Sensitivity Analysis of Photovoltaic Pumping Systems for Domestic Water Supply

Simon Meunier, Loic Queval, Arouna Darga, Philippe Dessante, Claude Marchand, Matthias Heinrich, Judith Cherni, Elvire de La Fresnaye, Vido Lionel, Bernard Multon, et al.

Sensitivity Analysis of Photovoltaic Pumping Systems for Domestic Water Supply

Simon Meunier, *Member, IEEE*, Loïc Quéval, Arouna Darga, Philippe Dessante, Claude Marchand, Matthias Heinrich, Judith A. Cherni, Elvire A. de la Fresnaye, Lionel Vido, Bernard Multon, *Member, IEEE*, Peter K. Kitanidis

***Abstract* — A sensitivity analysis is carried out on the parameters of a photovoltaic water pumping system (PVWPS) for domestic water supply in rural areas. The results show that the photovoltaic modules peak power, the motor-pump efficiency and the water tank volume strongly influence the system performance. This highlights that these parameters constitute judicious optimization variables. Besides, the cost of the motor-pump, the cost of the water tank and the lifetime of the PVWPS have the largest impact on the system cost. These 6 parameters are therefore of primary importance for the techno-economic optimal sizing of the system. Finally, it is shown that the hydraulic losses play a minor role and that it is not necessary to consider the evolution of the ambient temperature when modelling PVWPS for domestic water supply. This study can be useful to non-governmental organizations, companies and governments which install PVWPS for domestic water access. It can help them to determine the accuracy at which a given parameter has to be known to correctly model or size these systems. Besides, it can allow them to evaluate the robustness of PVWPS sizing to parameters variation with time and may guide their choice of components.**

***Index Terms* — Photovoltaic water pumping system, Seasonality, Sensitivity analysis, Lifecycle cost, Techno-economic optimization.**

This work was supported by a public grant overseen by the French National research Agency (ANR) as part of the "Investissement d'Avenir" program, through the "IDI 2015" project funded by the IDEX Paris-Saclay, ANR-11-IDEX0003-02. (*Corresponding author: Simon Meunier.*)

S. Meunier, L. Quéval, A. Darga, P. Dessante, and C. Marchand are with Université Paris-Saclay, CentraleSupélec, CNRS, GeePs, 91192, Gif-sur-Yvette, France and Sorbonne Université, CNRS, GeePs, 75252, Paris, France (email: simon.meunier@centralesupelec.fr, loic.queval@centralesupelec.fr, arouna.darga@centralesupelec.fr, philippe.dessante@centralesupelec.fr, claude.marchand@centralesupelec.fr).

M. Heinrich is with DargaTech SARL, Ouagadougou, 12BP407, Burkina Faso (e-mail: matthias.heinrich@ens-rennes.fr).

J. A. Cherni, and E. A. de la Fresnaye are with the Centre for Environmental Policy, Imperial College London, London, SW7 2AZ, UK (e-mail: j.cherni@imperial.ac.uk, elviredelafresnaye@gmail.com).

L. Vido is with the SATIE, Univ. of Cergy-Pontoise, Cergy-Pontoise, 95000, France (e-mail: lionel.vido@u-cergy.fr).

B. Multon is with the SATIE, ENS Rennes, Univ. of Rennes, CNRS, Bruz, 35170, France (e-mail: bernard.multon@ens-rennes.fr).

P. K. Kitanidis is with the Department of Civil and Environmental Engineering, Stanford Univ., Stanford, CA 94305, USA (e-mail: peterk@stanford.edu).

I. Introduction

PHOTOVOLTAIC water pumping systems (PVWPS) are an interesting solution for improving water access in rural areas [1], [2]. They are reliable [3], economically competitive in remote locations [4], have low maintenance needs [5] and do not emit greenhouse gases during operation [6].

In the past, several technical and economic models of PVWPS have been developed and some of them were used to perform sensitivity analyses.

The technical parameters considered are related to the following components of PVWPS: the photovoltaic (PV) modules, the motor-pump, the borehole and the water tank. The PV modules peak power was encountered to be the main driver of the water pumped volume in [7]. Differently, it was found to not significantly influence the PVWPS profitability in [8]. The motor-pump influence was investigated through the conversion efficiency. Study [9] reported that increasing the efficiency of the PVWPS (which includes the one of the PV modules and of the motor-pump) by 50% would allow to decrease the water cost by 15%. The borehole part was studied through the pumping head. Study [10] highlighted that the pumping head has a strong influence on the pumped volume. Reference [11] balanced the results of [10] by underlining that the influence of the pumping head on the pumped volume depends on the PV array configuration and on the chosen motor-pump. Reference [12] separated the pumping head into two components, namely the static water level and the drawdown. It was found that the static water level has a larger influence on the PVWPS operation than the drawdown. Finally, studies [13] and [14] found that the ratio between the tank volume and the water demand has a small influence on the water cost.

Regarding economic parameters, both investment and operating costs have been considered. In [15], the investment cost was found to have a stronger influence on the PVWPS profitability than the operating cost. Similarly, the influence of the investment cost was found to be three times higher than the one of the operating cost in [10]. Within the investment costs, the PV modules cost and the water tank cost were investigated. In [16], increasing the PV modules cost by 50% increases the overall PVWPS cost by 40%. Differently, in [17], increasing the PV modules cost by 50% increases the water cost by 12%. Study [17] also investigated the influence of the tank cost and encountered that increasing the tank cost by 50% increases the water cost by 5 to 8%. Within the operational costs, the influence of various economic rates and of the PVWPS lifetime

Postprint accepted in *IEEE Transactions on Industry Applications*. Acceptance date: 12 July 2020

was investigated. In [9], a 50% increase in the inflation rate increases the water cost by 4%. In [18], increasing the interest rate by 65% decreases the system's cost by 8%. In [19], increasing the discount rate by 50% decreases the water cost by less than 5%. Finally, in [9], increasing the PVWPS lifetime by 50% decreases the water cost by 30%. It is interesting to observe that, even though some studies considered the same technical or economic parameter, the results regarding the influence of the considered parameter were sometimes contradictory. This is probably due to the difference in PVWPS architecture, sizing and geographical location between these studies.

This literature review reveals that the influence of several technical and economic parameters, such as the thermal parameters of the PV modules, the pressure losses in the pipes and the motor-pump cost, has not been investigated in previous studies. This omission prevents from determining the accuracy at which these parameters have to be estimated when modelling and sizing PVWPS. Furthermore, it prevents from knowing the robustness of PVWPS sizing to technical parameters variation with components ageing (e.g. decrease of PV modules performance with time) and evolution of the local environment (e.g. groundwater resources). It also does not permit to predict future performances and cost of PVWPS as technology improves.

Additionally, technical models which were used in sensitivity analyses do not take the water collection time series as an input. This prevents from modelling PVWPS which include a water tank and a controller that stops and restarts the motor-pump depending on the water level in the tank (see Fig. 1) [20]. No sensitivity analyses have thus been performed for PVWPS with this architecture, which is nonetheless commonly used for domestic water supply.

Finally, to the best knowledge of the authors, the influence of seasonality on sensitivity analyses results was not evaluated in previous studies, although the operation of PVWPS changes with seasonality [20], [21].

