the SSA market were compiled from prominent manufacturers (Grundfos 2020e; Xylem 2020b; Pedrollo 2020; CNP 2020). The efficiency information was gathered from the pump hydraulic datasheets publicly available in the online product catalogs of the different manufacturers. The portfolio made up of these pumps covers an operating flow rate range of up to 18 $m^3 \cdot h^{-1}$ and a pressure head range of up to 250 m, which are sufficient for various sizes of farms and depths of borewells found in SSA (Van De Zande et al. 2020; Van De Zande et al. 2022; Lowder et al. 2016). Surveyed efficiencies were compared to the Anderson–Karassik model, and results suggest it was limited in its capability to predict pump efficiency for 4-inch MSPs in SSA, leading to an error of up to 0.24 in the low flow rate region (Fig. 2).

Therefore, an efficiency scaling law specific to the SSA operating conditions was derived to enable the framework to more accurately evaluate 4-inch MSP hydraulic efficiencies

Table 1 Statistically fitted parameters used in Eq. 9 for the original Anderson–Karassik model (Karassik et al. 2008) and the refitted model to predict the efficiency of 4-inch MSP hydraulic

Fitted parameters	Anderson–Karassik	GEAR lab model
C_1	0.08955	0.08494
C_2	− 0.21333	− 0.27246
RMSE	19.549	6.4391

at different operating conditions. To develop the new empirical scaling law, the coefficients (C1 and C2) in the Anderson–Karassik model were refitted to the SSA surveyed data. As shown in Fig. 2, the refitted model is able to predict hydraulic efficiencies more precisely for the 4-inch borewell pump over a range of flow rates in the SSA market. The refitted model results in a better RMSE value of 6.4391 as compared to the prior model's 19.549, as shown in Table 1.

The trend of the surveyed 4-inch MSP efficiencies in Fig. 2 conforms to the qualitative descriptions from the literature (Karassik et al. 2008; Gülich 2014). MSPs experience low efficiency at low specific speeds due to their long and radial impeller geometries, which translates to the low flow rate region for the 4-inch impellers. This geometry generates high secondary losses, such as disk friction losses, as well as a high ratio of leakage flow to total flow. As specific speed and flow rate increase, the impeller design becomes more axial, resulting in a significant reduction of secondary losses and the relative leakage flow, contributing to higher efficiencies. This behavior is apparent in the exponential increase of efficiency with specific speed. The efficiency eventually plateaus to a maximum value of approximately 68% for the surveyed 4-inch MSPs.

Efficiency characterization of 4-inch submersible motors

To characterize motor efficiency for use in the framework, efficiencies of 94 4-inch submersible motors currently sold in the SSA market were compiled, with an output shaft power ranging from 0.37 kW to 7.5 kW (Grundfos 2020c; Xylem 2020a; Lorentz 2020b; Davis and Shirtliff Group 2020). These motor efficiency data were collected from datasheets published by manufacturers in their online catalogs. Since the majority of borewell pumps sold in SSA are imported and originally designed for grid applications, all of the motors surveyed were AC induction motors (IMs), due to their simplicity and plug-and-play capability with the grid. A scaling law for motor efficiency was developed from this data, using established efficiency standards for induction motors as a basis for the model. The International Electrotechnical Commission (IEC) published the IEC 60034 specification (IEC 2014) which rates commercial induction motor efficiencies from IE1 to IE4, in the order of increasing efficiencies. The efficiency scaling of the IE ratings can be numerically extrapolated as a function of motor shaft power using a 4th-order logarithmic relationship (Eq. 11):

$$\eta_{motor}(\%) = C_1 \cdot \log_{10}(P_{shaft})^3 + C_2 \cdot \log_{10}(P_{shaft})^2 + C_3 \cdot \log_{10}(P_{shaft}) + C_4 \quad (11)$$

Therefore, the efficiency data of the surveyed IMs are also fitted to a scaling law of the same form, resulting in an RMSE of 4.7176. This enables direct motor efficiency scaling in the framework for solar pump motors operating in the various shaft power regimes, calculated based on the hydraulic operating points and efficiencies of the pump hydraulics (Eq. 2). The corresponding interpolation coefficients for scaling efficiencies of the IE ratings and the surveyed IMs are listed in Table 2.

