Enhancement of a photovoltaic drinking water pumping system design software tool

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Abstract

Easy access to safe, drinkable water is an essential requirement for societal growth and betterment. With the human population increasing and current climate changes, this key resource is becoming increasingly difficult to access in many locations across the globe, especially in areas without an electrical power grid. Solar-powered pumps are a good tool to help address this problem in many cases; however, taking into account all the parameters (water consumption, total dynamic head, local irradiance, etc.) to reach the cheapest design that satisfies requirements can be challenging. *pvpumpingsystem* is an open-source tool to assist in the design process and the determination of the model, number, and arrangement of photovoltaic panels, pump model, and reservoir capacity. This tool was recently enhanced to accommodate more detailed water consumption profiles and more realistic MPPT (Maximum Power Point Tracking) behaviour; the impacts of these new features on simulation results are the focus of the study described herein. The new consumption profiles have a significant impact (up to +/- 40% change to the load loss probability). The simulations also showed that using an MPPT with the perturb & observe algorithm, widely available in commercial devices, increases water output by as much as 6.7%. However, the detailed MPPT model did not affect results significantly compared to a generic 94% MPPT efficiency coefficient.

Keywords: software enhancement, photovoltaic, MPPT, pumping, drinking water.

1. Introduction

Easy access to clean water, safe for human consumption and basic sanitation needs, is an essential requirement for human comfort, growth, and betterment. WHO data for 2021 indicates that 771 million people don't have access to safe water sources within a 15-minute walking radius (WHO, 2021), and with the human population growing and current climate changes, this key resource is becoming increasingly scarce and difficult to access in many locations across the globe (Urama and Ozor, 2010), compounding health issues tied to contaminated water consumption (IHME, 2019) and an increased workload, often on women and girls (Boone et al., 2011). Pumping water from aquifers is, in many cases, a good solution to help address this problem; however, manual pumping seldom provides sufficient quantities and limits the depth at which water can be retrieved (Ghoneim, 2006). The common solution is to use pumps powered by fossil fuel engines (Quansah et al., 2016), but the recurrent and increasing costs of fuel, dependency on a steady fuel supply, and environmental impacts render this approach less than ideal. Electric pumps powered by photovoltaic solar panels address all those issues, and since pumped water can be stored in simple reservoirs, the intermittent nature of that form of renewable energy is easily addressed. Many studies demonstrate that, despite higher upfront costs, a solar-powered solution is significantly less expensive in the long term in many locations (Xie et al., 2021). A basic diagram of such a system is illustrated in Fig. 1.

However, designing such a system so that it adequately addresses the needs of the target community while taking into account all the parameters (total dynamic head, local irradiance, etc.) and keeping it as affordable as possible is not a simple problem. To help with this task, a bespoke software tool was developed to iterate through various solutions and assist in the selection of the best-suited option: *pvpumpingsystem* is an open-source and (to the best of our knowledge) unique software package written in the Python language by Tanguy Lunel and Sergio Gualteros (Gualteros and Rousse, 2021). Its initial version offered limited options for water consumption profiles and made use of a highly simplified maximum power point tracking system (MPPT)

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implementation; the objectives of this project are to add support for detailed water consumption profiles and for an accurate MPPT model, and then study the impact of those changes on the results obtained.

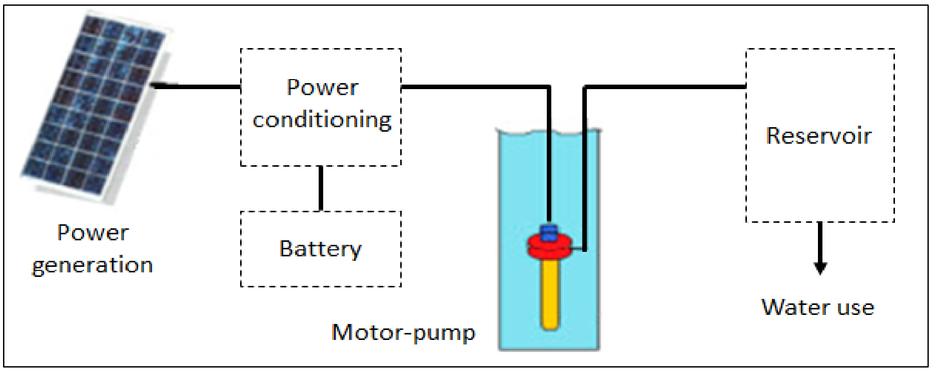

Fig. 1: Basic diagram of a photovoltaic pumping system (Lunel, 2020)