In this article, we evaluate the influence of the technical and economic parameters on the output of the technical and economic models of PVWPS for domestic water supply as well as on the results of the techno-economic optimal sizing of these systems [21].

The first originality of this article is that we consider 10 parameters (9 technical and 1 economic) that were not studied previously. The second originality is that we present a sensitivity analysis on a technical PVWPS model which takes water collection as an input. The third originality is that the sensitivity analysis is performed for both the dry season and the wet season, thus improving the robustness of the article's conclusions.

The technical and economic models and parameters are presented in section II. The methodology used for the sensitivity analysis is detailed in section III. The effect of the parameters variation on the output of technical and economic models is described in section IV. The optimal sizing methodology and the influence of parameters variation on the optimization results are presented in section V. In section VI, we focus on the influence of the ambient temperature on PVWPS performance and optimization results, highlighting possible simplifications of the technical model.

II. Photovoltaic Water Pumping System Models

A. System overview

Fig. 1 present the considered PVWPS architecture and the characteristic heights. Water is pumped from the borehole into the tank by the motor-pump powered by the PV modules. Water is collected at the fountain by the dwellers. The controller stops and restarts the motor-pump according to the water level in the tank, which is obtained by a float switch. The motor-pump set contains a maximum point tracking (MPPT) controlled inverter.

B. Technical model

The technical model of the PVWPS has been fully detailed in [20]. Fig. 2 shows its block diagram. The model inputs are the irradiance on the plane of the PV modules G_{pv}, the ambient temperature T_a and the water collected flow rate at the fountain Q_c. The model output is the water level in the tank H_{tk}.

For the sake of completeness, we remind here the various equations of the sub-models. The input power to the motor-pump P_{pv} at time t is given by:

$$P_{pv}(t) = \frac{G_{pv}(t)}{1000} P_{pv,p} \left(\beta \left(T_a(t) + \frac{NOCT - 20}{800} G_{pv}(t) - 25 \right) + 1 \right) b(t) \quad (1)$$

where $P_{pv,p}$ is the peak power of the PV modules in standard test conditions (STC), β is the coefficient of loss due to PV modules temperature, $NOCT$ is the nominal operating cell temperature. b is the controller trigger signal which is governed by an hysteresis function: it switches from 1 to 0 (the motor-pump stops) when the water level in the tank H_{tk} reaches the stop controller level and from 0 to 1 (the motor-pump restarts) when H_{tk} drops down to the restart controller level. The pump flow rate Q_p is given by:

$$Q_p(t) = \max\left(0, P_a\left(P_{pv}(t), TDH(t)\right)\right) \quad (2)$$

where TDH is the total dynamic head. The polynomial P_a fits the points of the characteristic of the considered motor-pump reference MP. The coefficients of P_a are denoted $k_{m,n}$. TDH is given by:

$$TDH(t) = -H_b(t) + H_{tk,b} + H_{tk,c} + H_{tk,i} + \nu Q_p(t)^2 \\ \text{and } H_b(t) = H_{b,s} - \kappa_0 Q_p(t) - \mu_0 Q_p(t)^2 \quad (3)$$

where ν is the coefficient associated to pressure losses in the pipe P1 (see Fig. 1), κ_0 is the aquifer losses coefficient and μ_0 is the borehole losses coefficient. The heights H_b, $H_{tk,b}$, $H_{tk,c}$, $H_{tk,i}$ and $H_{b,s}$ are defined in the legend of Fig. 1.

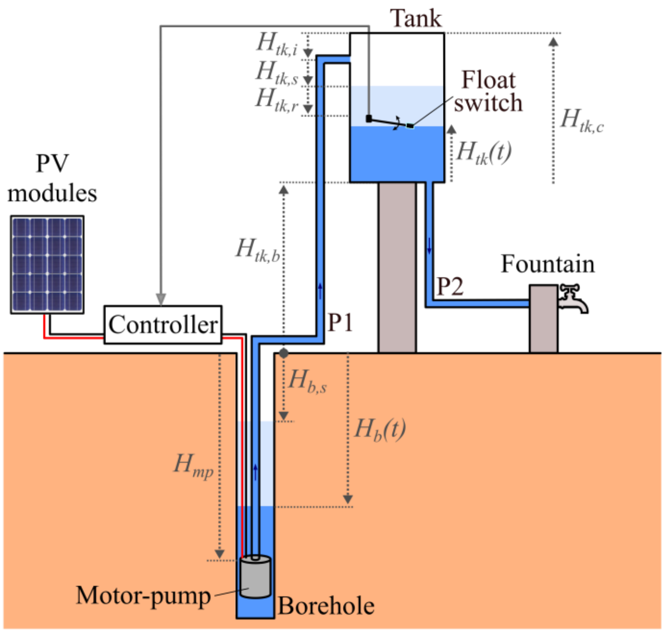

Fig. 1. Photovoltaic water pumping system architecture and heights definition. $\boldsymbol{H_{tk,b}}$: height between the floor and the bottom of the tank, $\boldsymbol{H_{tk,c}}$: tank height, $\boldsymbol{H_{tk,i}}$ (<0): height between the top of the tank and the water entry in the tank, $\boldsymbol{H_{tk,s}}$ (<0): height between the water entry and the stop controller level, $\boldsymbol{H_{tk,r}}$ (<0): height between the stop controller level and the restart level, $\boldsymbol{H_{tk}(t)}$: water level in the tank, $\boldsymbol{H_{b,s}}$ (<0): height between the floor and the static water level in the borehole, $\boldsymbol{H_b(t)}$ (<0): height between the floor and the water level in the borehole, $\boldsymbol{H_{mp}}$ (<0): height between the floor and the position of the motor-pump.

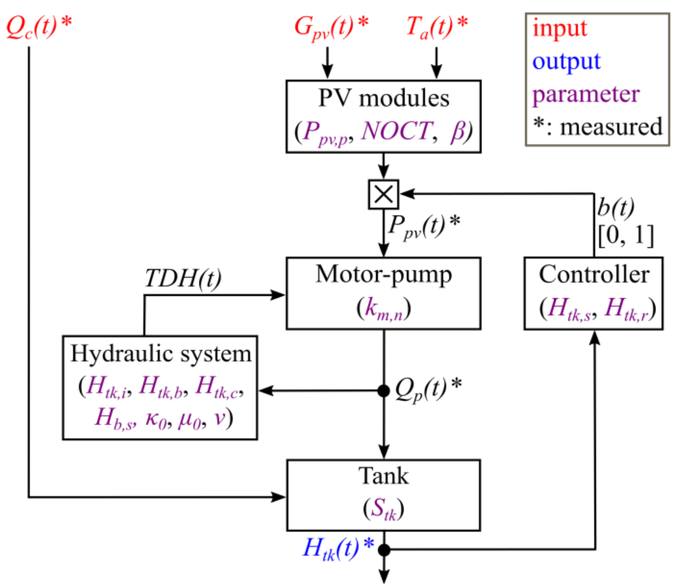

Fig. 2. Block diagram of the technical model.