The efficiencies of the 4-inch submersible IMs surveyed were compared to the four IE ratings. As shown in Fig. 3, the 4-inch submersible IMs currently sold on the market significantly underperform even the lowest IE1 motor efficiency rating by an average of 0.07. The low efficiencies of IMs are primarily due to the lack of a permanent magnet field and the induction losses in the coil of the rotor. The lower efficiencies in existing IMs on the market suggest a potential opportunity to improve PVPS system efficiency and achieve energetic cost reduction with higher efficiency motors. In practice, brushless-DC (BLDC) motors are often found to have comparable or even superior efficiency to the IE3 or IE4 efficiency rating as they operate with a permanent magnetic field (De Almeida et al. 2011). For example, the newer BLDC 4-inch submersible motors offered by Lorentz have an efficiency of up to 98% (Lorentz 2020b).

By simply adopting higher efficiency BLDC motors to replace existing IMs, PVPS designers can effectively reduce the size of the solar array and therefore lower upfront costs of the overall PVPS. Moreover, BLDC motors can also operate directly off the DC current generated from the solar array without the need for a DC-AC boost inverter, resulting in reduced complexity of the electrical system. Many solar pump manufacturers have recognized the benefits of the increased efficiency and reduced electronic complexity in using BLDC motors for solar-powered applications, and the pump industry is slowly transitioning to adopt BLDC motors from conventional IMs (Lorentz 2020a; Grundfos 2020g; Xylem 2014). However, the energetic tradeoffs between the gained efficiency and the additional capital cost of the BLDC motor remain not well understood and are hard to quantify.

Table 2 Coefficients for efficiency interpolation of the surveyed IMs and the four IE efficiency classes (2-poles, 3000 rpm) (IEC 2014)

Coefficients	Surveyed IMs	IE1	IE2	IE3	IE4
$0.12kW < P_{shaft} < 0.75kW$					
C_1	6.1369	11.9240	22.4864	6.8532	– 8.8538
C_2	– 10.5895	6.3699	27.7603	6.2006	– 20.3352
C_3	18.6090	30.0509	37.8091	25.1317	8.9002
C_4	67.5673	76.6136	82.4580	84.0392	85.0641
$0.75kW < P_{shaft} < 7.5kW$					
C_1	6.1369	0.5234	0.2972	0.3569	0.3400
C_2	– 10.5895	– 5.0499	– 3.3454	– 3.3076	– 3.0479
C_3	18.6090	17.4180	13.0651	11.6108	10.2930
C_4	67.5673	74.3171	79.0770	82.2503	84.8208

Note that the published IE standard has two individual sets of regression coefficients for each of the four efficiency classes in the two motor power ranges