2. Methodology and implementation

In most articles studied in the literature, a community's basic water needs vary greatly according to the time of year (+/- 10% to 30% of the average daily demand for the year) (Andey and Kelkar, 2009). This is mostly due to seasonal changes (dry vs. rainy season, warm vs. cooler season), which impact both the availability of surface water and the daily quantity required. Therefore, a water consumption model that relies on a constant daily value throughout the year is missing a key factor. To address this, two consumption models were added: the first allows the selection of a community's daily water requirements for each month of a year, and the second allows the selection of a community's daily water requirements for each day of a year. Combined with *pvpumpingsystem*'s already-existing feature which allows the selection of hourly water requirements for each hour of a day, this provides a flexible way of inputting the target community's water consumption, leading to a more realistic simulation. This was directly implemented in the software package through an expansion of the existing functions.

Three water consumption profiles were used in simulations for comparison:

- Scenario 1: constant 120 $L.h^{-1}$ (2880 $L.d^{-1}$) water consumption throughout the year, suitable for a population of about 25 to 100 people (Gleick, 1996) (WHO, 2003) (Singh and Turkiya, 2013). This is the reference/control scenario.
- Scenario 2: constant daily water consumption of 2880 $L.d^{-1}$ throughout the year with a variable hourly consumption (nil during nighttime, peaks around 8h00, 12h00, and 18h00), as illustrated in Fig. 2. This is the first new scenario, making use of the new features in *pvpumpingsystem*, reflecting variations throughout the day but neglecting seasonal factors.
- Scenario 3: constant daily water consumption for each month (higher from April to July, lower from October to February), illustrated in Fig. 3, with a variable hourly consumption (nil during nighttime, peaks around 8h00, 12h00, and 18h00), illustrated in Fig. 4. This is the second new scenario, making use of the new features in *pvpumpingsystem*, reflecting variations throughout the day and possible seasonal factors, and the one closest to what a real-world consumption profile could be.

All three scenarios amount to the same water consumption for the whole year, namely 1,051,200 litres.

Those scenarios were combined with PVGIS meteorological data for the year 2005 for five locations: near Tunis (Tunisia, 36°N 10°E), Aswan (Egypt, 24°N 33°E), Nairobi (Kenya, 1°S 36°E), Lima (Peru, 12°S 77°W), and Madrid (Spain, 40°N 3°W). It should be noted that the monthly water consumption profiles used in all scenarios are generic examples and do not reflect actual local needs. Identical system configurations were used for all locations, namely:

- 5 Canadian Solar CS5C 80M solar panels in a serial arrangement;
- Simulated basic MPPT with 96% efficiency;
- Sun Pumps SCB-10-150-120 BL (Kou modelisation) (Kou et al., 1998) pump/motor assembly;
- Plastic piping (100m length, 0.05m diameter);

- 20m total dynamic head.

