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Solar water pumping systems: A tool to assist in sizing and optimization

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A R T I C L E I N F O

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A B S T R A C T

The United Nations estimates that about 25% of the earth's population will live in countries where access to water will be a recurrent problem by 2025. This article proposes a methodology and open-access software tool for rural off-grid communities and users with little knowledge about solar photovoltaic water pumping systems (SPVWPS) to provide access to safe water for consumption. The proposed methodology assists in all stages of the project: conducting a prefeasibility study, sizing and optimizing, maintenance and financial analysis. It includes components selection, optimal dimensioning of the SPVWPS, behavior prediction, yearly distribution of the water shortage probability (WSP) and a basic financial analysis. The tool suggests a water tariff to help ensure the project's financial viability. The most interesting findings of this research is that the size – hence the feasabilty – of a project depends mostly on the population tolerance to water shortage. The concept of water shortage probability (WSP) is introduced to help in defining the appropriate size and cost of the systems. This WSP is calculated for each day of the year. A comprehensive literature review is presented and two case studies were used to validate its potential. It is found that only about 10% of the total energy produced by the PV modules is effectively used to fulfill the water needs.

1. Introduction

Access to an improved[1] water source is a fundamental condition for human life. Several organizations, governments, private enterprises and universities have been dealing with this problem for decades. However, studying this issue is still relevant in 2021 for the obvious reason that many small and relatively poor isolated communities still do not have access to an improved water source, but also since the optimal sizing of water pumping systems has yet to be improved.

According to UNICEF and the WHO, more than 600 million people or about one person out of ten did not have access to an improved water source in 2015 (UNICEF and WHO, 2015). Fig. 1 shows that most of these people live in Sub-Saharan Africa. In 2019, it was 785 million people (World Health Organization, 2019). The United Nations also estimates that about 25% of the earth's population will live in countries where access to water will be a recurrent problem by 2025 (Ki-Moon, 2016). A closer look shows that 80% of these people live in rural areas, most of which are off-grid isolated communities; Fig. 2 shows that poor access to an improved water source is also related to revenue.

The manual collection and transportation of water have also been studied by the United Nations. The study reveals that women are often responsible for this work in developing countries. On average, they have to carry 40-pound containers and travel an average daily distance of 3.5 miles (more than 5 km/day) (United Nations - Human Rights, 2010). Reducing the time taken to collect and transport water is essential not only to improve access to water, but also to improve access to education, to increase productivity and to enrich the quality of life of communities (Slaymaker and Bain, 2017).

Most of the countries that did not meet the millennium's development goals regarding water and sanitation access in 2015 are located between latitudes -40° and 40°, where the solar energy resource is abundant and where the number of hours of sunshine is relatively constant throughout the year (UNICEF and WHO, 2015).

Using solar energy to partially or completely solve this issue has been an option for a long time. The first solar photovoltaic (PV) water pumping systems date back to the early 1970s (Bahadori, 1978; Dannies, 1959; Pytilinski, 1978; Wenham, 2007). The efficiency and reliability of the technology and elements used to construct the solar PV modules have substantially increased while the system's cost has gone down significantly. Fig. 3 shows the recent drop in the cost of PV systems indicating that PV modules are now quite affordable and that the other

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[1] An improved source of water means that the water is collected in such a way as to prevent it from being contaminated.

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Nomenclature

Symbols

Ac	Solar panel surface [m^2]
I_{sc}	Short-circuit current [A]
V_{oc}	Open circuit voltage [V]
I_{mp}	Max Current [A]
V_{mp}	Max Voltage [V]
μV_{oc}	Voltage temperature coefficient [%/K]
μI_{sc}	Current temperature coefficient [%/K]
I_L	Radiation generated current [A]
I_o	Diode inverse saturation current [A]
a	Modified ideality factor
R_{sh}	Shunt resistance [Ω]
R_s	Series resistance [Ω]
n	Day of the year
k	Boltzmann constant
E_g	Gap energy [J]
I_T	Solar radiation over a tilted surface [W/hr.m^2]
I_d	Diffuse radiation [W/m^2]
I_b	Direct radiation [W/m^2]
R_b	Direct radiation coefficient
M_s	PV modules in series
M_p	PV modules in parallel
$M_{p,\ max}$	Maximum PV modules in parallel
nH_0	Number of hours for which the reservoir could be empty over a period of time, WV = 0
nH_{total}	Total number of hours for the period of time, usually a year (8760 h)
ΔWV	Variation step for reservoir size [L]
WV_{total}	Reservoir size [L]
WV_{max}	Maximum reservoir size [L]
WV_{min}	Minimum or initial reservoir size [L]
WV	Volume of water in the reservoir [L]
Q_{day}	Daily water consumption [L]
Q_{month}	Monthly water consumption [L]
T_c	Cell temperature [°C]
T_{day}	Mean daily temperature [°C]
Q_p	Amount of pumped water [L/day] and [L/hour]
Q_c	Water consumption [L/day] and [L/hour]

Greek characters

β	PV panels tilt angle [°]
δ	Sun declination [°]
γ	Azimuth [°]
φ	Latitude [°]
ρ	Albedo – Soil reflectivity
θ	Incident angle of direct solar radiation over a surface [°]
θς	Incident angle of solar radiation over an horizontal surface [°]
ω	Hourly angle [°]
$\omega_{\lambda\text{-}\chi}$	Sunset hourly angle [°]

Index/Exponent

Stat	Static
Cond	Conduct – friction
Sing	Singular losses
Valves	Losses trough the valves
i	Time period i
amb	Ambient temperature

Abbreviations

AC	Alternative Current
DC	Direct Current
EPW	Energy Plus Weather
LCC	Life Cycle Cost
LLP	Load Losses Probability or Loss of Load Probability (LOLP)
MPPT	Maximum Power Point Tracking
NOCT	Nominal Operating Cell Temperature
NPV	Net Present Value (USD)
PMSM	Permanent Magnet Synchronous Motor
PV	Photovoltaic
PWM	Pulse Width Modulation
ROI	Return Over Investment (%)
SPVWPS	Solar Photovoltaic Water Pumping System
TRNSYS	Transient System Simulation Tool
Wp	Watt-Peak
WSP	Water Shortage Probability [%]
NASA	National Aeronautics and Space Administration

Measuring units

Power	Watt-peak [W_p] for PV modules and Watt [W] for other sources/loads
Energy	Watt hour [Wh]
Volume	Cubic meter [m^3] or Liters [L]
Distance	Meters [m]
Voltage	Volts [V]
Current	Ampere [I]

components of a solar PV water pumping system (SPVWPS), namely the water reservoir, will become the financial threshold for the viability of a project.

Similar comments although to a lesser extent, can be formulated regarding the pumping equipment, which becomes more efficient and cost effective with every passing year, thus globally making the solar PV water pumping system (SPVWPS) an interesting solution.

Currently, the major problem that needs to be solved is the diffusion of information about such systems. Very few communities are aware that SPVWPS are available, that they are just as reliable as or even better than diesel systems, and moreover nowadays cheaper to operate. Communities that are aware of them tend to reject SPVWPS, because they consider PV modules expensive and "high-tech", and therefore believe that they are more complex and expensive to operate than in reality. One of the challenges to overcoming this, is the lack of information available and easily understood by end users and managers (e.g. community leaders and government employees amongst others). In fact, the World Bank offers a wide range of resources ranging from scientific articles and studies to evaluation programs, but since most end-users do not have the level of academic training required to understand what is available, these resources lose their intrinsic value and do not have the desired effect. The World Bank (The World Bank, 2015) also proposes a performance evaluation model that bases its assessment on the aptitudes and knowledge of a community to operate a water system, and when it comes to the financial aspect, it suggests that planning should be made based on a proper tariff for water. This evaluation can also be incorporated into a business model to promote the replacement of diesel-based systems by solar-based systems (The World Bank and Bloomberg New Energy Finance, 2015).

In this context, the main objective of this research is to develop a methodology software application able to size photovoltaic solar water pumping systems for small and relatively poor communities that are remotely located, i.e. isolated from water and electricity networks. The ultimate goal is to ensure that women and girls to spend less time fetching water. This methodology is to be implemented in a user-friendly and upgradable computer tool for free distribution. Based on the data entered by the user to define the characteristics of a particular pumping application, the tool will determine the size of the SPVWPS needed to deliver water reliably and also improve the economic viability of the project. The users can change the input parameters, so as to be able to analyze all the possibilities and select from these the best solution according to their community's needs.

The underlying purpose of the tool is to enable users with little knowledge about solar photovoltaic water pumping systems to obtain a pre-feasibility technical and economic study of the project; the tool will indicate the quantity and model of PV modules to be used, the pumping equipment required, and the size of the water tank. The system will also provide financial planning assistance by calculating the amount of money required for the initial investment, periodic costs and asset maintenance, as well as the tariffs for the service. Finally, easily readable diagrams of the energy and monetary fluxes of the system shall be produced to assist in understanding the operating principle and economic viability of the SPVWPS.

This article is organized as follows: section two presents a brief review of relevant and recent publications in solar PV water pumping systems and helps position the present research in this body of existing knowledge; section three presents the proposed methodology with sufficient details to enable the implementation of the main ideas into a custom code; finally the results are presented in section four as well as two case studies used to assess the validity and performance of the methodology compared to other methods. Naturally, the document closes with the conclusions of this research.

2. Literature review

Water pumping for remote off-grid zones is an application where the use of electric energy produced by solar PV panels can be well adapted, namely because a water reservoir can act as a battery to make up for the daily or weekly difference between the availability of energy and the need for water. Several researchers have dealt with this particular kind of application, tackling different aspects:

- sizing (Bakelli et al., 2011; Cuadros et al., 2004; Glasnovic and Margeta, 2007; Hamidat and Benyoucef, 2009; Meah et al., 2008; Mérida García et al., 2020; Pande et al., 2003; Setiawan et al., 2014; Zavala et al., 2020),
- optimization (Benlarbi et al., 2004; Betka and Attali, 2010; Campana et al., 2015; Ghoneim, 2006; Glasnovic and Margeta, 2007; Govindarajan et al., 2014; M. et al., 2013; Olcan, 2015; Sallem et al., 2009),
- financial performance (Carrêlo et al., 2020; Foster and Cota, 2014; Kolhe et al., 2002; Kumar and Kandpal, 2007; Lal et al., 2013),
- performance prediction (Benghanem et al., 2014, 2013; Flores et al., 2012; Hamidat and Benyoucef, 2008; Mokeddem et al., 2011; Salilih et al., 2020a,b)
- greenhouse emissions reductions and environmental aspects (Kumar and Kandpal, 2007; Todde et al., 2018), etc.

This section reviews these studies.