The water level in the tank H_{tk} is given by:

$$H_{tk}(t) = \max\left(0, H_{tk}(t_0) + \int_{t_0}^{t} \frac{Q_p(\tau) - Q_c(\tau)}{S_{tk}} d\tau\right) \quad (4)$$

where S_{tk} is the cylindrical tank base area. We initialize the model at a time t_0 at which the tank is full and the water level in the tank is therefore equal to the stop controller level. In total, the technical model has 14 parameters which cover the whole energy conversion chain (see Fig. 2).

C. Economic model

Fig. 3 shows the block diagram of the economic model. The model inputs are the PV modules peak power in STC $P_{pv,p}$, the tank volume V_{tk} and the motor-pump reference MP. The model output is the lifecycle variable cost LVC which is given by [22]:

$$LVC = CAPEX + \sum_{j=1}^{L} \frac{OPEX(j)}{(1+r)^j} \quad (5)$$

where

$$CAPEX = c_{pv} \cdot P_{pv,p} + c(MP) + c_{tk} \cdot V_{tk} \quad (6)$$

and

$$OPEX(j) = \frac{CAPEX}{100} + \begin{cases} c(MP) \text{ every 10 years} \\ c_{pv} \cdot P_{pv,p} \text{ every 20 years} \end{cases} \quad (7)$$

where c_{pv} is the cost per watt-peak of the PV modules, $c(MP)$ is the cost of the motor-pump reference MP, c_{tk} is the cost per cubic meter of the tank, L is the lifetime of the PVWPS and r is the discount rate. The motor-pump has to be replaced every 10 years and the PV modules every 20 years. The LVC is the part of the overall PVWPS cost that depends on the sizing of the PVWPS [22]. It does not include the fixed costs (e.g. preliminary geophysical study, borehole drilling) as they are not related to the system's sizing. In total, the economic model has 5 parameters which are related to both the capital and operating costs (see Fig. 3).

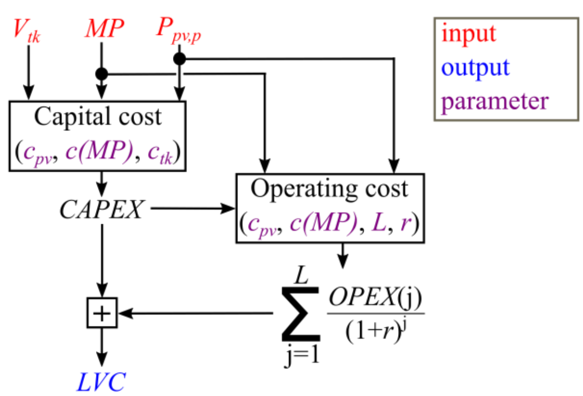

Fig. 3. Block diagram of the economic model.

D. Simulation and validation

In this section, the technical and economic models are applied to a PVWPS for domestic water access in the rural village of Gogma in Burkina Faso (see Fig. 4) [20] [23]. This system is composed of 620 W_p of multicrystalline PV modules, a motor-pump SQFlex 5A-7 [24] and a cylindrical steel tank of 11.4 m^3.

Regarding the technical model, we have determined the values of the 14 parameters for Gogma's system by direct measurement, identification or from the literature and these values are summarized in Table I [20]. We have also been monitoring the variables specified in Fig. 2 with a time step of ~2.2 s since January 2018 with a data logger. We rescaled the data to an equally spaced temporal resolution of 1 minute by nearest interpolation [25] [26].

Fig. 5 and Fig. 6 show the measured inputs of the model for one given day of our dataset: irradiance G_{pv}, ambient temperature T_a and water collected flow rate Q_c. Fig. 7 presents the simulated pumped flow rate Q_p, the water level in the borehole H_b and the total dynamic head TDH for the same day. Fig. 8 shows the simulated and the measured evolution of the model output, the water level in the tank H_{tk}.

The motor-pump stops (Q_p = 0 at 11 am for instance) when the tank is full (i.e. the water level in the tank H_{tk} has reached the stop controller level). H_{tk} must then go down to the restart level for the motor-pump to resume pumping. The long interruptions highlight that the system is oversized in comparison to the water collection. We also observe that the decrease of the water level in the borehole H_b varies with the pumped flow rate Q_p. When the motor-pump stops, the water level in the borehole H_b recovers to the static water level $H_{b,s}$ (-4.9 m).

For this dataset, a good agreement between the simulated model output and the measurement is observed (see Fig. 8). Note that extensive validations have been carried out for several two-week periods and the accuracy of the model was found to be higher than 94 % [20].

Regarding the economic model, we have determined the value of the 5 parameters for the Burkinabe market (see Table I) by combining results of a company survey performed in Burkina Faso, manufacturer's data and the literature [22]. In addition, the fixed costs for the PVWPS of Gogma amount $20k [12].

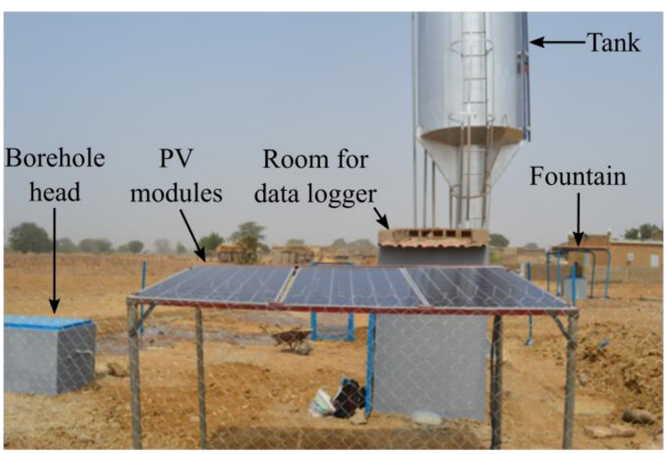

Fig. 4. Photovoltaic water pumping system for 280 people in the village of Gogma, Burkina Faso, sub-Saharan Africa.

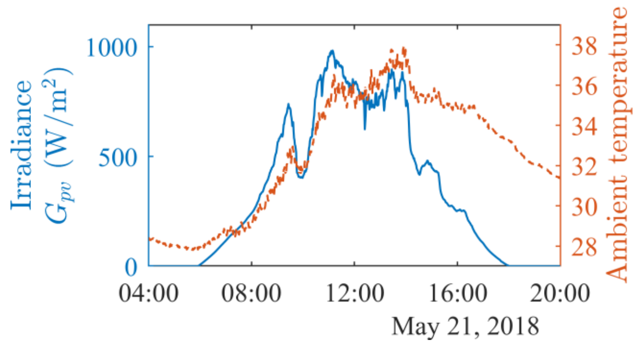

Fig. 5. Measured irradiance on the plane of the PV modules and ambient temperature (Model inputs).

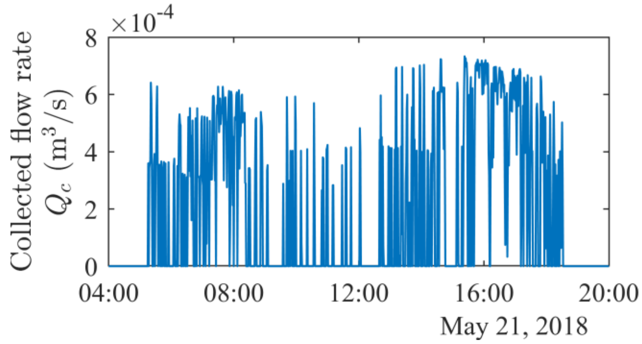

Fig. 6. Measured flow rate collected at the fountain (Model input).