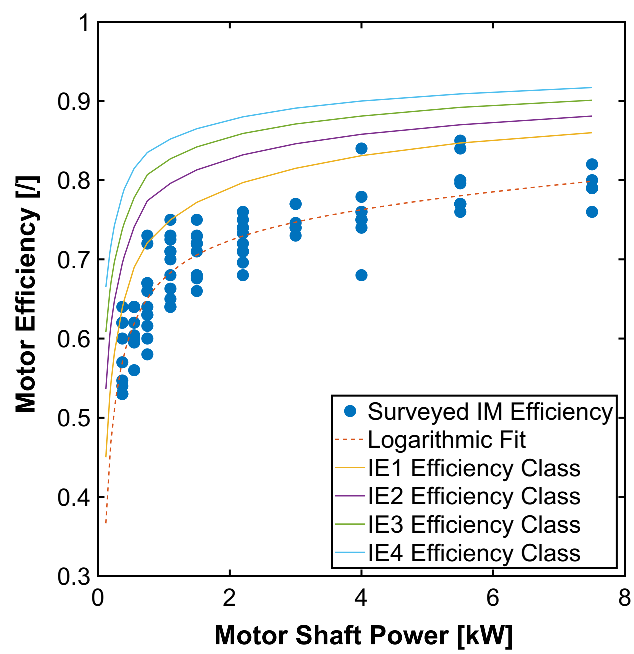


Fig. 3 Comparison of International Electrotechnical Commission (IEC) standard efficiency ratings to surveyed 4-inch induction motors (IM) from the Sub-Saharan Africa (SSA) solar pump market. Surveyed efficiencies of 4-inch induction motors (IM) used to drive borehole pumps in the SSA market are denoted by blue dots. The four IE motor efficiency ratings (solid lines) demonstrate a 4th-order logarithmic relationship to motor shaft output power. A 4th-order logarithmic trendline was fit on the surveyed data for comparison and is represented by the dashed line. The graph indicates the existing induction motors on the market underperform when compared to the IE efficiency ratings

Case study–demonstrating the application of the framework

The technoeconomic framework was used in combination with the efficiency prediction models formulated for the 4-inch borehole pump hydraulics and motors to conduct a case study analysis for SSA farms. Two analyses were conducted to compare solar pump architectures, primarily from the motor selection perspective. First, the energetic costs between solar pumps with two different motor architectures were compared over a range of operating flow rates and pressures, providing a spatial quantification of capital cost reduction in the solar array for the SSA operating space. In this analysis, both the absolute energetic cost reduction and the percentage energetic cost reductions between the two solar pump architectures were analyzed to elucidate the cost reduction scaling as a function of the operating conditions and its relative magnitude to the total panel cost. Secondly, the overall capital costs between solar pump architectures were compared for a specific operating point. The goal was to demonstrate how PVPS designers can use this framework to directly compare the quantified energetic costs to the capital costs of the hardware components when designing for a specific customer. This analysis also illustrates why efficiency matters when designing PVPS, as using more expensive but highly efficient hardware can potentially create PVPS with lower upfront costs due to the reduced size of the solar array. The case study demonstrates how solar pump manufacturers and PVPS designers can apply the framework to quantitatively relate solar pump efficiency to upfront cost, enabling them to make informed design decisions during the component selection process.

Case study parameters

Two solar pump architectures are compared in this case study: IM-driven MSPs and IE4 motor-driven MSPs. This represents the efficiencies of solar pumps with the surveyed IMs on the current market, and the improved efficiencies when the solar pump industry adopts BLDC motor architectures, respectively. The analysis is first conducted at an operating space level, where the energetic cost tradeoffs between the two solar pump architectures are quantified over a range of operating flow rates and pressures. Furthermore, a more detailed analysis including capital costs was conducted on a specific operating point that represents a typical 1-Ha farm in SSA. Studies have shown that SSA farms with similar sizes have been rapid first adopters of PVPSs (Van De Zande et al. 2020; Van De Zande et al. 2022), thus this case study represents a scenario of how PVPS designers can use the framework to design for a group of promising initial clients.