2.1. Sizing

Regarding sizing or dimensioning, proposed methodologies are very similar in the majority of the published articles (Bakelli et al., 2011; Cuadros et al., 2004; Hamidat and Benyoucef, 2009; Meah et al., 2008; Pande et al., 2003; Setiawan et al., 2014). In these papers, the components of the SPVWPS are considered as independent, that is, the interactions between them are left aside. Glasnovic and Mergeta (Glasnovic and Margeta, 2007) were among the first to present a method that embeds both sides of the problem: demand and production. Moreover, most of the dimensioning calculations are made for the so-called worst month, where solar radiation is lowest with no regards to water needs. The process of components selection is often neglected despite its capital importance. System dimensioning and components selection are the key steps in determining the initial investment and the SPVWPS system's long-term performance. In other words, a mistake in sizing can lead to higher initial investments than needed or poorer system performance by which the system is not capable of pumping enough water when confronted to the expected consumption. On the other hand, bad component selection is fairly widespread in SPVWPS and may cause performance losses of about 18% (Wenham, 2007).

Several optimal-sizing algorithms, able to manage multiple parameters simultaneously, can be used; however, the most common optimization criterion is the minimization of the PV generator's size (i.e., reduction of the number of PV modules in the system) while guaranteeing a certain amount of water is being pumped for a particular application. Sizing with this sole criterion in mind leads to several

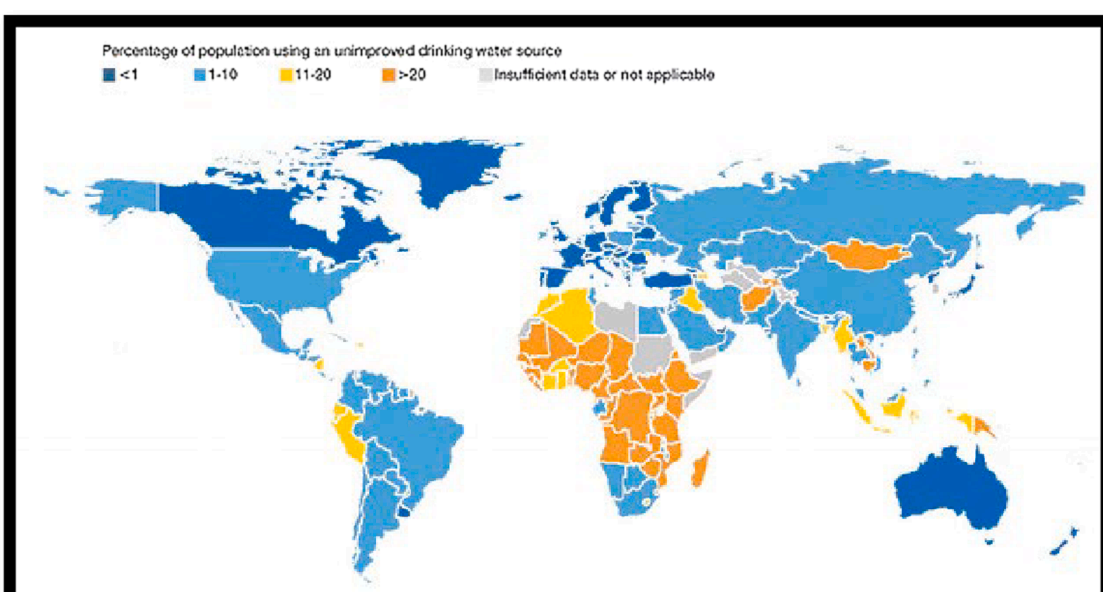

Fig. 1. Percentage of the population using an unimproved water source (UNICEF and WHO, 2015).

disadvantages. First, proper functioning for the months other than the "worst month" (Glasnovic and Margeta, 2007) cannot be guaranteed, second, the importance of other components in the system's performance are neglected and third, the financial behavior of the SPVWPS is not considered as a whole, since the cost of the water reservoir is not factored in.

Batteries can be integrated to a SPVWPS to make it possible to store electric energy for times when available solar radiation is lower than consumption needs, e.g. at night. In 2015, some 250 MW of utility-scale electricity storage (excluding pumped hydro and lead-acid batteries) were installed worldwide, up from 160 MW in 2014. Announced projects reached 1.2GW (Frankfurt School-UNEP and Bloomberg New Energy Finance, 2016). However, their long-term cost is still too high for remote off-grid rural communities despite a 77% drop in costs in recent years (Lambert, 2017). Another issue is their limited expected lifespan, normally between 2.5 and 10 years depending on the type of battery (Rydh and Sandén, 2005). Energy storage can then take the form of batteries but water reservoirs is more common and reported as less expensive (Muhsen et al., 2017). A suitably designed water reservoir can accomplish a similar function for a fraction of the cost, and with reduced maintenance and a longer lifespan (The World Bank and Bloomberg New Energy Finance, 2015).

Pande et al. (Pande et al., 2003) proposed several criteria for designing a photovoltaic pumping system for crop irrigation. First, water requirements are defined for each plant, as well as the theoretical energy required to pump water according to these requirements, while taking into account pressure losses. In terms of water consumption, several variables are mentioned, such as the phases of plant growth, soil type and season; also, the consumption pattern varies over time throughout the year. However, only the peak consumption is considered when dimensioning the system. The selection criteria for the pump are the volume of water to be pumped, the working pressure of the system, the pressure drops and the efficiency of the pump-motor assembly. However, the process of selecting the pump is not explicit. The number of PV modules is defined based on the theoretical efficiency of the pump-motor unit, the nominal power of the modules and the rated power of the pump, but the data and calculations are not shown.

The research carried out by Cuadros et al. (Cuadros et al., 2004) is based on a software tool developed in Matlab® for dimensioning SPVWPS used in an irrigation application. In that study, the selection of components is not considered; in other words, the components used (pump and solar PV panel model and type) are imposed. The size of the PV generator is estimated along with the calculated water needs for a specific crop that is to be irrigated. The study by Hamidat and Benyoucef (Hamidat and Benyoucef, 2009) is based on the Load Losses Probability (LLP) to dimension the SPVWPS, taking the water reservoir as an analog of the batteries, being able to provide water even during the night or in poor sunshine conditions. The solutions obtained with their methodology include the rated power of the PV generator and the reservoir size, depending on the desired LLP threshold. Although preponderant elements to be used are imposed, i.e. pump and PV modules model, several solution sets are possible depending on the chosen LLP. However, it is still not clear which solution would be best, since the financial criterion is not included in the analysis.

Bakelli et al. (Bakelli et al., 2011) have addressed this deficiency, determining the solution for which the Life Cycle Cost (LCC) is minimal. The authors include the LCC as a decision criterion for the SPVWPS dimensioning process. Nevertheless, at least one solution is possible for each LLP's desired value, meaning that it is necessary to define the LLP threshold depending on the particular application. Meah, Fletcher and Ula (Meah et al., 2008) mention criteria to consider when designing a SPVWPS: estimating the nominal power of the PV module, selecting which pump is to be used and that of the controller, if needed. Accurate information is required, particularly water consumption, available solar radiation and the type of water source. An oversize of 5% of the pump body and 20% of its motor rated power is recommended for sunny days, this regardless of geographical location. Sun-tracking systems, which increase the energy produced by the PV module, are sensitive to strong

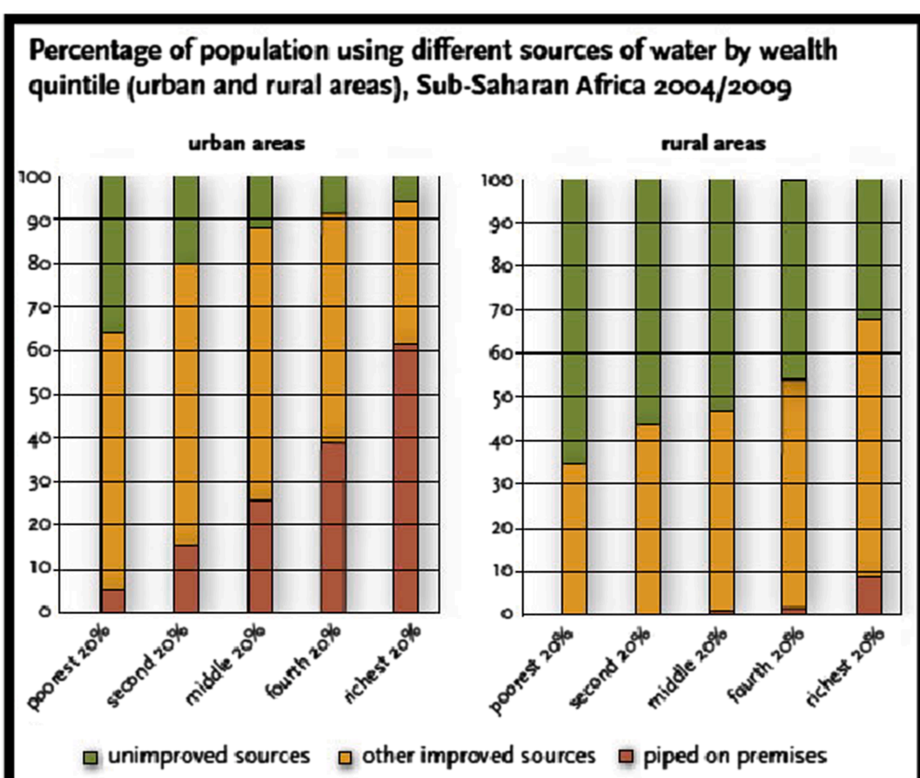

Fig. 2. Access to improved water sources with respect to wealth (FAO-UN FAO, 2011).

wind currents and require maintenance, so they are not recommended in that study.

Setiawan et al. (Setiawan et al., 2014) present a clear example of the actual dimensioning process being used in isolated communities, this time aiming at the replacement of a diesel based pumping system in Indonesia. The pump choice is based on the pumping distances, the frictional losses and the water mean consumption; the PV modules model is imposed (there is not any selection criterion) and the quantity is calculated based on its nominal voltage compared to the pump's nominal voltage (series quantity) and on the rated pump power (parallel quantity). The meteorological data is not included in the dimensioning process and only the rated efficiencies are considered, putting aside their variation over time and different operation conditions. An existing water reservoir is used but its volume is not considered as a variable for the SPVWPS. Finally, a performance analysis to determine whether the installation is well designed is not considered.

In several studies, a financial analysis makes it possible to assess the SPVWPS project's viability (Foster and Cota, 2014; Kolhe et al., 2002; Kumar and Kandpal, 2007; Lal et al., 2013). In most cases, the beneficiaries of this type of installation are located in remote rural communities, where financial resources are limited. Subsidy or donation needs can be estimated by calculating the Net Present Value (NPV). In a similar manner, a study of the system's expected lifespan can be used to predict the amount of money required to maintain and operate the SPVWPS, and to define strategies to raise those amounts (Short and Oldach, 2003).