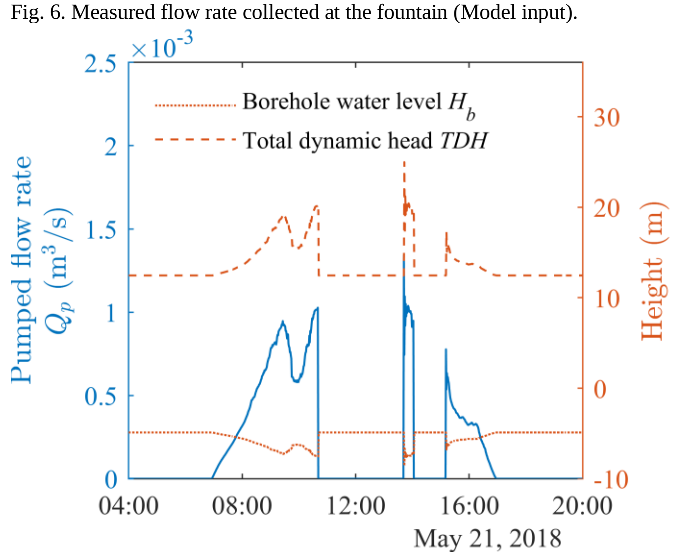

Fig. 7. Simulated pumped flow rate, water level in the borehole and total dynamic head.

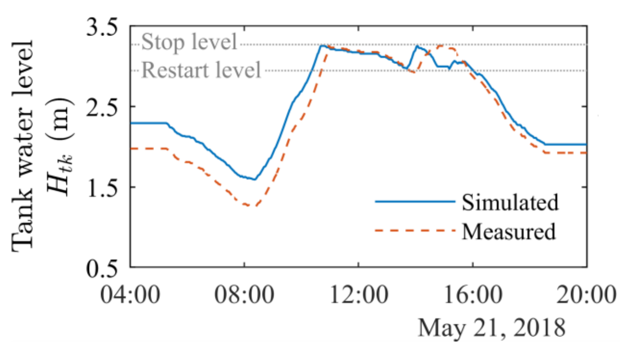

Fig. 8. Simulated and measured water level in the tank (Model output).

Postprint accepted in *IEEE Transactions on Industry Applications*. Acceptance date: 12 July 2020

TABLE I – PVWPS PARAMETERS

Parameter	Way of obtaining the parameter	Reference value	Factor(s) that may cause parameter variation
Technical parameters – Reference values relative to Gogma's PVWPS			
$NOCT$	Identification	32 °C	Inaccuracy, time, technology
β	Literature	-0.004 °C^{-1}	Inaccuracy, time, technology
$P_{pv,p}$	Identification	620 W_p	Inaccuracy, time, technology
$k_{m,n}$	Identification	16 coefficients [20]	Inaccuracy, time, technology
S_{tk}	Measure	3.3 m^2	Inaccuracy
$H_{tk,c}$	Measure	3.5 m	Inaccuracy
$H_{tk,i}$	Measure	-0.1 m	Inaccuracy
$H_{tk,s}$	Measure	-0.1 m	Inaccuracy
$H_{tk,r}$	Measure	-0.3 m	Inaccuracy
$H_{tk,b}$	Measure	4.2 m	Inaccuracy
$H_{b,s}$	Identification	-4.9 m	Inaccuracy, time
κ_0	Identification	2.0 10^3 s/m^2	Inaccuracy, time
μ_0	Identification	5.8 10^5 s^2/m^5	Inaccuracy, time, technology
ν	Identification	4.9 10^6 s^2/m^5	Inaccuracy, time, technology
Economic parameters – Reference values relative to the Burkinabe market			
c_{pv}	Company survey	\$0.86 /W_p	Technology, price dispersion
$c(MP)$	Manufacturer	\$2200	Technology, price dispersion
c_{tk}	Company survey	\$620 /m^3	Technology, price dispersion
L	Company survey	20 years	Technology
r	Literature	5.6 %	Economic environment

III. Sensitivity Analysis Methodology

The technical and economic parameters can vary around their reference value (see Table I) due to the following factors:

1) *Inaccuracy (for technical parameters only)*. The selected value of the parameter is different from its real value because of measurement or estimation errors.
2) *Time (for technical parameters only)*. The value of the parameter changes along the lifetime of the PVWPS due to ageing and/or evolution of the local environment (e.g. groundwater resources).
3) *Price dispersion (for economic parameters only)*. The price of the component varies from one seller to another.
4) *Economic environment (for discount rate only)*. Discount rates are set by the global and the local economic environment.
5) *Technology (for technical and economic parameters)*. The value of the parameter changes with the technology of the corresponding component.

The sensitivity analysis aims at quantifying the influence of the variation of each of the 14 parameters of the technical model and of the 5 parameters of the economic model. To carry out the sensitivity analysis, we consider a variation of the parameters of ±50% [9] [17] around their reference value. Note that a negative variation (e.g. -50%) of a negative parameter (e.g. $H_{b,s} < 0$) corresponds to a diminution of the absolute value of this parameter. Also note that all the coefficients of the motor-pump $k_{m,n}$ are all varied at the same time. This corresponds to modifying the efficiency of the motor-pump.

To account for the seasonality, we consider two periods of two weeks. The first period lasts from the 16th of May to the 29th of May 2018 and is representative of the dry season. The second period lasts from the 29th of July to the 11th of August 2018 and is representative of the wet season. The average irradiance during both seasons are similar but the daily water collection at the PVWPS is significantly higher during the dry season (~10 m^3/day) than during the wet season (~5 m^3/day).

IV. Sensitivity Analysis on Model Output

A. Technical model

We study here the effect of the variation of the 14 technical parameters on the technical model output, i.e. the water level in the tank. For each season, for each parameter and for each variation of the parameter, we:

1) simulate the water level in the tank H_{tk} during the considered two-week period.
2) compute the normalized root mean square error NRMSE on the water level in the tank:

$$\text{NRMSE} = \frac{1}{H_{tk,c,ref}} \sqrt{\frac{\sum_{i=1}^{n} \left(H_{tk}(i) - H_{tk,ref}(i)\right)^2}{n}}$$

where $H_{tk,c,ref}$ is the reference height of the tank, $H_{tk,ref}$ is the reference water level in the tank (obtained with the reference value of the parameters) and n is the number of time steps.

The results for the dry and wet seasons are given in Fig. 9. The results indicate that the thermal parameters of the PV modules $NOCT$ and β as well as the hydraulic losses coefficients κ_0, μ_0 and ν have a small impact on the model output (NRMSE < 2%) while the heights $H_{tk,i}$, $H_{tk,s}$, $H_{tk,r}$, $H_{tk,b}$, $H_{b,s}$ have a moderate impact (NRMSE ∈ [1.2%, 7.4%]).

