# Optimal design of photovoltaic water pumping systems for rural communities – a technical, economic and social approach

Simon Meunier

université
PARIS-SACLAY

NNT : 2019SACLS440

UNIVERSITÉ PARIS SUD
Comprendre le monde, construire l'avenir

# Optimal design of photovoltaic water pumping systems for rural communities – a technical, economic and social approach

Thèse de doctorat de l'Université Paris-Saclay
préparée à l'Université Paris-Sud

Ecole doctorale n°575 Electrical, optical, bio-physics and engineering, EOBE
Spécialité de doctorat: Génie Electrique

Thèse présentée et soutenue à Gif-sur-Yvette, le 06/12/2019, par

**Simon Meunier**

Composition du Jury :

| | |
|---|---|
| Anne Migan-Dubois<br>Professeur, Université Paris-Sud (GeePs) | Présidente du jury |
| Mohamed Machmoum<br>Professeur, Université de Nantes (IREENA) | Rapporteur |
| Stéphane Brisset<br>Professeur, École Centrale de Lille (L2EP) | Rapporteur |
| Frédéric Wurtz<br>Directeur de recherche, CNRS (G2ELAB) | Examinateur |
| Philippe Malbranche<br>Directeur de l'INES (Institut National de l'Énergie Solaire) | Examinateur |
| Judith Cherni<br>Research Fellow and Lecturer, Imperial College London (CEP) | Examinatrice (Co-encadrante) |
| Claude Marchand<br>Professeur, Université Paris-Sud (GeePs) | Directeur de thèse |
| Loïc Quéval<br>Enseignant-chercheur, CentraleSupélec (GeePs) | Invité (Co-encadrant) |

Encadrement :

| | |
|---|---|
| Philippe Dessante<br>Professeur, CentraleSupélec (GeePs) | Co-encadrant |
| Lionel Vido<br>Maître de conférences, Université de Cergy-Pontoise (SATIE) | Co-encadrant |

Thèse de doctorat

# Acknowledgements

I would like to thank Mohamed Machmoum and Stéphane Brisset for carefully reviewing this work and for their very interesting feedbacks. I also thank Anne Migan-Dubois, Frédéric Wurtz, Philippe Malbranche and Judith Cherni for examining this work and for their very valuable remarks.

I wish to express my sincere gratitude to my five PhD advisors. I thank Loïc Quéval for his commitment, his daily availability, his constructive suggestions and his professionalism. He pushed me to do my best during these last three years. I thank my PhD director Claude Marchand who was present and active throughout the thesis. His commitment and support allowed me to carry out my work in the best conditions. I also would like to thank Judith Cherni for her continuous support and her guidance on socio-economic aspects. I thank Philippe Dessante for his very constructive feedbacks and guidance throughout the whole PhD thesis. I thank Lionel Vido for his never-ending enthusiasm and knowledge filled inputs.

I am extremely grateful to Bernard Multon, Arouna Darga, Peter Kitanidis and Dale Manning for their selfless help and their extremely valuable inputs on systemic approaches, industrial aspects, hydrology and econometrics. They helped me to grow as a person and as a researcher. I thank Cedric Koeniguer and Bruno Darracq for their precious guidance on teaching and pedagogical aspects.

I would like to thank Matthias Heinrich, Thomas Vezin and Severin Darga for their great help on data collection, original scientific contributions as well as for all the exciting and fascinating discussions that we had. I thank all the students that I had the opportunity to advise during this PhD work for their cheerfulness and high quality contributions. Special mention to Vitali Caplain, Elvire de la Fresnaye and Vincent Roy for their exceptional investment. I thank all the 280 crowdfunders of the Turning Sun Into Water project, the NGO Respublica and the company DargaTech for making the installation of the photovoltaic water pump in Gogma possible. I thank the inhabitants of Gogma and Basile Darga for their warm welcome and a life-changing experience.

I thank all the teachers and researchers of the laboratory GeePs and of the energy department for their welcome and for all the technical and friendly discussions. I do not forget the technical and administrative team, especially Damien Huchet and Richard Beljio and Sophie Goncalvez, for their daily help.