2.2. Optimization

The choice of components is indeed important for the system, but optimization criteria are just as crucial in determining the appropriate system for a given situation. Optimization criteria are often proposed to make use of the components as efficiently as possible and to obtain the best performance for a given condition. Several types of results can be obtained from optimization, such as the optimal PV panel angle, pump control algorithm, and PV panel control algorithm.

Glasnovic and Margeta (Glasnovic and Margeta, 2007) used an objective function to minimize the SPVWPS size, taking into account the parameters involved in the process of dimensioning a SPVWPS for irrigation and their interactions. However, the authors neglect the above-mentioned interactions between components and solely use the worst month for solar radiation in their design, thus enabling the possible incompatibility between demand and available energy, along with the inability to guarantee the correct functioning of the system for the months other than the critical month. In (Glasnovic and Margeta, 2007), the storage of water to ride out sunny periods is also neglected. Since neither the use of an external tank nor the inclusion of batteries is considered, it is the price of PV modules that largely defines the price of the installation for this particular case.

The research of Campana et al. (Campana et al., 2015) proposes an economic optimization of a SPVWPS for tankless irrigation, to maximize crop revenues, while reducing the initial investment, which depends primarily on the price of the components. A dynamic model is evaluated for each hour and the results obtained are compared with experimental data. A genetic algorithm is used to find the size of the system for which the income is the highest. The main restriction of the method is the rate of replenishment of the water source in order to avoid overuse and oversizing of the PV module. The model of PV module to be used is imposed and the energy incident on the surface of the modules is calculated according to the isotropic radiation model (Duffie et al., 1980). Thanks to the affinity laws, a function linking required power and output flow for a given dynamic head makes it possible to determine the power of the PV module including the nominal efficiency of the engine and the inverter. This study shows a reduction in the PV panel size of 33.3% and a 10% increase in the energy produced due to the change in its inclination (originally equal to latitude). The initial investment is reduced by 18.8% due to the decrease in the number of PV modules. The capacity of replenishment of the water source is respected, therefore there is no over usage.

Similarly to the research published by Bakelli, Hadj Arab and Azoui (Bakelli et al., 2011), the recent contribution by Olcan (Olcan, 2015) aims to establish an analytical model of multicriteria optimization for the design of SPPV, mainly taking into account the probability of source failure, and economic analysis based on life-cycle costs (LCC). The targeted SPVWPS consists mainly in PV modules, a storage tank and a pump-motor assembly. Only two modes of manual slope change are considered, either monthly or seasonally. The results for a particular installation show that the manual change of the position of the panel reduces the required number of PV modules, but increases the LCC (the cost of the change of position is considered). Hence, the fixed panel solution is retained.

Nabil, Allam and Rashad (M. et al., 2013) studied an existing SPVWPS, in which a synchronous reluctance motor drives a centrifugal

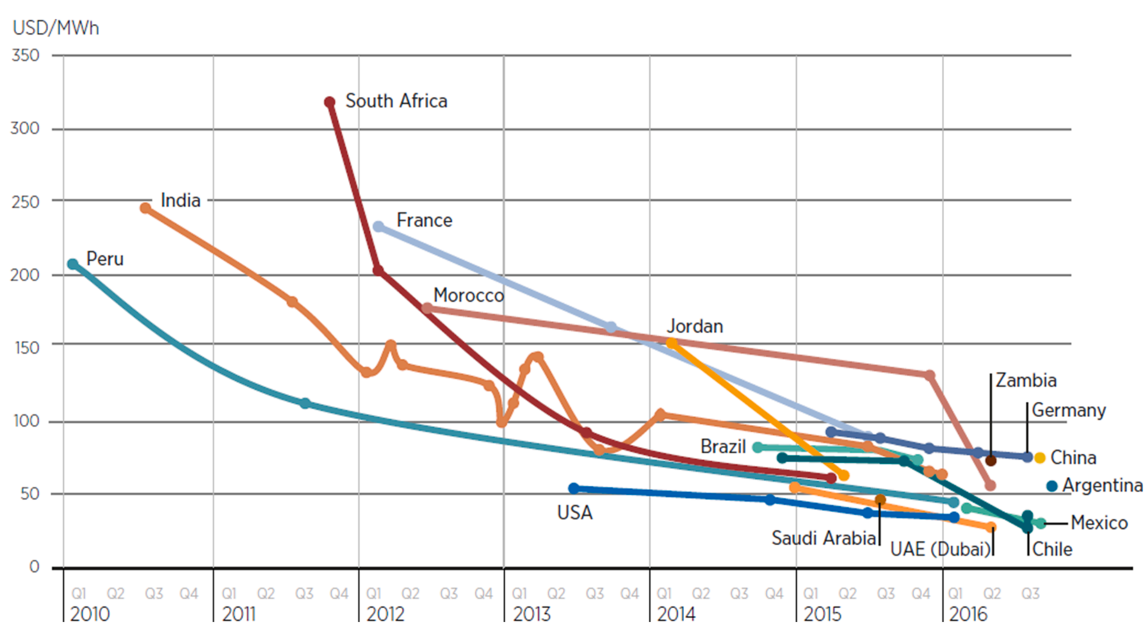

Fig. 3. Evolution of utility scale solar PV auction prices around the world (IRENA, 2017).

pump. The control strategy aims to maximize the amount of water pumped through the maximization of power allowing the engine to operate and pump water for a given pumping load. The system mainly involves a PV module, a DC-DC converter, a PWM (Pulse Width Modulation) AC-DC converter, and a motor and centrifugal pump assembly. With the proposed strategy, it is possible to reduce the solar radiation required to start the pump, which in turn increases the actual pumping time and the amount of water pumped. Similarly, the PV panel can operate at maximum power thanks to Maximum Power Point Tracking (MPPT), which controls the DC-DC converter and avoids an overshooting of the nominal voltage of the motor.

Govindarajan, Parthasarathy and Ganesan's (Govindarajan et al., 2014) investigation is based on an existing SPVWPS with a permanent magnet DC motor driving a centrifugal pump. In (Govindarajan et al., 2014), the PV panel is controlled by an MPPT algorithm. However, since the dimensioning is based on the average radiation incident on the surface, it is possible to obtain a voltage higher than the nominal power of the pump, which is why a voltage control strategy is implemented in order to protect the pump. The simulation is carried out on Matlab® Simulink® and validated using an experimental set-up.

The article of Betka and Attali, (Betka and Attali, 2010) also seeks to optimize the operation of a SPVWPS, the optimization criterion being the maximization of the quantity of water pumped per day with a control strategy for an induction motor resulting in a centrifugal pump. The use of an induction motor has several advantages, in particular its low cost, its minimal maintenance and the possibility of weathering. The proposed strategy reduces iron losses and losses on the motor's core, increasing the engine's efficiency and increasing the power available to the engine shaft. The result is an increase in pump output of 31.3%, as well as the possibility of starting the pump with 44.6% less sunshine than without the control strategy. In addition, it is possible to obtain the maximum power of the PV panel by implementing a MPPT algorithm.

The algorithm developed by Sallem, Chaabene and Kamoun (Sallem et al., 2009) optimizes the distribution of energy produced by the PV panel of a pumping installation in order to increase the effective pumping time during a typical day for three climatic conditions: cold season, warm season and an intermediate season that could correspond to autumn or spring. The system consists of PV modules, a centrifugal pump driven with an induction motor and a battery pack. The diffuse algorithm makes it possible to make decisions regarding the energy flows, since it is possible to supply the pump with three distinct operation strategies: using only the batteries, using the batteries with the support of the PV panel and using only the PV panel. And similarly, it is possible to store the excess energy produced in the batteries. The applied model makes it possible to increase the pumping time by 97%, all with a discharge level of the batteries less than 50%, which increases their useful life.

The article by Ghoneim (Ghoneim, 2006) evaluates the performance of a SPVWPS located in Kuwait using the Transient System Simulation Tool (TRNSYS®). The objective is to optimize system sizing, particularly optimizing the number of PV modules, their inclination and taking into account the characteristics of the pump assembly hydraulic motor (cc) circuit. The pump is modeled from the curves provided by the manufacturer, linking input power, flow rate and dynamic head. The PV modules are modeled with the five-equation model, which is suitable for amorphous, crystalline and polycrystalline silicon modules. Water consumption is assumed to be constant for a population of 300 people consuming 40 L/person/day. The study shows that for an imposed pump, the efficiency of the system varies with respect to the head, with a height value for which the efficiency is higher. Similarly, for the optimum dynamic head, it is possible to calculate the amount of money saved in comparison with a system equivalent to diesel, and the power of the PV module for which the amount saved is higher.

The diffuse optimization of the efficiency proposed by Benlarbi, Mokrani and Nait-Said (Benlarbi et al., 2004) takes into account three types of motors: DC with separate excitation, permanent magnet synchronous machine (PMSM) and induction machine, and seeks to maximize the speed of the motors to increase the pumping rate. The optimization algorithm acts on the ratio of a DC-DC converter allowing the adaptation of impedances between the load and the PV module. In (Benlarbi et al., 2004), the authors conclude that the optimized operating points of the DC and PMSM motors coincide with the operating points of the PV module where the output power is maximum (MPP). This behavior ensures maximum power extraction, while increasing the overall efficiency of the system. In addition, it is possible to start the pump earlier in the morning and to operate it during the last hours of the evening because the power supplied to the load is the highest. An increased 10% to 16% of pumped water is obtained in the simulations with the proposed optimization. The performance of the PMSM is also higher than that of the DC motor and the induction motor, so its use is recommended.

Zavala et al. (Zavala et al., 2020) proposed efficient new operation rules for standalone direct pumping PV irrigation systems in order to maximize the energy use efficiency as the available resource must be use readily. In the paper, the authors claim that an innovative analytical model was implemented in order to optimize the operation of a multisector PV irrigation system.

Salilih and co-workers (Salilih et al., 2020b) proposed a method for the modelling, simulation and analysis of solar PV water pumping system under different pumping heads. Using their generated performance equation and the calculated hourly power output data, the hourly performance of the solar driven water pump system was estimated. The analysis and simulation results show that a lower pump head results in higher flow rate regardless of the variation in solar irradiation level.

2.3. Economics

Project viability studies are necessarily based on economic analysis, since they determine financial flows over a defined period of time. Several techniques can be used to evaluate the profitability of any photovoltaic energy project.