In addition, for the height of the tank $H_{tk,c}$, the NRMSE on the model output is nearly equal to the variation of $H_{tk,c}$. Indeed, a change in $H_{tk,c}$ leads to a continuous offset on the simulated water level in the tank. This variation with $H_{tk,c}$ is therefore caused by the definition of the parameters describing the tank geometry. Finally, the PV modules peak power $P_{pv,p}$, the "efficiency" of the motor-pump $k_{m,n}$ and the tank surface S_{tk} have the highest impact on the model output. Indeed, $P_{pv,p}$ and $k_{m,n}$ strongly influence the pumped flow rate Q_p while S_{tk} is directly related to the water tank volume. Selecting optimization variables related to the PV modules, the motor-pump and the water tank is therefore relevant for the optimal sizing of PVWPS (see section V).

Finally, we observe in Fig. 9 that, in general, the variation of the parameters has a lower effect on the model output for the wet season than for the dry one. This suggests that, in the case of PVWPS for domestic water access, performing sensitivity analyses on model output for both the dry and the wet season is relevant.

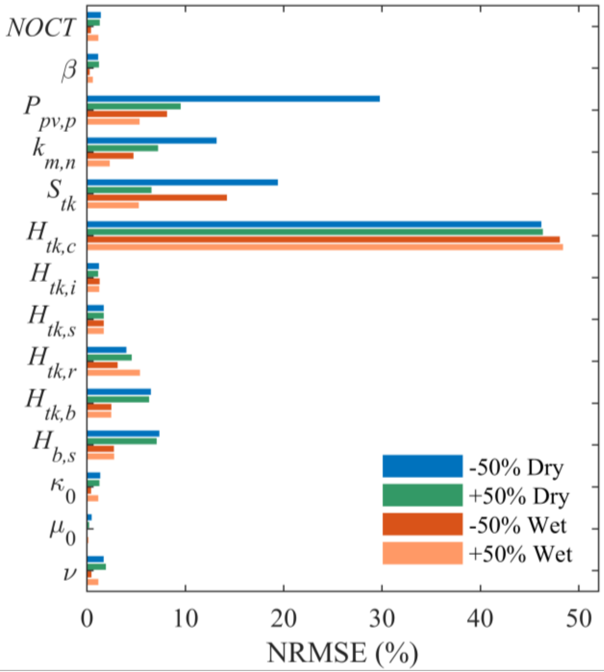

Fig. 9. Influence of the parameters value on the NRMSE on the simulated water level in the tank H_{tk}.

B. *Economic model*

We now study the effect of the variation of the 5 economic parameters on the economic model output, i.e., the lifecycle variable cost LVC. For each parameter and for each variation of the parameter, we:

1) compute the lifecycle variable cost LVC.
2) compute the normalized error on the cost ΔLVC:

$$\Delta LVC = \frac{LVC - LVC_{ref}}{LVC_{ref}}$$

where LVC_{ref} is the reference LVC, which is computed for the reference values of the economic parameters and for the current sizing of the PVWPS ($P_{pv,p}$ = 620 W_p, MP = SQFlex 5A-7, V_{tk} = 11.4 m^3). LVC_{ref} is equal to \$12.2k.

The results are given in Fig. 10. We observe that the variation of the cost of the PV modules c_{pv} has a lower influence on the LVC variation than the cost of the motor-pump $c(MP)$ and of the tank c_{tk}. This is due to the fact that the cost of the PV modules is relatively low compared to the one of the motor-pump and of the tank. Therefore, PVWPS installers should pay increased attention to the selection of the most economical motor-pump and tank (without neglecting their quality). Besides, results indicate that a variation of the PVWPS lifetime L has a significant impact on the LVC, which is due to the number of motor-pump replacements. The development of motor-pumps with an increased lifetime could therefore improve the financial viability of PVWPS.

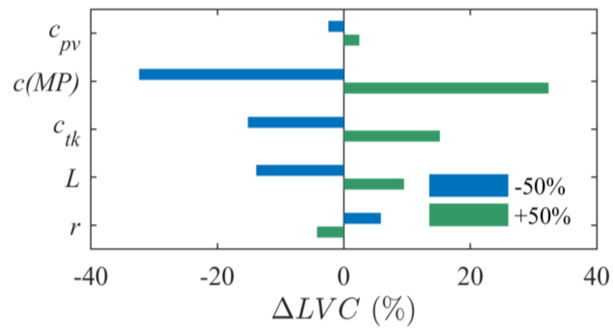

Fig. 10. Influence of the economic parameters on the economic model output.

V. Sensitivity Analysis on Techno-Economic Optimization Results

In this section, we study the influence of the parameters on the optimal sizing of the PVWPS.

A. *Techno-economic optimal sizing*

The optimisation problem is written as follows:

$$\begin{aligned} \underset{P_{pv,p}, MP, V_{tk}}{\text{minimize}} \quad & LVC \\ \text{subject to} \quad & H_{tk}(t) > 0, \forall t \\ & H_b(t) > H_{mp} + 10, \forall t \\ & TDH(t) < H_{p,max}(MP), \forall t \end{aligned} \tag{8}$$

The objective function is the lifecycle variable cost LVC. The variables of the optimization are the PV modules peak power $P_{pv,p}$, the motor-pump reference MP and the water tank volume V_{tk}. We have digitized the characteristic curves of 8 submersible SQFlex motor-pumps from Grundfos [12], [27]. Note that, despite the fact that the 8 motor-pump references do not have the same performances, they all have the same price.

The first constraint of the optimization is that the water level in the tank H_{tk} (Fig. 1) must remain positive, in order to fulfil the water needs of the inhabitants. The second constraint is that the water level in the borehole H_b (Fig. 1) must not drop below the position of the motor-pump (H_{mp} = -30 m), with a safety margin of 10 m, in order to prevent the motor-pump from running dry. The 10 m margin allows to account for hydrological change with time [28]. The third constraint is that the total dynamic head TDH must remain lower than the maximum pumping height $H_{p,max}(MP)$ specified in the datasheet of the motor-pump reference MP.

To perform this optimization we use the differential evolution algorithm presented in [29], that we implemented in MATLAB.

B. *Optimization results for the reference parameters values*

We start by performing the optimization for the reference values of the parameters (see Table I). The optimal value of the lifecycle variable cost LVC obtained is referred to as the "optimal reference LVC", LVC_{ref}. This optimization is performed for the dry season and the wet season. The optimal reference LVC and the associated values of the variables are presented in Table II. As expected, the optimal PVWPS is larger for the dry season (higher LVC_{ref}) than for the wet one.

This is due to the larger water collection by the inhabitants during the dry season (see section III).

TABLE II
OPTIMIZATION RESULTS WITH THE REFERENCE VALUES OF THE PARAMETERS

	Dry season	**Wet season**
LVC_{ref}	\$6.7k	\$6.2k
$P_{pv,p}$	900 W_p	480 W_p
MP	SQFlex 2.5-2 [30]	SQFlex 2.5-2 [30]
V_{tk}	3.1 m^3	2.9 m^3

C. *Sensitivity analysis*

We now study the influence of the variation of the 5 economic parameters and of 10 technical parameters on the optimization results (the remaining 4 technical parameters are related to optimization variables). For each season, for each parameter and for each variation of the parameter, we:

1) perform the optimization and find the optimal cost LVC.
2) compute the normalized error on the optimal cost ΔLVC:

$$\Delta LVC = \frac{LVC - LVC_{ref}}{LVC_{ref}}$$

where LVC_{ref} is the optimal reference LVC provided in Table II.