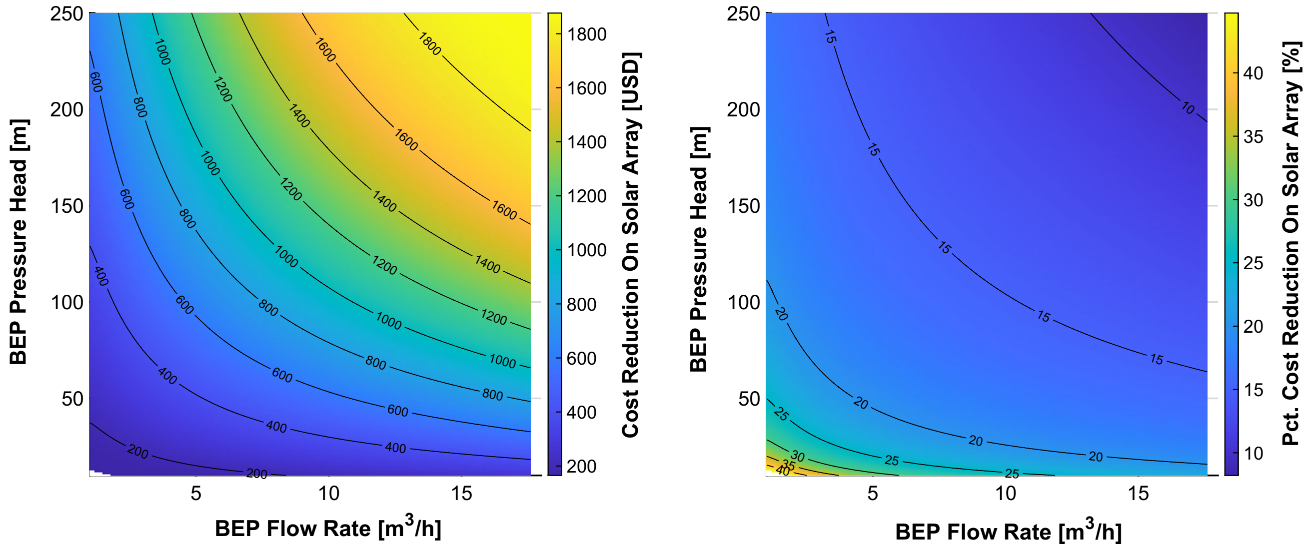
Table 3 Input parameters used for the example case studies in SSA

Input parameters	Values
Location	Nairobi, Kenya
Latitude	−1.2921
Longitude	36.8219
PV_{out} (GSA)	4.19 $kWh \cdot kW_p^{-1}$
t_{irr}	6 h
C_{sol}	\$810 $USD \cdot kW_p^{-1}$

The operating location for the analyses is in Nairobi, Kenya, where farmers have a high interest in solar irrigation products (Van De Zande et al. 2020; Van De Zande et al. 2022). The simulated flow rate ranges from 1 to 18 $m^3 \cdot h^{-1}$ and the pressure head ranges from 10 to 250 m for the operating space analysis. The range of operating conditions is chosen based on the capable operating range of 4-in MSP designs which are suitable for the SSA market. The specific operating flow rate and pressure head for the operating point selected in the second analysis are 3 $m^3 \cdot h^{-1}$ and 100 m, representing a typical 1-Ha farm with a borehole depth of 100 ms. The irrigation time was chosen to be 6 h, which is typical according to interviews with SSA farmers who have a PVPS (Van De Zande et al. 2020; Van De Zande et al. 2022). The location-specific PV output potential is 4.19 $kWh \cdot kW_p^{-1}$ based on modeled solar GIS data for the latitude and longitude of Nairobi (ESMAP 2019). The retail price of the solar panels is 810 $USD \cdot kW_p^{-1}$ reported locally (Coalition Energy for Access 2019). These input parameters are listed in Table 3.

Comparative analysis of energetic cost reduction

The difference in absolute energetic costs (Eq. 6) between the IM-driven MSPs and the IE4-driven MSPs is plotted in Fig. 4a. This difference represents the CAPEX cost reduction in the solar array achieved by improving solar pump efficiency using more efficient BLDC motors. Based on the simulated results shown in Fig. 4a, the absolute energetic cost reductions scale primarily with the solar pump hydraulic power. The largest cost reduction is observed in the high hydraulic power region, up to \$1800 USD. At high hydraulic power, the higher IE4 motor efficiency makes a larger impact on the required electrical power and size of the solar array. These results suggest there may be a large economic incentive for solar pump manufacturers to provide higher efficiency motors in the high-power region (e.g., larger farms) because the energetic cost reduction will likely outweigh the additional capital cost of the more efficient motor. Moreover, Fig. 4a also provides a guideline on the capital cost premium



(a) Absolute capital cost reduction in PV

(b) Pct. capital cost reduction in PV

Fig. 4 Absolute capital (energetic) cost reductions (**a**) and percentage cost reduction (**b**) in the solar array when using high-efficiency IE4-rated BLDC motors over conventional induction motors, for the operating space in SSA. A larger magnitude of cost reduction (and percentage reduction) is represented by the brighter color (yellow), while the duller color (blue) represents a smaller magnitude. The highest absolute capital cost reduction is in the high-power range (high flow and high pressure) while in contrast, the highest percentage cost reduction is in the low-power range

that a more efficient motor can have before the cost benefits from the efficiency gain break even.