The paper by Kolhe, Kolhe and Joshi (Kolhe et al., 2002) examines the viability of stand-alone PV systems using a comparison with diesel systems in India with Life Cycle Cost (LCC) analysis and a parametric study. For the initial investment of the PV system, the authors consider the prices of PV modules, DC-AC converters and batteries, with an amount per W_p (PV modules and converter) or per kWh (batteries). For operating and maintenance costs, a percentage of the initial investment is proposed. Asset maintenance is done only for batteries, based on the number of charge–discharge cycles and the recommended discharge depth. For the diesel system, its estimated lifespan is six years with a load of 25% in relation to the nominal load. Operation and maintenance costs include oil changes, filter elements and a generator upgrade with a defined periodicity. Inflation on fuel is also included. The parametric study shows that PV systems are more advantageous than diesel, especially for loads below 30kWh/day with a discount rate of 20%. Similarly, with a diesel price of 0.15USD/L, the PV system is more profitable for loads less than 28kWh/day. In addition, when the available solar radiation is 4 kWh/m2/day, the LCC of the PV system is lower for loads up to 53kWh/day. This case is quite similar to a PV's cost of 2.25USD/Wc. The author also shows that reliability has a significant impact on LCC for autonomous PV systems, since if the percentage of reliability is reduced, the LCC also decreases considerably. It should be noted that the stand-alone PV system is very competitive, because the maintenance and operation costs are quite low and the costs related to asset maintenance are lower than the costs of a diesel-based system.

Lal, Kumar and Rajora (Lal et al., 2013) use the net present value (NPV) to evaluate an existing SPVWPS, taking into account initial investment, maintenance and savings in relationship to the use of a diesel or natural gas system with a nominal power of 5.88 kW. The payback period, based on 2013 figures, for the SPPV is 1.814, higher than that of the diesel system (1.354), but less than that of the natural gas system

(3.787). The emission reduction of greenhouse gases is also estimated at 14 977 kg/year. The savings generated by the SPVWPS is estimated at 1.948 USD/year for a diesel system that operates 1 447 h per year (16.5% of the time). Finally, subsidies to fossil fuels were found to have a negative impact on the implementation of SPVWPS.

Similarly, in 2014, Foster and Cota (Foster and Cota, 2014) discussed the fact that the cost of PV modules has steadily decreased by 80% from 2003 to 2013, while fossil fuel prices have risen by nearly 250% over the same period. In 2014, the authors found a tremendous use of SPVWPS in a wider range of power output, up to 25 kWp. According to this article, typical applications for SPVWPS are human consumption, irrigation and livestock, all in rural areas. Initial investments are around 8 USD/Wp (pumping equipment included) and operating costs are approximately 0.15 USD/kWh. The payback period is an estimated two to three years with a lifespan of around 25 years for the PV modules. Fig. 3 shows that the prices continue to decrease for PV technologies despite oil and gas prices being lower than a few years ago. The payback period for SPVWPS should then decrease even more. Since 2014, the capacity of installed PV panels grew from 135 GW in 2013, to 172 GW in 2014 and 219 GW in 2015 with an expected 591 GW in 2020 and 1591 GW ten years later (International Renewable Energy Agency (IRENA), 2016).

The SPVWPS can also be considered as a technological option for the reduction of greenhouse gas (GHG) emissions, as proposed by Kumar and Kandpal in 2007 (Kumar and Kandpal, 2007), who implemented a methodology for evaluating the unit cost of reducing GHG emissions with a SPVWPS. A comparison is made between the NPV of the solar versus diesel systems taking into account the savings and another comparison involves a grid-connected coal-based plant and the PV solar system regarding GHG emissions. The results show that for a SPVWPS of 1.8 k Wp of rated power, the mitigation cost is 169 USD/ton of CO_2 avoided compared to the diesel system and 405 USD/ton of CO_2 avoided compared to the system connected to the grid. These values indeed depend on the initial investment, the price of fuel, the useful life of the system and the discount rate. As PV module prices continue to decline, the cost of mitigation will also tend to decrease.

Economics for remote sites are studied by Meah, Fletcher and Ula (Meah et al., 2008). Among the challenges encountered at the facilities, the authors emphasize the use of resources that can be purchased from local suppliers, as this facilitates the maintenance and maintenance of assets. Similarly, training in maintenance and operation significantly increases the survival of the system, as it is not cost effective to pay local suppliers for this type of task. As for the economical aspect, the NPVs of three types of pumping systems are compared, namely a diesel system, a solar system and a system connected to the grid. The study shows that the NPV of the solar option is lower than those for the other systems, mainly due to the very low maintenance and operating costs and the relatively favorable lifespan of the PV modules. The financial flows of the grid-connected facility are very similar to the SPVWPS, but the initial investment is too high, because of the cost of extending the grid wires from the grid to the pumping site.

Carrêlo and co-workers (Carrêlo et al., 2020) presented a comparative economic feasibility analysis of five large-power PV irrigation systems (PVIS) in the range from 40 to 360 kWp in the Mediterranean region. The results show that the investment in PVIS in the Mediterranean region is always profitable, for all of the PVIS configurations and the powers considered in the study despite frequent lacks of water that oblige the PVIS to stop.

The last paper to be reviewed herein accounts for life cycle assessments (LCA). Todde et al. (Todde et al., 2018) evaluated the cumulative energy demand and the related environmental impact of three large-power stand-alone photovoltaic (PV) irrigation systems using a LCA methodology. The authors stress that the production of PV modules accounted for the main portion (about 80%) of the primary energy embodied into the whole PV irrigation system (PVIS). The outcomes of the study also show that the energy return on investment depends on the PV generator dimension, ranging from 12.9 to 4.8 and that energy payback time increased from 1.94, to 5.25 years and carbon payback time ranged from 4.62 to 9.38 years. But the interesting result is that the study shows an inverse trend of the energy and carbon payback times respect to the PV power size.

2.4. Summary

The review of the various publications presented in this paper shows that photovoltaic pumping is an economically and technically well-suited solution for irrigation, livestock and human consumption in rural areas where a connection to the electricity grid is complicated, expensive and/or non-existent.

With respect to **sizing**, in most papers the approach for determining the components to be used is not explicitly indicated, so these components are defined or fixed at the beginning of the paper without any particular selection procedure. Globally, the procedures mentioned in the literature for dimensioning a SPVWPS include calculating the size of the PV module itself for the critical month of the year, using the nominal efficiencies (PV panel and pump-motor assembly) and the peak of water consumption.

Several **optimization** criteria are presented with several objective functions. Since the ultimate goal of a system is to supply water according to a given consumption, the load losses probability methodology is the approach that allows the SPVWPS to be sized to meet the required consumption capacity. Other optimization criteria make it possible to establish that a pump driven by an induction machine or by a permanent magnet synchronous motor can operate at the maximum power point of the PV module in order to obtain the maximum power. In addition, several articles show that it is possible to connect the input electrical power to the pump-motor assembly by a single mathematical function. This function can be constructed from experimental data, mathematical models of the engine and pump or data supplied by the manufacturer.

Lastly, the LCC and the NPV are useful for analyzing a solar PV pumping system from a **financial** point of view. In particular, the net present value makes it possible to establish the cost of operating, maintaining and replacing assets for the system in order to carry out the financial planning that will ensure the sustainability of the project. Aspects such as available load/energy compatibility and variation in component efficiency should be considered for more accurate results.

These observations were the backdrop from which the methodology proposed in this paper was devised. It is presented in the next section. For more on the subject two thorough reviews could be mentioned to the interested reader. First, the paper by Li and co-workers (Li et al., 2017) and the paper by Sontake and Kalamar (Sontake and Kalamkar, 2016). A more recent review work has also been reported by Shepovalov, Belenov and Chirkv (Shepovalov et al., 2020).

3. Methodology

The proposed methodology includes components selection (mainly pump, PV modules, controller and reservoir, structure is not considered in this paper), the optimal dimensioning of the SPVWPS, the behavior prediction for a typical meteorological year, the yearly distribution of the water shortage probability (WSP) and a basic financial analysis. Fig. 4 presents a compact diagram of the overall functions of the program proposed herein with their successive connections. The choice of the appropriate pump and later those of the PV array and reservoir are discussed in more details in Figs. 5 and 8. Optimization is carried-out to lower the cost of an acceptable solution, predictions are carried-out to verify that the system really meets the needs otf the community and a simple financial analysis provides the fare or cost of the system.

A software tool with easy to use interfaces implements this methodology with the aim of allowing rural communities to benefit from this research. For instance, one of the first interfaces allows to enter the location either with latitude and longitude, city name and country code or preferably using a .epw file. Then, the pumping data are entered

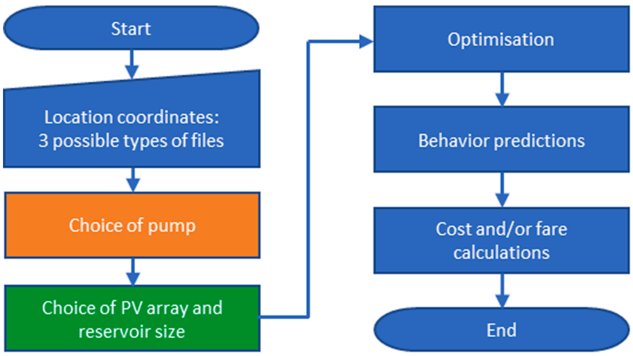

Fig. 4. Overall schematic of the proposed methodology.

(horizontal distance to the source, vertical drop, river or well), the water consumption profile (either monthly or hourly), etc.

The software tool was developed in Python® language, thus permitting its open distribution, as much for the software tool as for the source code.

3.1. User input data

Although basic information is provided to start the dimensioning process, several assumptions complete this information.

In the first implementation of the methodology, the user is required to provide an Energy Plus Weather (.epw) meteorological data file. The data to be extracted is thus related to the direct and diffuse solar radiation over a horizontal surface and the ambient temperature. The data is then treated to account for the slope of the array. When there is no EPW file for a specific location, the program can allow to provide the latitude, longitude and the ISO 3166 country code and to use NASA Surface meteorology and Solar Energy – Global data sets. This alternative source provides information for every combination of latitude and longitude, which ensures data availability. As a third way to input relevant meteorological data, this data could be taken from the NREL Solar Radiation Research Laboratory, if need be (Andreas, 2019). This is why Fig. 4 indicates 3 possible types of data. When required, the files for direct, diffuse radiation and ambient temperature were downloaded from the website, but the monthly values were converted into daily values (Duffie et al., 1980; Wenham, 2007). These daily values are used to obtain hourly values by use of the Collares-Pereira correlation (Duffie et al., 1980) described by Eqs. (1)–(5).

$$a = 0.409 + 0.5016\sin(\omega_{l-c} - 60) \tag{1}$$

$$b = 0.6609 - 0.4767\sin(\omega_{l-c} - 60) \tag{2}$$

$$R_t = \frac{\pi}{24}(a + b\cos\omega)\frac{\cos\omega - \cos\omega_{l-c}}{\sin\omega_{l-c} - \frac{\pi\omega_{l-c}}{180}\cos\omega_{l-c}} \tag{3}$$

$$R_d = \frac{\pi}{24}\frac{\cos\omega - \cos\omega_{l-c}}{\sin\omega_{l-c} - \frac{\pi\omega_{l-c}}{180}\cos\omega_{l-c}} \tag{4}$$

$$R_t = \frac{I}{H} et R_d = \frac{I_d}{H_d} \tag{5}$$

The proposed method also verifies that the latitude and longitude values are between -180° and $+180^\circ$ to avoid errors when searching the data inside the files. Regarding the first option (.epw file), the data are recorded hourly and no conversion is necessary. Finally, the method saves the data and shows a confirmation with the amount of available data as well as the latitude and longitude.