The results for the dry and the wet season are presented in Fig. 11.

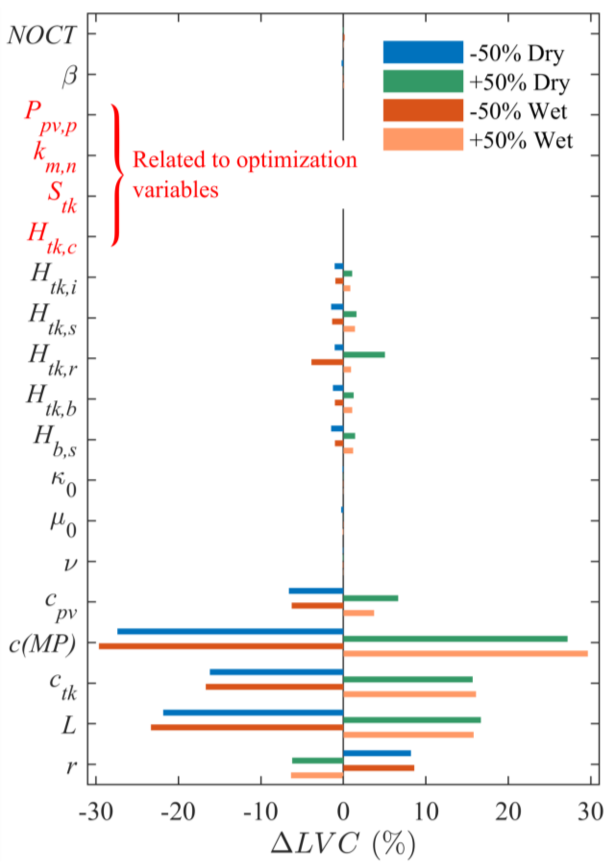

Fig. 11. Influence of the parameters values on the optimal system cost.

The results indicate that the economic parameters have the largest influence on the optimal LVC. Nevertheless, it is important to keep in mind that the technical parameters which strongly influence the model output have been selected as optimization variables.

Regarding the technical parameters, we observe that the thermal parameters of the PV modules $NOCT$ and β, and the hydraulic losses coefficients κ_0, μ_0 and ν have a small impact on the optimal LVC. We also observe that the heights $H_{tk,i}$, $H_{tk,s}$ $H_{tk,r}$, $H_{tk,b}$ and $H_{b,s}$ have a larger impact on the optimal LVC. $H_{tk,i}$ is the height between the top of the tank and the water entry in the tank ($H_{tk,i} < 0$). $H_{tk,s}$ is the height between the water entry and the stop controller level ($H_{tk,s} < 0$). A variation of $H_{tk,i}$ or $H_{tk,s}$ influences the percentage of the tank volume that is available for storing water. For instance, a variation of -50% of $H_{tk,i}$ or $H_{tk,s}$ increases this percentage and therefore decreases the LVC. $H_{tk,r}$ is the height between the stop controller level and the restart level ($H_{tk,r} < 0$). It sets the water level at which the motor-pump will restart after being stopped due to the tank filling. For instance, a variation of -50% of $H_{tk,r}$ allows the motor-pump to restart earlier, to increase the use factor of the motor-pump and therefore to lower the LVC. $H_{tk,b}$ is the height between the floor and the bottom of the tank ($H_{tk,b} > 0$) and $H_{b,s}$ is the static water level in the borehole ($H_{b,s} < 0$). A variation of -50% of $H_{tk,b}$ or $H_{b,s}$ decreases the total dynamic head TDH and therefore allows increasing the pumped flow rate Q_p for the same input power P_{pv} to the motor-pump. This explains why the LVC decreases. This result on the static water level $H_{b,s}$, which is in line with [12], highlights that it may be relevant to consider the evolution of $H_{b,s}$ with time when sizing PVWPS. During the lifetime of a PVWPS (20 years), $H_{b,s}$ can vary of up to several dozen meters [12], [28].

Regarding the economic parameters, results are aligned with the ones on model output: the cost of the motor-pump $c(MP)$, the cost of the tank c_{tk} and the lifetime of the PVWPS L have the largest influence.

Finally, we observe that the influence of the season (dry or wet) on the results of the sensitivity analysis on optimal sizing is limited. This suggests that either season may be used indifferently for performing sensitivity analyses on optimal sizing.

VI. INFLUENCE OF THE AMBIENT TEMPERATURE

The small influence of the PV modules thermal parameters $NOCT$ and β on the technical model output and on the optimization results suggests that it may not be required to consider the evolution of the ambient temperature T_a as an input of the PVWPS model (see Fig. 9 and Fig. 11). T_a could then be considered as a parameter. This would simplify the implementation of the model and reduce the amount of data to collect.

To investigate this more in detail, we consider here that T_a is a constant, equal to the minimum, average or maximum value of the time series during the whole two-week period considered. Besides, we do not take the minimum, average and maximum values provided by the locally measured data but the one provided by the publicly available online database MERRA-2 [31], in order to investigate if local temperature measurements are necessary. We then simulate the evolution of the water level in the tank H_{tk} and compute the NRMSE with the reference water level in the tank $H_{tk,ref}$ (see section IV. A). We also perform the techno-economic optimization and compute the normalized error on the optimal cost ΔLVC (see section V. C). The results are given in Table III.

TABLE III
INFLUENCE OF CONSIDERING THE AMBIENT TEMPERATURE EVOLUTION ON THE TECHNICAL MODEL OUTPUT AND ON THE OPTIMAL COST

Dry season			Wet season		
T_a	NRMSE	ΔLVC	T_a	NRMSE	ΔLVC
Minimum (23 °C)	1.69%	-0.37%	Minimum (21 °C)	0.48%	-0.28%
Average (30 °C)	0.83%	-0.07%	Average (26 °C)	0.18%	-0.07%
Maximum (39 °C)	2.12%	0.47%	Maximum (31 °C)	0.96%	0.01%

Table III confirms that the ambient temperature has a small influence on the technical model output and on the optimization results. Besides, the evolution of the measured temperature can be replaced by the average temperature calculated from a public database without significant accuracy loss. However, it is important to keep in mind that this result is valid only for PVWPS with tank for domestic water access, and that the ambient temperature has a larger influence on the system's performance for PVWPS for irrigation as shown in [32].

VII. CONCLUSION

In this study, we firstly highlighted the technical and economic parameters involved in the modeling of PVWPS for domestic water access. Secondly, we presented the factors that may lead to a variation of these parameters: inaccuracy of estimation, variation in time through ageing and evolution of the local environment, price dispersion between sellers, economic environment and technology (use a component instead of another one). Thirdly, we investigated the impact of a ±50% variation of each parameter on the output of technical and economic models of PVWPS. Fourthly, we presented the techno-economic optimal sizing of PVWPS and the influence of parameters variation on optimization results. Finally, we looked more specifically at the influence of the evolution of the ambient temperature on the results of the technical model and of the optimization.