The percentage of energetic cost reduction was calculated (Eq. 7) to represent the relative magnitude of reduced solar array costs from efficiency improvement to the total costs of the solar array (Fig. 4b). The simulation result shows that the largest percentage of the cost reduction occurs in the low hydraulic power region, which correlates with smaller farms. In the low hydraulic power region, the efficiency difference between an IE4 motor and an IM is larger, and the energetic cost associated with the power losses in the hardware is also more prominent. This directly contrasts the trends in the absolute amount of cost reduction shown in Fig. 4a. Therefore, although the largest absolute amount of cost reduction is in the high-power region, the economic impact of efficiency gain relative to the total panel cost is most pronounced in the low-power region. It demonstrates the potential need for low-cost, high-efficiency motors for PVPS in the low-power region, which represents the operating space of smallholders, who are more likely to be in poverty.

Capital cost tradeoffs about a specific operating point

The energetic costs in the solar array, quantified by the presented framework, can be compared to the capital cost difference in the hardware components. This further elucidates how an efficiency-driven design mindset for solar-powered applications can potentially lead to more cost-effective PVPSs. In this example, the capital cost difference is the cost premium of a highly efficient but more expensive IE4 motor over the cheaper, less efficient IM. The analysis focuses on a specific operating point to formulate an explicit example for comparing the tradeoffs between efficiency-related energetic costs and motor capital costs. Within the SSA operating space, an operating point of 3 $m^3 \cdot h^{-1}$ flow rate and 100 m pressure head was selected to represent a typical 1-Ha smallholder farm with a borewell depth of 100 ms (Van De Zande et al. 2020; Van De Zande et al. 2022). The capital cost of the pump hydraulics was approximated to be $400 USD and the IM motor was approximated to be $350 USD based on Grundfos SP 3A-25 pricing (Grundfos 2020f, d). The IE4 efficient BLDC motor was approximated to be $610 USD, which is around 75% more expensive than the conventional IM given the corresponding power requirement.

The combined costs of the solar array (energetic cost) and the capital costs of the motor for the two solar pump architectures are shown in Fig. 5. The simulation results show that even though the more efficient IE4 motor comes with a more expensive cost premium, the cost reduction in the solar array due to the improved efficiency outweighs the additional motor cost. The use of a more efficient IE4 motor effectively reduces the size of the solar array when compared to the use of conventional IM, leading to lower overall system costs for this specific operating point. The

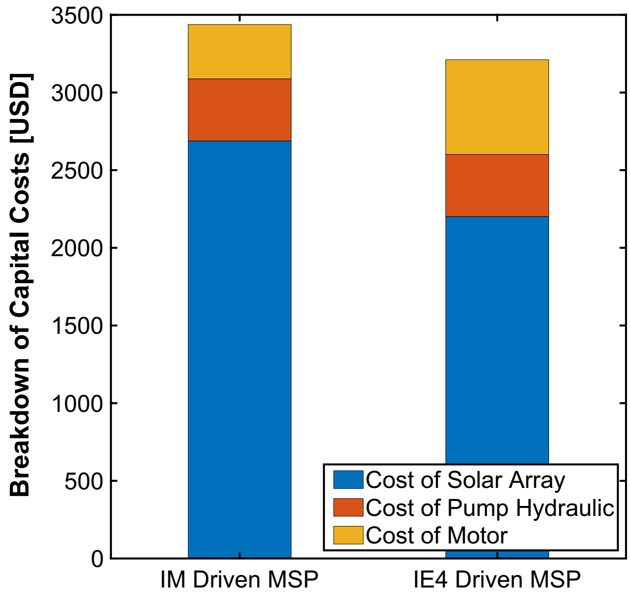


Fig. 5 Simulated capital costs comparison of a photovoltaic pumping system (PVPS) when using a conventional induction motor versus an IE4 efficient BLDC motor. The simulated PVPSs were designed for the operating point of a typical 1-Ha farm, with a flow rate of 3 $m^3 \cdot h^{-1}$ and a borehole depth of 100 m. Capital costs are broken down into solar array costs (blue), pump hydraulic costs (orange), and motor costs (yellow)