When using data files, one has to consider their related margin of error according to guidelines and methodologies such as those of ASHRAE Guideline 14-2014, the International Performance Measurement and Verification Protocol (IPMVP) and the Federal Energy Management Program (FEMP). Moreover, one should be aware that a typical meteorological year (TMY) may not be (in fact, is almost never) representative of a given year.

Then, the choice of an appropriate pump begins (Fig. 5). The pumping distances (horizontal and vertical) are indicated by the user and the type of water source is selected (river or well, (Karassik and Karassik, 2008)). A water consumption profile must be provided. This

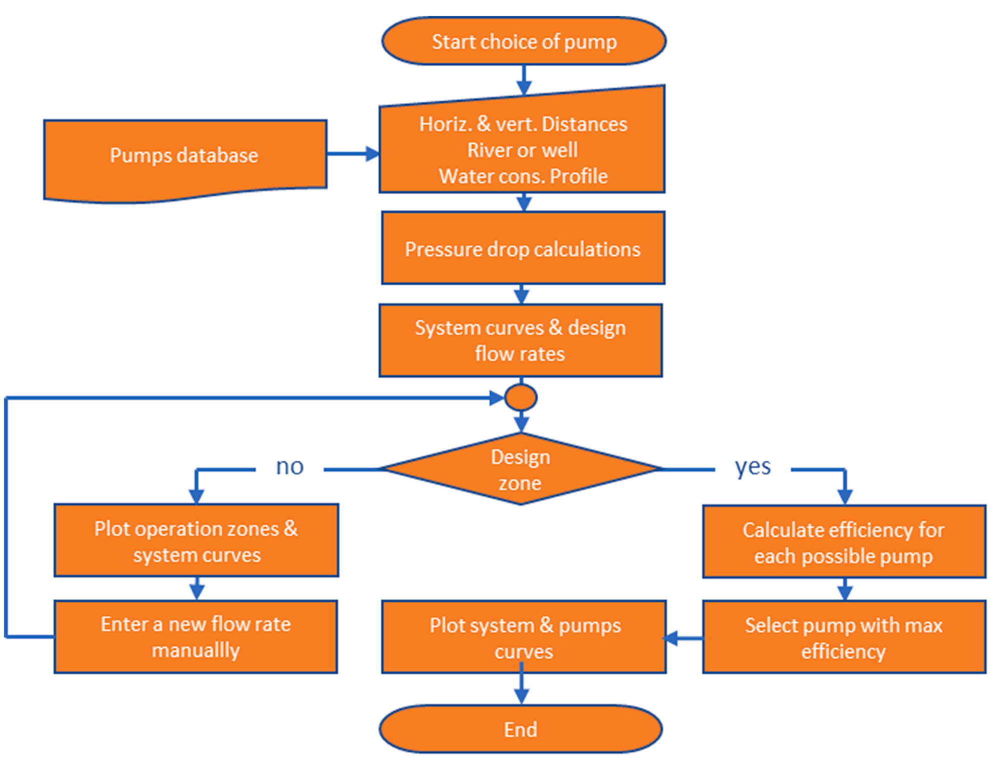

Fig. 5. Dimensioning process diagram (pump selection).

can be done in two different ways, either through a text file indicating hourly consumption in liters for one year, or with the monthly total consumption values in combination with one of the proposed consumption profiles. When monthly values are available, the proposed tool links the consumption with temperature to provide daily consumptions (Wenham, 2007) using Eq. (6):

$$Q_{day}(i,j) = Q_{month}(j)\left(\frac{\overline{T_{day}(i,j)}}{\sum_i T_{day}(i,j)}\right) \quad \text{where} \quad \sum_{i=1}^{i_{max}(j)}\left(\frac{\overline{T_{day}(i,j)}}{\sum_i T_{day}(i,j)}\right) = 1 \qquad (6)$$

Then, two acknowledged models (Brière, 2012) are implemented to provide hourly consumption profiles. Hourly consumption values throughout the year recorded as 8 760 entries in a text file is needed for the final validation analysis. Fig. 6 proposes two typical daily consumption profiles.

With input data the code computes the pressure drop and provides system curves and design flow rates for the required pump. When these parameters fall in the design zone, each possible pump from the database is considered and that with highest efficiency is selected. If not, new operation parameters are implemented a manual flow rate is prescribed and the test is carried out to meet the desired requirement.

For the rest of the calculations, since the system does not consider the use of batteries, another correction must be applied to the data. The tool calculates the sunrise and sunset times for each day to identify the consumption that takes place at night; this consumption is then added to the consumption during the sunny hours in order to create a consumption profile which ensures that during the day, enough water will be pumped to meet nigh needs.

Finally, the albedo, ρ, or soil reflectivity, must be provided as the last input data. A pop-up table proposes typical albedo values (Holman, 2010) depending on the type of soil.

3.2. Optimal sizing

Since the characteristics of the pump do not change with the PV generator size, nor with the reservoir size, the first dimensioning step is in choosing the pump-motor assembly. From the pumping distances and the water consumption data, it is possible to plot the Flow vs. Total Head characteristic curves of the system. Then, based on the information from the provider that is stored, calculations are made in order to characterize the pump. First, the data is used to create functions that describe the behavior of the pump. Next, the points of maximum efficiency are identified to finally establish the theoretical zone of operation of the pump on the plane Flow vs. Total Dynamic Head.

These curves consider the pressure losses inside the pipes due to friction, as well as the losses in the accessories and valves. As those losses vary as a function of the inner diameter of the pipes, several curves are calculated and plotted depending on the possible output diameters of the available pumps. Eq. (7) is used to calculate the total head (Karassik and Karassik, 2008).

$$H_T(m) = H_{stat} + H_{cond} + H_{sing} + H_{valves} \qquad (7)$$

The software tool involves a database containing some 50 pump-motor assemblies with available submersible surface and centrifuge models. The choice of pump type depends on the type of water source type indicated by the user. For the centrifugal pumps, the optimal operation zone is between 85% and 105% of the flow rate, where the efficiency is at a maximum (American Society of Heating and Air-Conditioning Engineers, 2016); therefore, this area can be located for each pump in the database. The software tool compares the system curves for total dynamic head, in m, with respect to the volumetric flow rate, in liters per minute, with the possible operating areas of the available pumps in the database and chooses the pump with maximum efficiency in this area. This is depicted in Fig. 7. In this case, the pump with overall 54.8 efficiency would be selected

From the technical datasheets and the intersection points between the system curve and the pump operating curves, it is possible to determine a function linking the power input to the motor and the output flow rate produced by the pump. This function is then used to calculate the number of PV modules in parallel (M_p) required; the number of PV modules in series (M_s) required is defined by the nominal voltage of the pump and the panel (Gasque et al., 2020).

Several solutions are possible for a particular system, nevertheless, the proposed methodology must seek the optimal one. From the equation linking power input to the motor and output flow rate, the rated power must be found for which the pumping rate can effectively deal with the water requirements. A variable size water reservoir, is included in the system; the software tool looks for all possible solutions while varying the reservoir size to match the water demand, the type and model of PV module, the tilt angle β; in order to finally determine the optimal solution.

3.3. Mathematical model

As this part of the mathematical model implemented herein does not show particular novelties, it is presented in Appendix 1 for the reader who want to reproduce the predictions carried out in this paper. For PV module modeling, a classic one diode, 5 parameters model (Duffie et al., 1980) is used.

The method is based on the isotropic model (Kalogirou, 2014) to calculate the incident energy on surfaces. One could argue that an anisotropic model could improve the global model but first the objective here is not to test or discuss models, and one may always find studies into which an isotropic model (that of Badescu for instance) was

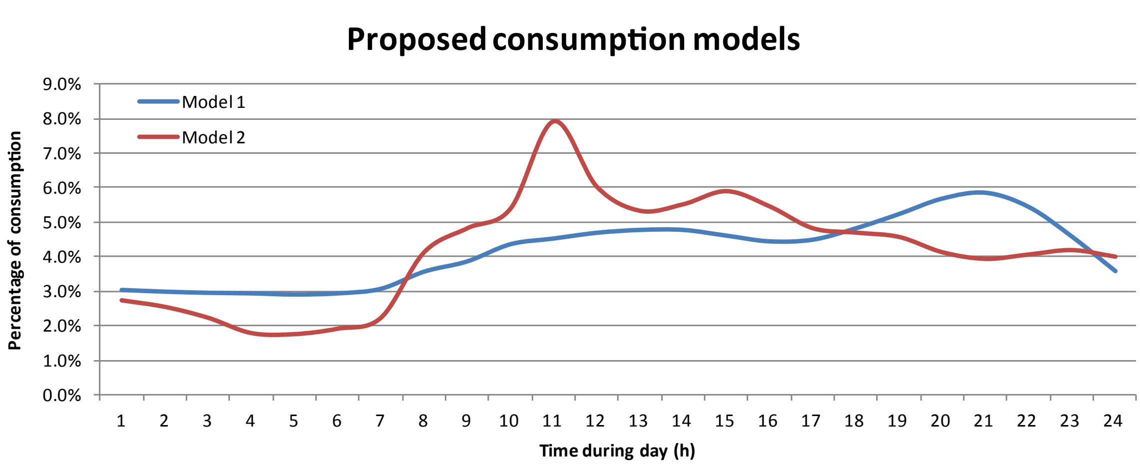

Fig. 6. Two typical hourly water consumption profiles.

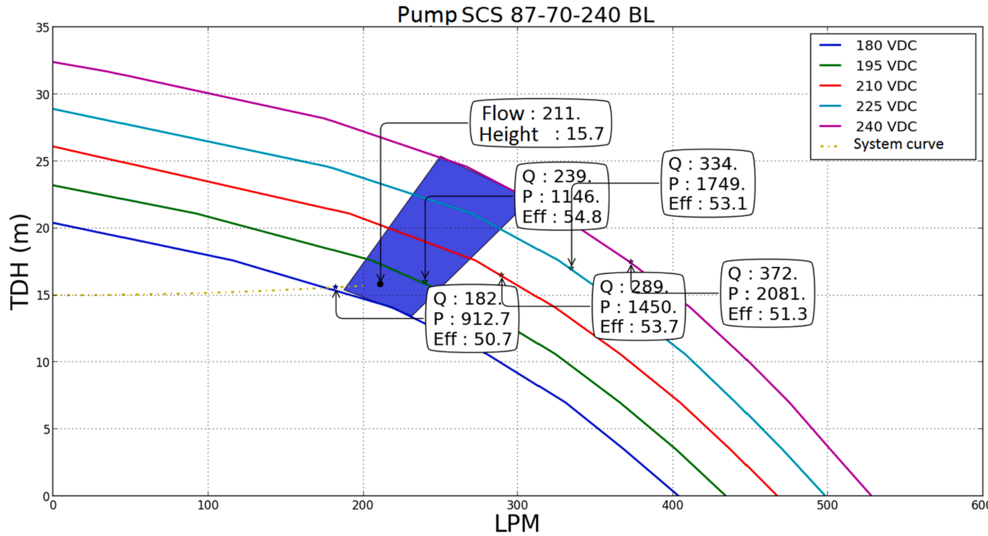

Fig. 7. System Total Dynamic Head [m] vs Volumetric flow rate [LPM] curves. and possible pump choices area.