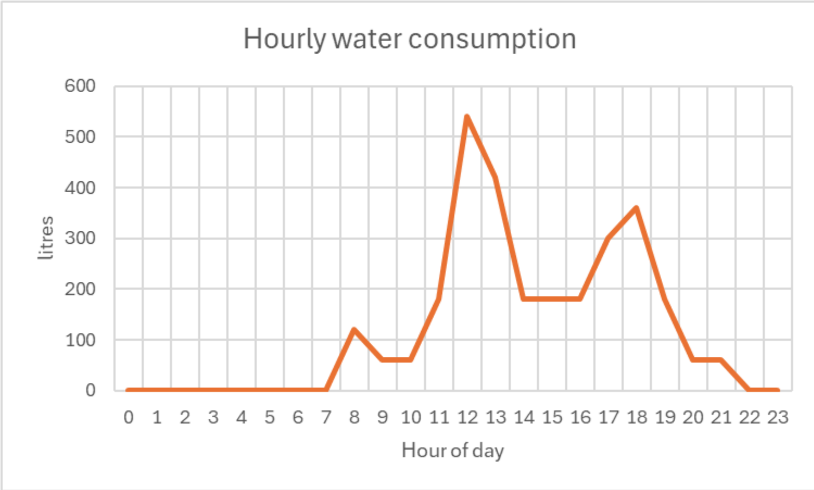

Fig. 2: Hourly water consumption for each hour of the day for Scenario 2

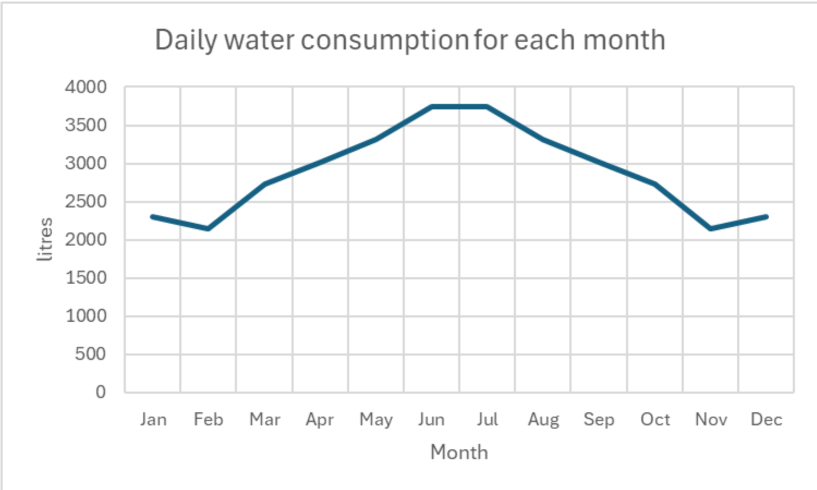

Fig. 3: Daily water consumption for each month of the year for Scenario 3

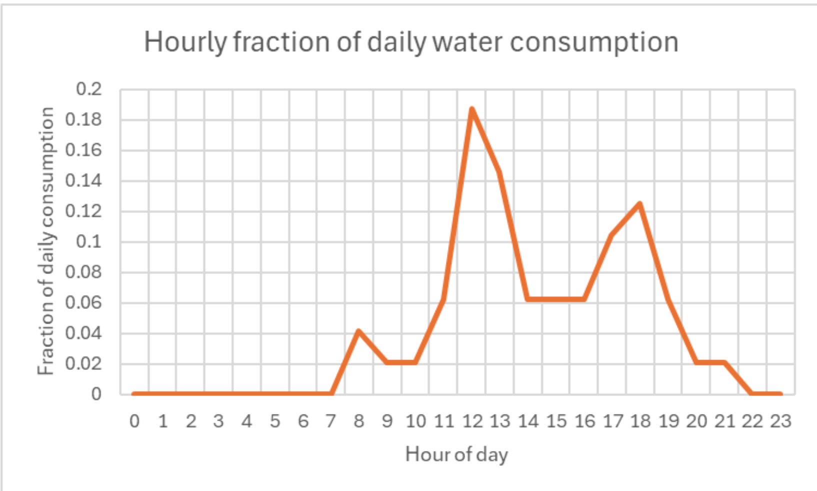

Fig. 4: Fraction of the daily water consumption for each hour of the day for Scenario 3

Solar panel azimuth was due south for the northern hemisphere and due north for the southern hemisphere; tilt was equivalent to the local latitude, although the best slope is usually slightly higher for most latitudes (Memme and Fossa, 2022).