The results indicate that the PV modules peak power $P_{pv,p}$, the motor-pump efficiency $k_{m,n}$, and the water tank surface S_{tk} have the highest influence on the technical model output. Thus, in the case of PVWPS for domestic water supply, the PV modules peak power, the motor-pump reference and the tank volume are relevant choices of optimization variables. Besides, we observe that the motor-pump cost $c(MP)$, the tank cost c_{tk} and the PVWPS lifetime L have the largest influence on the economic model output.

Regarding the optimization results, we see that economic parameters have a larger influence on the optimal cost than technical ones. Amongst economic parameters, the motor-pump cost $c(MP)$, the tank cost c_{tk} and the PVWPS lifetime L have a larger influence than the PV modules cost c_{pv} and the discount rate r. Amongst technical parameters, the various heights ($H_{tk,i}$, $H_{tk,s}$, $H_{tk,r}$, $H_{tk,b}$ and $H_{b,s}$) have a non-negligible influence on the optimization results. Consequently, these heights should be accurately determined when setting-up PVWPS. Otherwise the optimal sizing obtained could in reality not respect the design constraints. In addition, it may be important to consider the evolution of the static water level $H_{b,s}$ over time when sizing a PVWPS. Otherwise, a system that was sized correctly at year 1 may not meet the specifications at year 20 anymore.

Furthermore, the results show that the thermal parameters of the PV modules ($NOCT$ and β) and the ambient temperature have a small impact on the technical model and optimization results. Thus, considering only the average ambient temperature from a public database instead of its measured evolution is sufficient for the design of PVWPS for domestic water supply, which simplifies the PVWPS technical model and decreases the amount of data to collect.

This study can be useful to non-governmental organizations, companies and governments which install PVWPS for domestic water supply. Firstly, it can allow them to decide the accuracy at which system's parameters have to be determined at the design stage. Secondly, it can help them to evaluate the robustness of PVWPS sizing to parameters change with the evolution of the local environment (particularly groundwater resources) and components' ageing. Thirdly, it may orientate their choices of components and may help them to predict future performances of PVWPS as technology improves.

ACKNOWLEDGMENT

We thank the 280 contributors of the Turning Sun Into Water project and the associations Eau Fil du Soleil and Respublica that allowed to finance the photovoltaic water pumping system of Gogma. We would like to thank the reviewers for their comments and suggestions which allowed to improve the article.

REFERENCES

[1] S. Murshid and B. Singh, "Implementation of PMSM drive for a solar water pumping system," *IEEE Trans. Ind. Appl.*, vol. 55, no. 5, pp. 4956–4964, Sep./Oct. 2019.

[2] A. Hmidet, N. Rebei, and O. Hasnaoui, "Experimental studies and performance evaluation of MPPT control strategies for solar-powered water pumps," in *Proc. 10th International Conference on Ecological Vehicles and Renewable Energies (EVER)*, Monte Carlo, Monaco, Apr. 2015, pp. 1–12.

[3] B. Singh, A. K. Mishra, and R. Kumar, "Solar powered water pumping system employing switched reluctance motor drive," *IEEE Trans. Ind. Appl.*, vol. 52, no. 5, pp. 3949–3957, Sep. 2016.

[4] S. S. Chandel, M. N. Naik, and R. Chandel, "Review of solar photovoltaic water pumping system technology for irrigation and community drinking water supplies," *Renew. Sustain. Energy Rev.*, vol. 49, pp. 1084–1099, Sep. 2015.

[5] J. V. M. Caracas, G. de C. Farias, L. F. M. Teixeira, and L. A. de S. Ribeiro, "Implementation of a high-efficiency, high-lifetime, and low-cost converter for an autonomous photovoltaic water pumping system," *IEEE Trans. Ind. Appl.*, vol. 50, no. 1, pp. 631–641, Jan./Feb. 2014.

[6] E. T. Maddalena, C. G. da S. Moraes, G. Bragança, L. G. Junior, R. B. Godoy, and J. O. P. Pinto, "A battery-less photovoltaic water-pumping system with low decoupling capacitance," *IEEE Trans. Ind. Appl.*, vol. 55, no. 3, pp. 2263–2271, May/June 2019.

[7] I. Odeh, Y. G. Yohanis, and B. Norton, "Influence of pumping head, insolation and PV array size on PV water pumping system performance," *Sol. Energy*, vol. 80, no. 1, pp. 51–64, Jan. 2006.

[8] C. Lorenzo, R. H. Almeida, M. Martínez-Núñez, L. Narvarte, and L. M. Carrasco, "Economic assessment of large power photovoltaic irrigation systems in the ECOWAS region," *Energy*, vol. 155, pp. 992–1003, July 2018.

[9] B. Ali, "Comparative assessment of the feasibility for solar irrigation pumps in Sudan," *Renew. Sustain. Energy Rev.*, vol. 81, pp. 413–420, Jan. 2018.

[10] I. Odeh, Y. G. Yohanis, and B. Norton, "Economic viability of photovoltaic water pumping systems," *Sol. Energy*, vol. 80, no. 7, pp. 850–860, July 2006.

[11] A. Boutelhig, A. Hadjarab, and Y. Bakelli, "Comparison study to select an optimum photovoltaic pumping system (PVPS) configuration upon experimental performances data of two different dc pumps tested at Ghardaïa site," *Energy Procedia*, vol. 6, pp. 769–776, 2011.

[12] T. Vezin, S. Meunier, L. Queval, J.A. Cherni, L. Vido, A. Darga, P. Dessante, P.K. Kitanidis and C. Marchand, "Borehole water level model for photovoltaic water pumping systems", *Applied Energy*, vol. 258, art 114080, Jan. 2020

[13] B. Bouzidi, "New sizing method of PV water pumping systems," *Sustain. Energy Technol. Assess.*, vol. 4, pp. 1–10, Dec. 2013.

[14] J. Ramos and H. Ramos, "Solar powered pumps to supply water for rural or isolated zones: A case study," *Energy for Sus. Dev.*, vol. 13, no. 3, pp.151–158, Sep. 2009.

[15] M. Montorfano, D. Sbarbaro, and L. Moran, "Economic and technical evaluation of solar-assisted water pump stations for mining applications: a case of study," *IEEE Trans. Ind. Appl.*, vol. 52, no. 5, pp. 4454–4459, May 2016.

[16] M. Al-Smairan, "Application of photovoltaic array for pumping water as an alternative to diesel engines in Jordan Badia, Tall Hassan station: Case study," *Renew. Sustain. Energy Rev.*, vol. 16, no. 7, pp. 4500–4507, Sept. 2012.

[17] D. H. Muhsen, T. Khatib, and H. T. Haider, "A feasibility and load sensitivity analysis of photovoltaic water pumping system with battery and diesel generator," *Energy Convers. Manag.*, vol. 148, pp. 287–304, Sept. 2017.

[18] H. Liu, S. Ye, and R. Ye, "Research on comparative advantages of SPV pumping irrigation systems," *IOP Conference Series: Earth and Environmental Science*, vol. 227, 2019.

[19] B. Bouzidi, M. Haddadi, and O. Belmokhtar, "Assessment of a photovoltaic pumping system in the areas of the Algerian Sahara," *Renew. Sustain. Energy Rev.*, vol. 13, no. 4, pp. 879–886, May 2009.