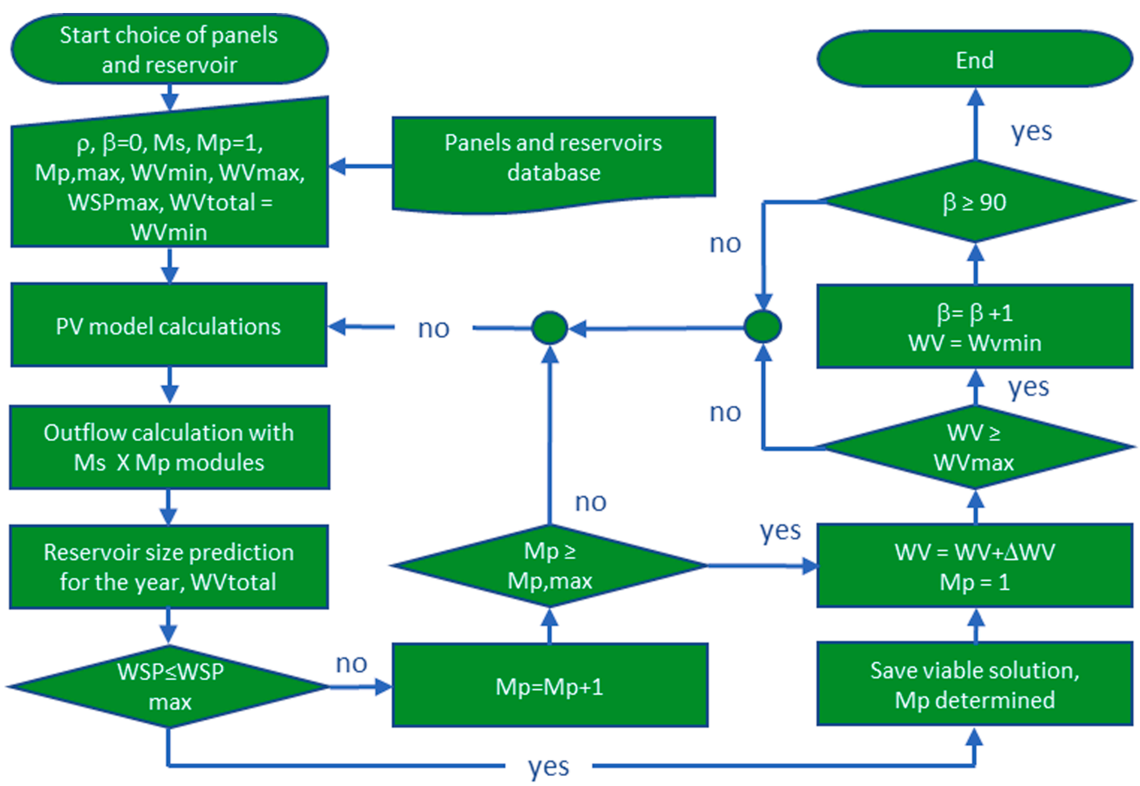

Fig. 8. Dimensioning process diagram (PV modules and reservoir selection).

preferred for estimation of solar radiation incident on tilted surface with smallest statistical errors among the 6 models investigated (among them that of Hays and Davis) and produced close agreement with measured data (Shukla et al., 2015). Hourly values are stored in a linear vector involving 8760 positions.

It is then possible to use the parameters of the PV modules to calculate the maximum output power available for each type of PV module in the database. The number of PV modules to be used in series is defined before starting any power calculations, which involves dividing the nominal voltage of the selected pump by the nominal voltage of the PV modules (V_{mp}). The process of calculating output power is iterative and based on the model with a single diode.

An estimate of a module's efficiency for a given surrounding temperature and incident radiation (I_T) enables the calculation of the cell temperature (T_c) (Appendix 1). With T_c, it is then possible to compute the parameters that are surface temperature dependent. Hence, the model accounts for modules temperature variations (Duffie et al., 1980).

3.4. Main assumptions.

The main assumptions accepted in the optimal dimensioning process are:

– The maximum number of PV panels is limited to 50;

– The maximum reservoir size, WV_{max}, can be defined by the user (in this particular study, it is limited to 48 m^3);
– The SPVWPS is not equipped with a solar-tracking device;
– The SPVWPS is not equipped with batteries;
– The water source replenishment rate is higher than the pumping rate at any time.

4. Main contribution

The criterion that establishes whether or not a particular configuration is a valid solution is the Water Shortage Probability (WSP), which is introduced along with the user-defined water consumption profile. The WSP should be lower than a pre-defined set point (in this particular study the set point is 1% although in practice it would have to be discussed with the community where the system is implemented), which can be varied by the user. A 1% threshold means that there could be a water shortage in the community about 3,5 days yearly. This threshold has to be determined with the community according to their needs and alternatives for water (rain, for instance, or a few days of traditional seek-and-carry). It is set with respect to their financial situation, application (domestic and/or irrigation) and acceptability of a temporary modification of their consumption for a specific period of the year. The WSP could be thought of as an LLP or lost of load probability mostly used in power systems. The WSP denomination is thus a special case of LLP.

This WSP is calculated using Eq. (8).

$$WSP\ \ (\%) = \frac{nH_0}{nH_{total}} \times 100 \tag{8}$$

It is then defined as the ratio of nH_0, the number of hours for which the reservoir could be empty over a defined period to nH_{total} the total hours of the period: this period is conveniently as 365 days or 8,760 h according to the required precision and to validate the selection of a specific design. The WSP is defined as probability as there is no certainty that the reservoir will indeed be empty as the input file for solar radiation is an average over several years for the location. The lower the WSP, the bigger the size of the system and the higher the capital expenditure (CAPEX). This is found to be the critical parameter to be set by the user. And it is one of the key concepts introduced herein to propose an appropriate design to the community it should serve. Indeed, the higher the tolerable WSP, the cheaper the system. One has to understand that a slight modification to the profiles illustrated in Fig. 6 can lead to the major impact on the WSP. This is the reason why provision is made in the model to modify the consumption profile to allow the community to lower the cost of their installation in critical periods on the year.

At the beginning of the calculations, the number of PV panels in parallel is set to one, the initial reservoir size is set to $WV_{min} = \Delta WV$ (in this particular study, it is set to 3 m^3) and the tilt angle β is set to 0°. The software tool calculates the incident radiation on the tilted plane using the isotropic sky model (Kalogirou, 2014). As for the pumps, the software tool has a solar PV-panel database; the one diode five parameters model is used to calculate the electrical energy produced per PV module model from the calculated incident radiation and ambient temperature. A 20% loss is considered, to account for dust and controller related losses (Duffie et al., 1980).

After this, a test is performed to emulate the system behavior for one year. With the available electric power, it is possible to calculate the theoretical pumping rate. Iterative calculations are then carried out for the 24 h of each day. The daily amount of water in the reservoir is defined according to Eq. (9).

$$WV_i = WV_{i-1} + Qp_i - Qc_i; \quad 0 \le WV \le WV_{total} \tag{9}$$

where i represents the actual period of time and Q the consumed, Qc, and pumped, Qp, flow rates in liters per period of time. If the WSP is above the prescribed limit, then the number of PV panels in parallel M_p is increased by one and the process starts over again. The same process occurs for every panel model listed in the database, for each tilt angle value and for each possible reservoir size. The first series of simulations is carried out on a daily basis to sweep the year in 365 steps. Then, the final analysis is calculated on an hourly basis to confirm the results. Fig. 8 schematically depicts this dimensioning process. Before the optimization process begins (Fig. 4) all possible combinations of array, tilt angle and reservoir are saved as potential solutions to fulfill the needs of the community.

4.1. Financial analysis

The financial analysis aims at determining the Net Present Value (NPV) of the project. It is also used to plan the rate at which water should be sold to ensure the viability of the project over its lifespan. Once the software tool has determined every possible technical solution, the cost is first calculated for each one of them; particularly the variable part of the initial investment is determined by the price of the PV panels and the reservoir, including transportation and installation as well as a 5% provision for fittings, cables, pipes and structural elements. Variable costs including maintenance and operations as well as those related to assets replacement are also accounted for.

Since all of these solutions have a WSP below the established threshold, the one solution associated with a minimal variable part of the initial investment is indeed the optimal solution for this particular application. It is also possible to obtain several solutions with the same variable costs; in this case the solution with a minimal WSP value is selected. In order to ensure the project's subsistence, two water pumping service tariffs (in USD/m^3) are proposed: one that assumes that the initial investment is paid by a fixed rate loan and the other that assumes that this investment is entirely paid at the beginning of the project, i.e. there is no initial debt.

4.2. Result files

The software tool produces three files containing the dimensioning process results as follows:

- A text file that compiles the information about the complete SPVWPS proposed solution, the reservoir behavior, the pumping potential as well as the financial analysis results.
- A polar graph showing the WSP distribution during the year. It visually indicates the moments when a water shortage may occur, as shown in Fig. 9. In this example, shortages are most probable in December, month during which the community should manage the water carefully according to the selected WSP, there should not be ANY WSP between mid-January and the end of October;
- A Sankey diagram (starting with the total electricity production by the modules) showing the energy flux per year, including losses across the system (pump-motor, controller) and energy excesses, is show in Fig. 10.

Fig. 10 explicitly shows that less than 10% (387.51 kWh/4249.29 kWh) of the total power produced by the modules is effectively used to fulfill the water needs, the rest are losses to the controller excess pumping and excess power that cannot be used to pump water due to an insufficient voltage to start the pump. The losses to the controller cannot completely be avoided. However, in this example 63% of the total energy produced by the PV modules is lost to the controller and pump. These losses could be minimised by using high-efficiency controllers, well-conceived motor-pump assemblies, as well as by regular pump maintenance. The losses to the pumps are intrinsically linked to the efficiency of the pumping process averaged over a year. The excess produced energy is the amount of energy that cannot be used to pump water due to an insufficient voltage to start the pump. This excess could be

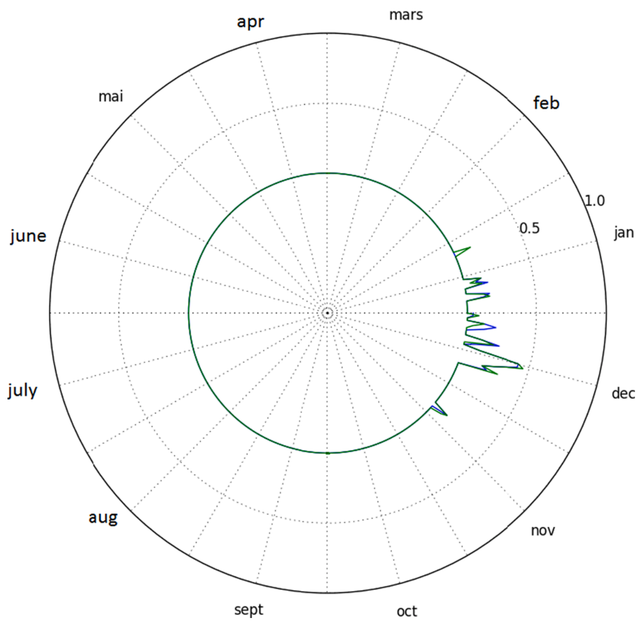

Fig. 9. Water Shortage Probability (WSP).