MPPT systems are often combined with solar panels to maximize their power output (Elgendy et al., 2008), therefore increasing the quantity of water pumped (Oi et al., 2009) (Allouhi et al., 2019). This is achieved by dynamically adjusting the load presented to a panel's electrical outputs so that it produces the maximum power available under the current operating conditions. This specific optimal load is susceptible to change based on environmental conditions like solar irradiance (intensity and distribution on the panels) and panel temperature (Podder et al., 2019). Therefore, most MPPTs dynamically seek the maximum power point (MPP) through various algorithms (Subudhi and Pradhan, 2012). The most popular of these in commercial implementations are perturb & observe (P&O) and incremental conductance (IC) (Podder et al., 2019), because of their simplicity and acceptable performance under most conditions.

The basic MPPT model in *pvpumpingsystem* was implemented by taking the maximum theoretical available power supplied by the solar panels under current irradiance and temperature conditions and applying an efficiency factor (usually between 94% and 96%) to determine the power available at the motor. To achieve a more faithful simulation, the following elements were added:

- A control circuit using a basic perturb-and-observe (P&O) algorithm (Elgendy et al., 2011), with a customizable duty cycle step size (default value 0.01) and execution frequency (default value 100Hz); and
- A detailed buck-boost DC-DC conversion circuit (Amri and Ashari, 2015) model operating at a 1kHz switching frequency, using linear extrapolation of the various components sampled at 100kHz.

The P&O algorithm modifies the duty cycle of the buck-boost circuit by a step value at each iteration and compares the current power output of the solar panels to the power output of the previous iteration. If the power output increased, it is assumed that the change brought the solar panels closer to their MPP, and the same step change is applied to the duty cycle at the next iteration. If the power output decreased, it is assumed that the change brought the solar panels further from their MPP, and the sign of the step change is flipped (multiplied by -1) before applying it to the duty cycle at the next iteration. The algorithm's flowchart is illustrated in Fig. 5.

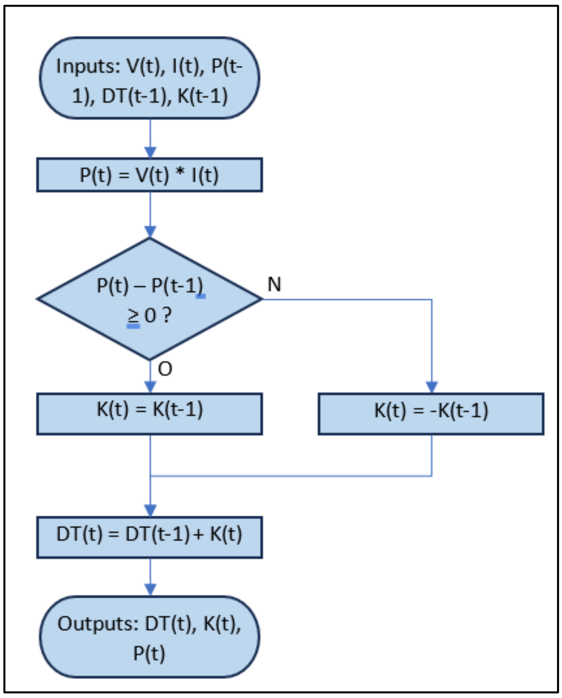

Fig. 5: The Perturb & Observe MPPT algorithm

In this flowchart, V is the voltage at the solar panels' output, I is the current at the solar panels' output, DT is the duty cycle of the buck-boost conversion circuit, K is the step change of the duty cycle, t is the algorithm's current execution cycle, and t-1 is the algorithm's previous execution cycle.

The main advantages of the P&O algorithm are its simplicity and speed of execution (Ahmad et al., 2019). However, since it is always "chasing" the MPP, it tends to induce harmonics in the power supply that can be detrimental to the load's behaviour (Elgendy et al., 2009). Furthermore, it is vulnerable to "false MPPs", i.e. a local maximum that is not the true maximum of the power curve (Tsang and Chan, 2015). Nevertheless, because of the simplicity of the setup and in the context of this study, it was deemed an adequate choice, especially since it is widely used in commercial products.