result suggests the importance of component efficiency in a solar-powered system, which provides benefits that outweigh the capital costs of hardware components due to the relatively higher cost of solar panels. PVPS system designers can follow this process to quantify tradeoffs between energetics and capital costs using the presented framework and produce a more cost-effective PVPS architecture through an efficiency-driven design mindset.

Discussion

Currently in the solar pump industry, there is a poor understanding of the effect of small borewell pump efficiency on overall system cost. This knowledge gap is exasperated by the small irrigation space, which also lacks characterization of pump efficiency. Without a quantitative process to directly correlate solar pump efficiency to the integration of solar system costs, practitioners need to rely on common practice and intuition when designing PVPSs, which may not produce the most cost-optimal designs. The proposed framework has demonstrated that designers can benefit from incorporating a quantitative, systematic method that considers the energetic tradeoff of solar pumps to create lower cost higher performance PVPSs. Designers can also leverage the efficiency characterizations of the 4-inch borewell pumps for other applications that use borewell pumps of similar size. The case study successfully demonstrated the utility of the framework in extrapolating cost tradeoffs and provides an example process for practitioners to use as a guide when designing for their specific applications.

Expanding the framework to other applications

Although the scope of the presented framework is considering the design space of the small solar-powered irrigation system for up to 5 Ha in SSA, the architecture of the energetic cost framework and the design thinking behind it can be expanded to other solar-powered applications. These further applications include other pump hydraulic types, different operating conditions, and various PV systems such as desalination, and hydrogen production. When analyzing a different market with potentially different operating conditions and hardware options, the efficiencies of the corresponding pump hydraulics and motors in that market can be recharacterized using the methods outlined in Sect. "Framework to quantify the impacts of efficiency on system costs". The location-specific parameters used in the framework analysis such as the PV output potential can be adjusted according to the local operating conditions. The solar panel price can also be modified to more accurately reflect the price in the various local markets and the potential price changes in the future. With appropriate modifications, this energetic framework can be adapted for various solar-powered applications outside of solar pumping, and geographical locations with different solar irradiances and solar panel prices.

Efficiency-based design mindset to reduce cost

When designing solar-powered irrigation systems, an efficiency-driven mindset during the component selection process can be an effective strategy to reduce the capital upfront cost of the system and reduce the financial burdens on smallholder farmers. As shown in the case study, the improved efficiency of a permanent magnet motor (e.g., IE4) has technoeconomic benefits that tend to outweigh the higher motor capital cost compared to a cheaper, lower efficiency IM, making PVPSs more affordable for developing markets. This is because the impact of the efficiencies from hardware components (e.g., motors) on the CAPEX of solar array often outweighs the CAPEX of the components themselves. The solar pump is the primary energy consumer and its efficiency has a direct impact on the size of the solar array which is the dominating cost of the overall system (Van De Zande et al. 2020; Van De Zande et al. 2022).

However, a CAPEX-driven design mindset is a common practice among solar pump manufacturers during the procurement process, as most of the hardware is designed for grid-tied applications (Grundfos 2020a; Xylem 2020d). This is because when designing for grid-tied applications, customers are often more sensitive to the lump sum upfront costs of the hardware than the electricity costs over the hardware's operating lifetime. Yet, the CAPEX-driven design mindset does not fully capture the additional upfront costs in the solar array which arise from the inefficiencies of the system in off-grid solar-powered applications. It is important for the industry to rethink the component selection process to prioritize efficiency and be aware of the key difference when designing off-grid solar-powered systems versus grid-tied systems. In a solar-powered system, the primary cost of energy is a CAPEX which is primarily attributed to the upfront cost of the solar array. But in a grid-tied system, the primary cost of energy is an OPEX, deriving from the electricity cost it uses over its lifetime of operation.