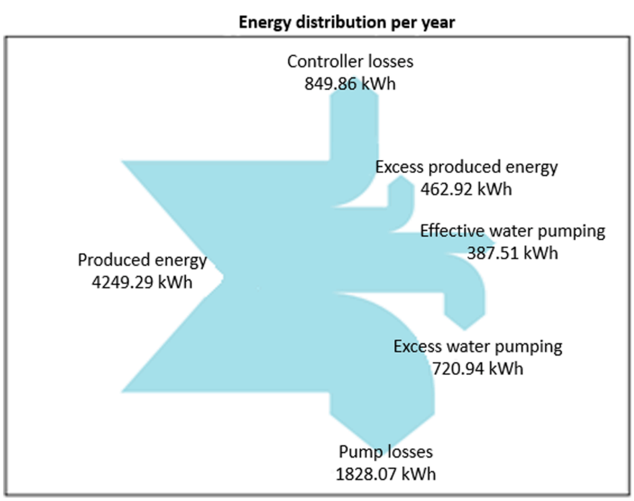

Fig. 10. Sankey Diagram with electric power. Produced by the PV modules as the input (example).

recovered for other use but a storage device would be required. Similarly, the system could pump water in several situations for which the reservoirs are completely filled. When this occurs, the electrical energy could also be stored for other use. Combining both Excess water pumping (720.94 kWh) and Excess produced energy (462.92 kWh), a total amount of 1183.86 kWh could be recovered that is about 28% of the whole production. Applications such as lighting or charging small devices (cell phones or tablets) are well-suited for isolated communities.

5. Results

The proposed methodology and software tool have been tested by means of a comparison of predicted systems against results found in other articles dealing with the dimensioning of SPVWPS. Two specific cases are presented here to highlight the interest of the proposed tool. The capital expenditure won't be compared, as the dates and sites of the proposed cases aren't similar, and materials and installation costs are highly variable with respect to time and location. Nevertheless, financial potential advantages will be discussed.

5.1. Antalya, Turkey

Olcan (Olcan, 2015) based his work on a solar PV pumping installation without batteries located in Turkey. He proposes a multi-criteria optimization to dimension the entire system. The same input data were used in the software tool for comparisons. In Olcan's study, several parameters were not specified. A water consumption profile had to be created (but a constant consumption is supposed to occur between 6:00 and 18:00). The albedo was assumed to be 0.22 corresponding to a typical vegetable farm field and a horizontal distance of 200 m was used. The comparative results for a fixed optimal orientation are listed in Table 1.

Table 1 shows that the required rated power, P_{nom}, of the PV panels is 41% lower with the proposed predictions than those of the original system. The size of the reservoir, WV_{total}, is found to be reduced by more than 50%. These results should ultimately lead to substantial money savings for the same performance. Moreover, in Olcan's article all components are imposed, while the proposed software tool makes it possible to select them from a comprehensive and updatable database. There is also a preponderant difference in the optimal tilt angle, because Olcan calculates it in order to maximize the energy production during the year, while the proposed software tool looks for the best possible match between the load and the available energy. Finally, the water shortage probability (WSP) predicted by the present tool is lower than that presented in the original article. This also means that the reliability of the proposed system is slightly improved.

5.2. Wulanchabu, China

The article published by Campana et al. (Campana et al., 2015) deals with the economic optimization via genetic algotrithm of a SPVWPS used in farmland irrigation in the Wulanchabu desert grassland area, Inner Mongolia, China, which latitude, longitude and altitude of the site are 41.32°N, 111.22°E and 1590 m above the mean sea level. A financial analysis is proposed accounting for the sales revenues generated from the agricultural products. In this particular case, the water consumption is calculated monthly, thus the moment of the day (or even during the week) at which the water is consumed was not previously considered, while the proposed software tool could consider the hourly water consumption over the entire year.

Campana et al. (Campana et al., 2015) do not consider the use of a water reservoir, which can help operate the system during cloudy days. Table 2 presents the results for this comparison. The calculated rated power requirement for the PV system, P_{nom}, predicted with the proposed tool is about half of that presented by the authors. The pump-motor rated power prediction is also reduced by about 50%, meaning that this component was likely to be overrated. Using a 3 m^3 water reservoir (the smallest considered by the software tool) allows for an important reduction regarding the PV modules' and pump rated power, thus reducing the initial investment (components, installation and transportation) of the project.

Table 1
Predictions of the required PV pumping system: A first comparison for Antalya, Turkey.

Results Comparison Component	Original solution [8]	Proposed Software Tool
Pump-motor	PS Lorentz centrifugal PS1200 C-SJ5-8	Sun Pumps submersible SCS 10–210-120Y
PV panel	Astronergy CHSM6610P	KU270-6MCA
P_{nom} PV Panels	5500 W	3 240 W
Tilt angle (°)	33	11
WV_{total}(L)	13,000	6000
WSP	2.650%	0.970%

Table 2
Predictions of the required PV pumping system: A second comparison for Wulanchabu, China.

Results Comparison		
Component	Original Solution [9]	Software Tool
Pump-motor	1.1 kW submersible	559.5 W submersible
PV panel	160 Wp not specified	KU270-6MCA
P_{nom} PV Panels	1080 W	540 W
Tilt angle (°)	10	0
WV_{total} (L)	0	3000
WSP	0.000%	0.000%

5.3. Concluding remarks

One must note that the aforementioned examples where not selected to thoroughly benchmark the proposed tool as this would have been strictly impossible due to the lack of complete and required information in the reviewed papers. In fact, no papers were found to propose enough data and details to achieve a complete validation of the proposed methodology and software tool. The two examples were indeed selected to show that the proposed tool can lead to a substantial decrease in system size and provide a similar or better reliability (lower WSP). In fact, in the two proposed comparisons, it is clear that fewer PV modules and smaller reservoirs may produce the desired performance. In other words, a 40–50% reduction in the PV panel rated power would lead to a somewhat similar capital expenditure reduction, as well as a reduction in the operation and maintenance costs. Similarly, a smaller reservoir is easier to install and to maintain.

6. Discussion

Further analysis of the validation process provides more insights regarding the dimensioning process executed by the software tool. It is acknowledged herein that the optimal solution obtained is a function of the available elements within the databases, particularly of their technical characteristics and their price; nevertheless, some tendencies were observed. Only three issues are discussed in the last section before conclusion

First, the tilt angle for the solar PV panels is often defined in a way that the solar radiation over the surface of the PV panels is maximized, so the annual electric energy production is maximized ($\beta = \varphi$), but the match load vs available resources is neglected. Particularly, in the first comparison (Antalya), it is possible to see that the latitude is close to 36°, but the optimal tilt angle is not 33° (which produces a maximum of yearly electrical output) but finally 11° as shown in Fig. 11. This figure shows that to lower the WSP slightly below 1%, the tilt angle should be comprised between 8° and 14°.

Second, the optimization algorithms dealing with dimensioning are intended to minimize the PV generator size, in other words, to reduce the number of PV panels. This concept neglects the importance of the water reservoir, because it assumes that the PV panels are the most influent factor in the initial investment. As the PV module price continues to fall, this assumption is no longer valid. Fig. 12 shows the variable part of the initial investment (for the first validation, Antalya) vs. the water reservoir size. Although it is clear that a bigger reservoir reduces the number of required PV modules, the initial overall investment increases considerably with reservoir size.

Third, the fact that the PV generator size is minimized does not guarantee that its cost is minimized. For most of the dimensioning methodologies, the PV panels are imposed *a priori*, this aspect is often neglected, but the relationship between panel rated power and price influences the choice process. Fig. 13 shows that for theses cases (Antalya and Wulanchabu), a SPVWPS operating with panel model SW-285 (fourth from the left) presents a minimal rated power (blue line), however panel model KU-270 (first on left) is the cheapest (red line) for this particular application. Moreover, the individual rated power of the panel is also important, as a smaller panel allows the software to better approach the optimal rated power for a particular application.

7. Conclusion

About 10% of the world's population still does not have access to an improved water source. Hence, the goal of this project was to design a free, simple and yet accurate prefeasibility design tool to enable solar photovoltaic water pumping in small remote off-grid communities.

The software enables users with little knowledge about solar photovoltaic water pumping systems to obtain a prefeasibility study of the project, indicating the quantity and model of PV modules to be used, the pumping equipment required, and the size of the tank.

The proposed methodology integrated into the software tool is able to determine the optimal solution for a solar PV water pumping system (SPVWPS). The output data and files provided by the software provide the user with a financial and energy analysis according to a predefined tolerance to water shortage defined herein as the water shortage probability (WSP). The tolerance to and choice of an appropriate WSP is found to influence the project more than any other parameter. A

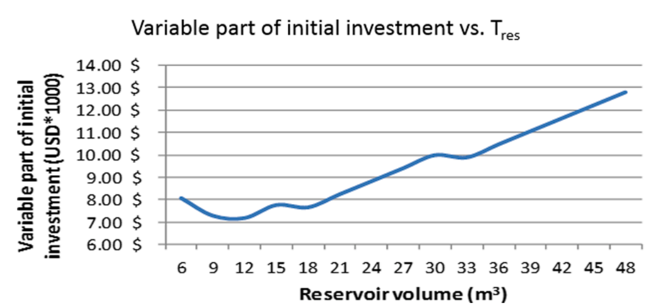

Fig. 12. Variable part of the initial investment (USD) vs. reservoir size (m^3).