The buck-boost conversion circuit, illustrated in Fig. 6, was modeled through nodal and loop analysis of its components in both its operational states (closed transistor and open transistor, as illustrated in Fig. 7), which lead to the following equations:

Closed transistor:

$$I_L(t) = I_L(0) + \frac{dI_L}{dt} * \Delta t \quad \text{(eq. 1)}$$

$$V_C(t) = V_C(0) + \frac{dV_C}{dt} * \Delta t \quad \text{(eq. 2)}$$

$$V_R(t) = \frac{V_C(t)}{R_C + R} + V_C(t) \quad \text{(eq. 3)}$$

Open transistor:

$$I_L(t) = I_L(0) + \frac{dI_L}{dt} * \Delta t \quad \text{(eq. 4)}$$

$$V_C(t) = V_C(0) + \frac{dV_C}{dt} * \Delta t \quad \text{(eq. 5)}$$

$$V_R(t) = V_C(t) + \left(R_C * C * \frac{dV_C}{dt}\right) \quad \text{(eq. 6)}$$

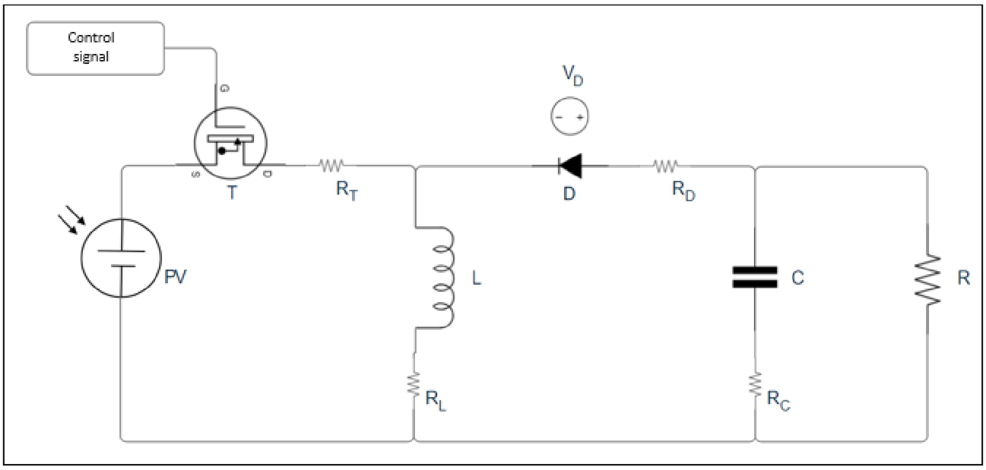

Fig. 6: The buck-boost circuit diagram

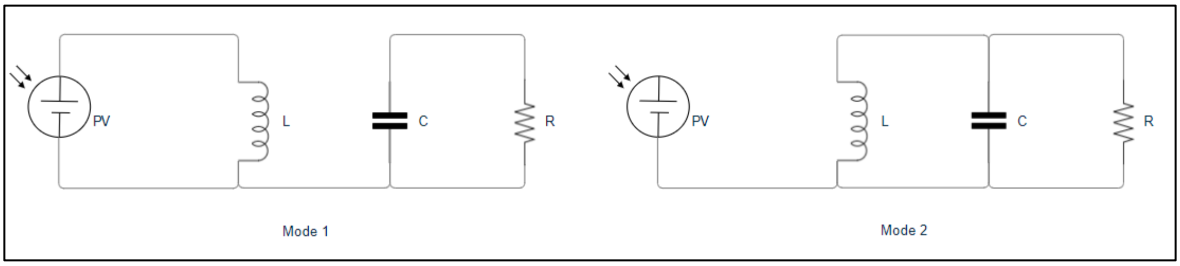

Fig. 7: The buck-boost circuit diagram in closed transistor mode (1) and open transistor mode (2)

The behaviour of the simulated buck-boost circuit was successfully compared to the results of an identical simulation in MATLAB/SIMULINK to verify its accuracy.

This detailed MPPT model was added to *pvpumpingsystem* through an expansion of the existing MPPT module. To determine its impacts, three scenarios were combined with PVGIS meteorological data for the year

2005 for the five locations previously selected (Tunis, Aswan, Nairobi, Lima and Madrid):

- Scenario 4: no MPPT.
- Scenario 5: simplified basic MPPT with a 96% efficiency.
- Scenario 6: detailed MPPT with P&O algorithm and simulated buck-boost circuit, making use of the new features added to *pvpumpingsystem*.