[20] S. Meunier, M. Heinrich, L. Queval, J.A. Cherni, L. Vido, A. Darga, P. Dessante, B. Multon, P.K. Kitanidis, C. Marchand, "A validated model of a photovoltaic water pumping system for off-grid rural communities," *Applied Energy*, vol. 241, pp. 580-591, May 2019

[21] S. Meunier, L. Queval, A. Darga, P. Dessante, C. Marchand, M. Heinrich, J.A. Cherni, E.A. de la Fresnaye, L. Vido, B. Multon, P.K. Kitanidis, "Modelling and optimal sizing of photovoltaic water pumping systems – Sensitivity analysis," in *Proc. 14th International Conference on Ecological Vehicles and Renewable Energies (EVER)*, Monte Carlo, Monaco, May 2019.

[22] E. André de La Fresnaye, "A financial and technical assessment of solar versus hand water pumping for off-grid area – the case of Burkina Faso," M.S. thesis, Imperial College London, United Kingdom, 2018.

[23] S. Meunier, "Optimal design of photovoltaic water pumping systems for rural communities – a technical, economic and social approach," PhD thesis, University of Paris-Saclay, France, 2019.

[24] Grundfos, "Performance curve of SQFlex 5A-7 motor-pump," [Online]. Available: https://product-selection.grundfos.com/product-detail.product-detail.html?custid=GMA&productnumber=95027342&qcid=342768342, Accessed on: Oct. 10, 2019.

[25] S. Meunier, L. Queval, A. Darga, P. Dessante, C. Marchand, M. Heinrich, J. A. Cherni, L. Vido, and B. Multon, "Influence of the temporal resolution of the water consumption profile on photovoltaic water pumping systems modelling and sizing," in *Proc. 7th International Conference on Renewable Energy Research and Applications (ICRERA)*, Paris, France, Oct. 2018, pp. 494-499.

[26] S. Meunier, L. Queval, M. Heinrich, E. A. de la Fresnaye, J. A. Cherni, L. Vido, A. Darga, P. Dessante, B. Multon, P. K. Kitanidis, and C. Marchand, "Effect of irradiance data on the optimal sizing of photovoltaic water pumping systems," *in Proc. 46th IEEE Photovoltaic Specialists Conference (PVSC)*, Chicago (IL), United States, June 2019, pp. 653-658.

[27] Off-grid Europe, "Off-grid Europe products," [Online]. Available: https://www.off-grid-europe.com/, Accessed on: Sept. 21, 2019.

[28] A. Rubio-Aliaga, J. M. Sánchez-Lozano, M. S. García-Cascales, M. Benhamou, and A. Molina-García, "GIS based solar resource analysis for irrigation purposes: rural areas comparison under groundwater scarcity conditions," *Sol. Energy Mater. Sol. Cells*, vol. 156, pp. 128–139, Nov. 2016.

[29] K. Price, R. M. Storn, and J. A. Lampinen, "Differential Evolution: A Practical Approach to Global Optimization (Natural Computing Series)." Secaucus, NJ, USA: Springer-Verlag New York, Inc., 2005.

[30] Grundfos, "Performance curve of SQFlex 2.5-2 motor-pump," [Online]. Available: https://product-selection.grundfos.com/product-detail.product-detail.html?custid=GMA&productnumber=95027330&qcid=465405409, Accessed on: Oct. 10, 2019.

[31] NASA, "Modern-Era Retrospective analysis for Research and Applications, Version 2," 2017. [Online]. Available: https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/, Accessed on: Oct. 12, 2019.

[32] M. Chahartaghi and M. H. Jaloodar, "Mathematical modeling of direct-coupled photovoltaic solar pump system for small-scale irrigation," *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, Nov. 2019.

Simon Meunier received the MSc degree in sustainable energy from Imperial College London, London, UK, in 2015.

He is currently a PhD Student with the GeePs laboratory (Université Paris-Saclay, CentraleSupélec, CNRS, Sorbonne Université, France). His current research interests include energy systems modelling and optimization.

Loïc Quéval received the Ph.D. degree in science from the University of Tokyo, Tokyo, Japan, in 2013.

He is currently an Assistant Professor with the GeePs laboratory (Université Paris-Saclay, CentraleSupélec, CNRS, Sorbonne Université, France). His current research interests include renewable energy, transportation and applied superconductivity.

Arouna Darga received the Ph.D. degree in science from Sorbonne University, Paris, France, in 2007.

He is currently an Associate Professor with the GeePs laboratory (Université Paris-Saclay, CentraleSupélec, CNRS, Sorbonne Université, France). His main research interests include photovoltaics and energy systems.

Philippe Dessante Philippe Dessante received his PhD thesis in physics from the University of Paris Sud, France in 2000. He obtained his habilitation in 2012 on the optimization, design and modeling of electrotechnical systems.

He is currently a professor at CentraleSupélec and a member of the GeePs laboratory (Université Paris-Saclay, CentraleSupélec, CNRS, Sorbonne Université, France). His main areas of research are simulation and optimization of electrotechnical systems.

Claude Marchand received the Ph.D. degree in electrical engineering from the University of Paris-Sud, Orsay, France in 1991.

He is currently a Full Professor and the Head of the GeePs laboratory (Université Paris-Saclay, CentraleSupélec, CNRS, Sorbonne Université, France). His main research interests include the design and control of electrical machines.

Matthias Heinrich received the MSc degree in electrical engineering from Ecole Normale Supérieure de Rennes, Rennes, France in 2018.

He has been working with DargaTech SARL, Ouagadougou, Burkina Faso, on the design of photovoltaic water pumping systems. He is currently undertaking a Specialized Master with the Ecole des Ponts and AgroParisTech, Paris, France. His main research interests include electrical systems and data science.

Judith A. Cherni received the Ph.D. degree in geography environment and economics from London School of Economics & Political Science, London, UK in 1997.

She is currently a Research Fellow and Lecturer with the Centre for Environmental Policy with Imperial College London, London, UK. Her main research interests include international development and environmental policy.

Elvire A. de la Fresnaye received the MSc degree in sustainable energy from Imperial College London, London, UK, in 2017.

She is currently an Investment Analyst with Mirova, Paris, France. Her main research interests include economic analysis and financing of energy systems.

Lionel Vido received the Ph.D. degree in electrical engineering from the Ecole Normale Supérieure Paris-Saclay, Cachan, France, in 2004.

He is currently an Associate Professor with the SATIE Laboratory, University of Cergy-Pontoise, Cergy, France. His main research interests include the design, modeling, and control of novel hybrid and permanent-magnet machines.

Bernard Multon received the Ph.D. degree in electrical engineering from Sorbonne University, Paris, France in 1985.

Since 1995, he has been a Full Professor with Ecole Normale Supérieure de Rennes, University of Rennes, CNRS, Bruz, France. His main research interests include the sizing of electromechanical chains and the management of renewable electrical conversion systems throughout their lifecycle.

Peter Kitanidis received a Ph.D. in Water Resources from the Massachusetts Institute of Technology, Cambridge, Massachusetts, USA, in 1974.

He is a Professor with the Department of Civil and Environmental Engineering and the Institute for Computational and Mathematical Engineering, Stanford University, Stanford, USA. His research interests include groundwater resources, computational science, and data science.