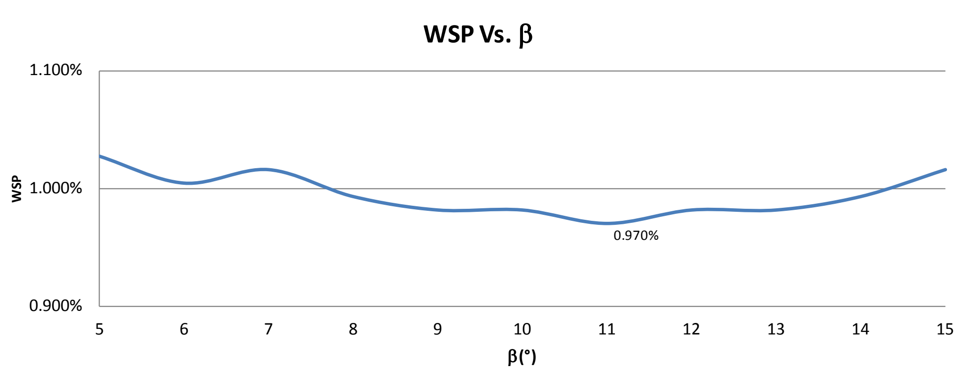

Fig. 11. WSP vs. β for a site located at a latitude close to 36°.

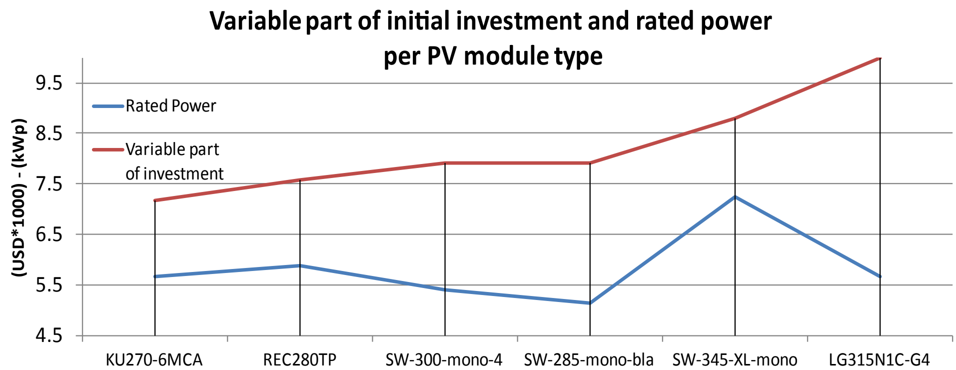

Fig. 13. Variable part of initial investment and rated power for different panel models.

modification of a few percentage points may double the size of the required PV array or that of the reservoir. Hence, the user is able to perform parametric analyses. The hourly consumption profile can be manually edited for critical days – or even hours – of the year in attempts to lower the WSP below a tolerable threshold.

8. Recommendations and future work

At the time of this publication, the interface is only available in French and is currently being tested with a community in Burkina Faso (called Laongo-Yanga) located about 30 km from Ouagadougou. This community participated in meetings to establish their need and understand what the pumping system does and why they might run out of water or pay too much for the system that would be oversized, thus establishing their tolerance for water scarcity (WSP).

Several improvements are considered, as possible extensions of this work and some are already under investigation in the work of another researcher of the group which employs already existing packages for photovoltaic and fluid mechanics modeling, namely “pvlib-python” and “fluids”:.

- Further study of demand variability, this is a preponderant goal to match the WSP with the community budget;
- Addition of a non-potable water reservoir for irrigation applications with a spillway;
- Investigation of adjoining supercapacitors to assist the starting pump therefore to reduce the wasted energy;
- Study of the variability of the water level in the water table;
- Addition of precipitations to the main reservoir on cloudy days;
- Different models for OPEX;
- Quotes for the actual costs of the components;
- Standardization of components, in particular the tank which is likely to become that most expensive item as there is no battery in the standard system;
- “Lego” design of structural elements to lower production costs;
- Voltage maximization to reduce wiring losses;
- Addition of permanent magnet pumps;
- Addition of AC pumps;
- Adding a battery in larger facilities to store and smoothen the current fluctuations;
- Simulations with commercial software for comparisons (PV syst, for instance);
- Coupling/validation with the two small benches now under construction (despite COVID) in our lab.
- Coupling/validation with a full-size pumping station currently under design for Burkina Faso.
- Enabling manual solar tracking to improve load-available resource match;
- Enabling the user to change more parameters, such as the number of valves and accessories considered to calculate the frictional losses.

It is expected that the current drastic fall in PV prices will make the reservoir the critical component of the systems in the near future.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix 1. Global mathematical model.

For PV module modeling, a classic one diode, 5 parameters model (Duffie et al., 1980) is used, because it considers the efficiency variation caused by the cells temperature and it is highly reliable while modeling several PV modules models. Eq. (10) general equation, (11) short circuit equation, (12) open circuit equation, (13) maximum power equation and (14) maximum power derivative, are the PV module’s governing equations and are used to calculate the output power.

$$I = I_L - I_0\left[e^{\left(\frac{V+IR_s}{a}\right)} - 1\right] - \frac{V+IR_s}{R_{sh}} \tag{10}$$

$$I_{sc} = I_L - I_0\left[e^{\left(\frac{I_{sc}R_s}{a}\right)} - 1\right] - \frac{I_{sc}R_s}{R_{sh}} \tag{11}$$

$$0 = I_L - I_0\left[e^{\left(\frac{V_{oc}}{a}\right)} - 1\right] - \frac{V_{oc}}{R_{sh}} \tag{12}$$

$$I_{mp} = I_L - I_0\left[e^{\left(\frac{V_{mp}+I_{mp}R_s}{a}\right)} - 1\right] - \frac{V_{mp}+I_{mp}R_s}{R_{sh}} \tag{13}$$

$$\frac{I_{mp}}{V_{mp}} = \frac{\frac{I_0}{a}e^{\left(\frac{V_{mp}+I_{mp}R_s}{a}\right)} + \frac{1}{R_{sh}}}{1 + \frac{I_oR_s}{a}e^{\left(\frac{V_{mp}+I_{mp}R_s}{a}\right)} + \frac{R_s}{R_{sh}}} \tag{14}$$

To account for temperature variation (Duffie et al., 1980) on the efficiency, the following set of standard equations (15)–(17) is used:

$$\mu_{Voc} = \frac{V_{oc}(T) - V_{oc}(T_{ref})}{T - T_{ref}} \tag{15}$$

$$\frac{a}{a_{ref}} = \frac{T}{T_{ref}} \tag{16}$$

$$I_o(T) = I_o(T_{ref})\left(\frac{T}{T_{ref}}\right)^3 e^{\left(\frac{Eg_{ref}}{kT_{ref}}\left(1-\left(1-C(T-T_{ref})\frac{T_{ref}}{T}\right)\right)\right)} \tag{17}$$

Which influence the former five equations.

Here E_g is the gap energy (1.794 e-19 J for silicium), k is the Boltzmann constant (1.381 e-23) and C is set to 0.0002677 for silicium. Initial values for the system of equations are:

- $R_{sh} = 100\ \Omega$;
- $I_L = I_{sc}$;
- $a = \frac{1.5kT_{ref}Nc}{q}$; where $Nc = \#$ of modules in series and $q = 1.602*10^{-19}J/V$;
- I_o is obtained by (12);
- R_s can be estimated with (10) by using the initial values and dismissing the value of R_{sh}.

The method is based on the isotropic model (Kalogirou, 2014) to calculate the incident energy on surfaces. Hourly values are stored in a linear vector involving 8760 positions. Eqs. (18)–(21) and the calculation procedure are:

$$\delta = 23.45\sin\left(360\frac{284+n}{365}\right) \tag{18}$$

$$\omega_{l-c} = \cos^{-1}(-\tan\varphi\tan\delta) \tag{19}$$

$$\theta = \cos^{-1}(\sin\delta\sin\varphi\cos\beta - \sin\delta\cos\varphi\sin\beta\cos\gamma + \cos\delta\cos\varphi\cos\beta\cos\omega + \cos\delta\sin\varphi\sin\beta\cos\omega\cos\gamma + \cos\delta\sin\gamma\sin\beta\sin\omega) \tag{20}$$

$$\theta_z = \cos^{-1}(\cos\varphi\cos\delta\cos\omega + \sin\varphi\sin\delta) \tag{21}$$

The calculation of coefficient R_b which accounts for direct radiation depends on ω with respect to $\omega_{l\text{-}c}$. Since ω is an hourly angle, it can be converted into hours and minutes. $\omega.h$ is the integer value in hours that corresponds to this angle.

- If $\omega.h = -\omega_{l\text{-}c}$, two values are defined $\omega_1 = -\omega_{l\text{-}c}$ and $\omega_2 = \omega_1.h + 1$.
- If $\omega.h = \omega_{l\text{-}c}$, two values are defined $\omega_1 = \omega_{l\text{-}c}$ and $\omega_2 = \omega_1.h$.

For both cases, the value of R_b is given by Eqs. (22) and (23):

$$R_b = \frac{\begin{array}{c}(\sin\delta\sin\varphi\cos\beta - \sin\delta\cos\varphi\sin\beta\cos\gamma)(\omega_2 - \omega_1) + \\ (\cos\delta\cos\varphi\cos\beta + \cos\delta\sin\varphi\sin\beta\cos\gamma(\sin\omega_2 - \sin\omega_1) \\ -\cos\delta\sin\gamma\sin\beta(\cos\omega_2 - \cos\omega_1))\end{array}}{\cos\varphi\cos\delta(\sin\omega_2 - \sin\omega_1) + \sin\varphi\sin\delta(\omega_2 - \omega_1)} \tag{22}$$

While for other cases:

$$R_b = \frac{\cos\theta}{\cos\theta_z} \tag{23}$$

Finally, the isotropic model is defined by Eq. (24) and yields:

$$I_T = I_b R_b + I_d\left(\frac{1+\cos\beta}{2}\right) + I\rho\left(\frac{1-\cos\beta}{2}\right) \tag{24}$$

It is then possible to use the parameters of the PV modules to calculate the maximum output power available for each type of PV module in the database. The number of PV modules to be used in series is defined before starting any power calculations, which involves dividing the nominal voltage of the selected pump by the nominal voltage of the PV modules (V_{mp}). The process of calculating output power is iterative and based on the model with a single diode.

An estimate of a module's efficiency for a given surrounding temperature and incident radiation (I_T) enables the calculation of T_c (Eq. (25)). With T_c, it is then possible to compute the parameters that are surface temperature dependent (Duffie et al., 1980). The *Nominal Operating Cell Temperature* (NOCT)[2] values are used to compute T_c.

$$T_c = T_{amb} + (T_{noct} - T_{\infty noct})\left(1 - \frac{eff}{0.9}\right)\left(\frac{I_T}{G_{noct}}\right) \tag{25}$$

$$E_{g2} = E_g\left[1 - C\left(T_c - T_{ref}\right)\right] \tag{26}$$

$$R_{sh} = R_{sh}\left(\frac{1000}{I_T}\right) \tag{27}$$

$$I_L = \frac{I_T}{1000}\left[I_L + \mu I\left(T_c - T_{ref}\right)\right] \tag{28}$$

The values of I_L and V_{mp} are used as guess values to initialize the solution process that will determine the voltage and current values for the maximum power, by calculating the values with Eqs. (25)–(28).

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