The results of this study suggest an efficiency-driven design mindset of utilizing more expensive but efficient hardware in a solar-powered system can potentially drive down the overall system costs, which is counterintuitive to the conventional CAPEX-driven design process in the industry. This technoeconomic implication is especially important when designing systems for off-grid developing markets where customers are much more sensitive to CAPEX than OPEX. The majority of the CAPEX comes from the costs of the solar array, which is correlated to system efficiencies (Van De Zande et al. 2020; Van De Zande et al. 2022). In fact, the shift in design thinking of prioritizing efficiency over component CAPEX aligns with the trend observed in the industry, as solar pump manufacturers are starting to pursue higher efficiency permanent magnet BLDC motors specifically for solar-powered applications (Lorentz 2020a; Grundfos 2020g; Xylem 2014).

Implications of solar pumping system design

The case study demonstrates a representative application of how solar pump manufacturers and PVPS designers can use the energetic framework to conduct analytic comparisons between the capital costs and the efficiency-related energetic costs when selecting different components. The framework's ability to directly quantify the impact of efficiency to cost during the design process can be valuable to industrial practitioners, as it enables them to provide potentially lower cost, yet more efficient, solar-powered irrigation systems to the smallholder farmers in the developing market of SSA who may not have affordable options with current component prices.

While the case study results show that an efficiency-driven design process can be useful in driving down the costs of the PVPSs, there's a trend in decreasing solar panel prices over time which may make the affordability of a PVPS less sensitive to solar pump efficiency (Feldman et al. 2020). The importance of efficiency diminishes with lowering solar panel prices because the capital cost associated with the additional solar array required to compensate for the power losses may become less expensive. There exists a breakeven point where the cost of pump efficiency improvement provides diminishing returns, and local system designers will have to rely on their local price report to determine whether the cost premiums of more efficient hardware are justified. Nevertheless, the declining costs of solar panels will continue to make PVPSs more price-competitive than the conventional diesel-powered pumping systems used in many developing communities (Schmitter et al. 2018; Closas and Rap 2017).

Since off-grid, solar-powered pumping systems are the focus of this study, the framework primarily focuses on the impact of efficiency on the cost of the solar array. When considering potential grid-tied, hybrid systems, the electricity cost over the systems' operating lifetime can be aggregated and added to the capital cost of the solar array. A similar efficiency-related energetic cost comparison to the capital cost of the hardware can then be conducted for grid-tied pumping systems using the modified framework. The incorporation of electricity costs will ensure the framework remains useful and relevant to designers for grid-tied applications, as "microgrids" become more popular among developing rural communities without reliable grid infrastructure (Murenzi and Ustun 2015).

Assumptions and limitations

During the formulation of the presented framework, several assumptions were made and some limitations resulted. The solar array required to support the power demand of a solar pump is sized using the conservation of electrical energy generated from the solar array on a daily basis. This assumes the energy generated can be stored in a sufficiently large energy buffer such as a tank or batteries. By doing so, the average daily PV output potential can be directly used and the intra-day variation in solar irradiance is not captured, reducing computational complexity. Future work for a lower-level framework can be developed to capture the intra-day operating performance of a specific system design using higher fidelity models that account for the daily and seasonal weather variation, solar profile, and operating characteristics of the hardware. The model also excluded losses that can occur during energy transfer in a physical system from pipe loss and electrical resistance. The amount of losses during energy transfer varies based on the size of the system and its actual operation, which is not practical to model with the generalized framework presented in this paper. In addition, these losses are minor compared to the dominant power losses in the solar pump hydraulic and motor, so are expected to have minimal impact on the cost implications calculated.