3. Results and discussion

Tab. 1 presents the Load Losses Probability (LLP, here equivalent to the Water Shortage Probability, i.e., the fraction of the year during which a water shortage is experienced) for each scenario for the five locations:

Tab. 1: Load Losses Probability/Water Shortage Probability, for three different types of water consumption profiles.

Location	Scenario 1 (Constant consumption)	Scenario 2 (Constant monthly, variable hourly)	Scenario 3 (Variable monthly, variable hourly)
Tunis	0.0958	0.0578	0.0397
Aswan	0.0031	0.0010	0.0001
Nairobi	0.0816	0.0473	0.0611
Lima	0.2523	0.2067	0.2326
Madrid	0.1280	0.0930	0.0729

The use of hourly consumption profiles significantly impacts the LLP, lowering it by 20% to 66%. This is because the daily profile used heavily skews the water consumption towards daytime, when the solar resource is available to power the pump. The addition of monthly consumption profiles, which skews the water consumption towards the April to July period, has a significant impact as well, but this impact can be positive (lower LLP) or negative (higher LLP). This negative impact is explained by a combination of geographical mismatch (in the southern hemisphere, the solar resource is lower in the April-July period, while the consumption profile used demands more water during those months) and local meteorological characteristics. However, since the monthly consumption profile used is generic and does not reflect actual local data, these values are purely illustrative of the possible impact of the use of such scenarios and do not indicate real-world performance.

For the MPPT simulation, Tab. 2 presents the total water pumped for the year (in litres) for each scenario for the five locations:

Tab. 2: Total yearly water production, [litre], for the cases of no MPPT, a basic MPPT and a detailed MMPT.

Location	Scenario 4 (No MPPT), [litre]	Scenario 5 (Basic MPPT), [litre]	Scenario 6 (Detailed MPPT), [litre]
Tunis	2,488,034	2,645,250	351,514
Aswan	3,384,703	3,611,701	611,402
Nairobi	2,708,110	2,869,420	463,955
Lima	1,969,246	2,088,440	304,650
Madrid	2,560,211	2,736,773	424,482

As expected, using the basic MPPT model increases significantly the volume of water pumped in a year, since more power is extracted from the solar resource. However, the detailed MPPT model led to dramatically reduced values; this is explained by a flaw in the initial design. Buck-boost converters leave the power source in an open circuit during their complementary duty cycle period (open transistor), which leads to a very significant loss in average available power and total energy available to the pump’s motor when solar panels are used, and therefore in total pumped water.

Furthermore, it was observed that the execution time of the various simulations differed greatly according to the scenario; running on a standard Intel Core i5-8365U processor with 16 GB RAM, the Scenario 4 simulations took on average 10 seconds, the Scenario 5 took on average 2 seconds, and the Scenario 6 more than 2 hours, after code optimisations. This is explained by the very high number of iterations required by the conversion circuit simulation (1,000,000 iterations per simulated second) to produce accurate results.

4. Conclusions

As stated in the introduction, the objectives of this project were to add support for detailed water consumption profiles and for an accurate MPPT model, and then study the impact of those changes on the results obtained from the *pvpumpingsystem* software. The results clearly indicate that the use of more detailed water consumption profiles has significant impacts on the results provided by *pvpumpingsystem*. Of course, this means that data needs to be collected for the targeted community, ideally at least over a year; the more precise the data, the more accurate the results. It should also be taken into account that increased accessibility to water usually leads to an increase in consumption.

As for the detailed MPPT model, the flaw in the original design renders it unusable as is for *pvpumpingsystem* simulations. Nevertheless, further simulations and extrapolations have indicated that for simple solar panel configurations and normal operational conditions, the basic MPPT model with a 94% efficiency provides power outputs that match detailed simulations sufficiently well to supply reliable results. Since execution time is much shorter compared to the detailed MPPT model, it makes the basic MPPT model a better option for simulations. A different power conversion circuit topology (Ćuk, for example) could be simulated to verify this extrapolation, and could be the subject of a subsequent project.

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