Moreover, the prices for solar panels and system hardware remain highly variable in SSA due to economic dependence on geographic location, import policies, and manufacturers. This framework does not capture socioeconomic factors that will occur in the real market scenario such as import duty of specific countries, transportation costs of the hardware, markups of the distributors, labor costs of installation, and system maintenance costs. Since these factors are hard to capture holistically in a generalizable framework, local practitioners will need to reflect on their specific local market dynamics when using this framework to design PVPS. The costs of the power electronics and energy buffers (e.g., batteries and tanks) are also not captured, as their sizing largely depends on the actual design of the system and its operating requirements (e.g., voltage, control scheme, and irrigation schedule). PVPS designers may still want to take into account the costs of these power system components during the design of a specific system. Recently, researchers have created in-depth models to optimize the sizing of system components (e.g., battery and tanks) which designers can leverage in conjunction with the presented framework during the design of a solar-powered irrigation system (Grant et al. 2022). As pointed out by Grant et al., the specific cost breakdown of a solar-powered irrigation system depends on the design layout of the actual system. Local system designers must also do their due diligence to account for the tradeoffs in the auxiliaries to create cost-effective PVPS for the irrigation market.

The efficiencies of the solar pump hydraulics were modeled and characterized at their best efficiency point (BEP) since it is the designed operating point of any pump hydraulics. In reality, a pump's hydraulics typically have a preferred operating range (POR) from 70% to 120% of the BEP flow rate. Operation away from the BEP may lead to an efficiency penalty, typically up to a drop of 8% depending on the efficiency curve shape of the specific design (Xylem 2019). This may lead to a potential deviation between the actual operating efficiency of the pump from the model approximation. This deviation is not captured by the model since the efficiency penalty away from BEP is design specific. However, manufacturers should be able to incorporate it from their existing sizing software which already contains the efficiency curves of their specific designs (Xylem 2020c; Grundfos 2020b). In addition, the cost reduction calculated based on the efficiency models are generalized approximations of the hardware, and these results do not represent the efficiency performance of any specific manufacturer. This is because the efficiency data from multiple manufacturers are lumped together to formulate the efficiency prediction models to describe the general market.

Conclusions

This study shows that an efficiency-driven design mindset can help reduce the upfront costs of solar-powered pumping systems (PVPSs) in the SSA smallholder irrigation space, which is counterintuitive to the industry's conventional upfront-cost-driven design thinking. A technoeconomic framework was created to quantify the impact of solar pump energetics to the overall upfront costs of solar array in a PVPS. The efficiencies of 4-inch multistage centrifugal pump (MSP) hydraulics and induction motors commonly used in SSA PVPSs were characterized and new efficiency scaling models were formulated. When compared to the IE efficiency standard, it was found induction motors used in the current solar pump market underperform even the lowest IE1 efficiency standard. Using a permanent magnet BLDC motor, which typically has an equivalent efficiency of IE3 to IE4, PVPS efficiency can be increased by up to 20%, effectively reducing the upfront costs of the solar array.

A case study was set forth to compare cost impact of solar pump efficiency between the current induction motor and an IE4-equivalent efficiency BLDC motor, for a PVPS that can be used in a 1-Ha farm with a 100 m well depth. The simulated results have shown that the use of a more expensive yet highly efficient BLDC motor can lead to an overall lower cost PVPS design, reducing its solar array cost by $480 USD while increasing energy efficiency by 18%. This demonstrates the framework is capable of identifying a potential pathway for the solar pump industry to rethink its design process to create more cost-effective, energy-efficient PVPSs for smallholder irrigation markets. Moreover, the utility of this framework can be valuable to industrial practitioners by enabling them to make informed design decisions with a quantitative foresight that directly connects solar pump energetics to the costs of the integrated solar-powered system.

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Data availability The efficiency data used to generate Figs. 2, 3 are publicly available on the online product catalog of the corresponding solar pump manufacturers.

Declarations

Conflict of interest The authors do not have relevant financial or non-financial interests to disclose. Research funding from industrial partner Xylem Inc. did not bias the authors on the research process and its outcomes.

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