It is now time to thank all my doctoral friends. We had a lot of fun and I know it is only the beginning of our friendship. A special mention to my “co-bureau” Mokrane Bala with whom we shared amazing moments and listened to great Algerian songs. I also thank my great friends from the Tennis Club CentraleSupelec, with whom we visited the whole Essonne. Special mention to Jose de Freitas for his unconditional support. My thoughts are also with my friends in France. I thank them for their support and encouragement during this adventure. I am really glad to have them in my life.

I thank my family and my parents. I am truly grateful for their trust and support during all these years. Finally, I thank my girlfriend Marine for all the special moments that we spent together and the unconditional support during difficult times.

# Table of contents

# List of figures

# List of tables

# Abbreviations

| | |
|---|---|
| ISAG | Institut Superieur d'Application des Géosciences |
| GIS | Geographic information system |
| GHG | Greenhouse gases |
| PA | Pipe assembly |
| PV | Photovoltaic |
| PVWPS | Photovoltaic water pumping system |
| STC | Standard test conditions |
| std | Standard deviation |
| WASH | Water, sanitation and hygiene |

# Nomenclature

| | |
|---|---|
| $AOI(t)$ | Angle of incidence between the sun's rays and the PV array (rad) |
| $b(t)$ | Triggering signal from the controller |
| $CAPEX$ | Capital cost ($) |
| $dr$ | Discount rate (%) |
| $G_{dh}(t)$ | Diffuse horizontal irradiance (W/m$^2$) |
| $G_{dn}(t)$ | Direct normal irradiance (W/m$^2$) |
| $G_{gh}(t)$ | Global horizontal irradiance (W/m$^2$) |
| $G_{pv}(t)$ | Irradiance on the plane of the PV array (W/m$^2$) |
| $H_b(t)$ | Height between the ground level and the water level in the borehole (m) |
| $H_{b,s}$ | Height between the ground level and the static water level in the borehole (m) |
| $H_{b,d}(t)$ | Height between the static water level and the water level when there is pumping (drawdown) (m) |
| $H_{t,b}$ | Height between the ground level and the bottom of the tank (m) |
| $H_{t,i}$ | Height between the bottom of the tank and the level at which water enters the tank (m) |
| $H_{t,r}$ | Height between the bottom of the tank and the restart level (m) |
| $H_{t,s}$ | Height between the bottom of the tank and the stop level (m) |
| $H_{t,t}$ | Height between the bottom of the tank and the top of the tank (m) |
| $H_{pa1}(t)$ | Additional head due to pressure losses in pipe assembly (PA) 1 (m) |
| $H_t(t)$ | Height between the bottom of the tank and the water level in the tank (water level in the tank) (m) |
| $h$ | Household |
| $\boldsymbol{h}$ | All the households of the village |
| $\boldsymbol{h_{sur}}$ | Households surveyed |
| $\boldsymbol{hs_{bef}}$ | Water sources where the households go before installation of the PVWPS |
| $\boldsymbol{hs^*_{aft}}$ | Water sources where the households wish to go after installation of the PVWPS |
| $\boldsymbol{hs_{aft}}$ | Water sources where the households effectively go after installation of the PVWPS |
| $I_{pv}\ (t)$ | Current from the PV array (A) |
| $k_{m,n}$ | Coefficients for the fitting of the motor-pump characteristic |
| $Lat$ | Latitude |
| $Lon$ | Longitude |
| $LCC$ | Life-cycle cost |
| $MP$ | Motor-pump reference |
| $NOCT$ | Nominal operating cell temperature (°C) |
| $n_v$ | Number of households in the village |
| $n_d$ | Number of households that wish to go to the PVWPS (number of demanders of the PVWPS) |
| $n_c$ | Number of households that consume water at the PVWPS (number of consumers of the PVWPS) |
| $n_{c,hp}$ | Number of households that consume water at the PVWPS and used to consume water at a hand pump before installation of the PVWPS |
| $n_{c,ow}$ | Number of households that consume water at the PVWPS and used to consume water at an open well before installation of the PVWPS |
| $OPEX$ | Operational cost ($) |
| $P_{pv,p}$ | PV array peak power (W$_p$) |
| $P_{pv}(t)$ | Power produced by the PV array (W) |

| | |
|---|---|
| $P_{max}(MP)$ | Maximum power input to the motor-pump reference $MP$ |
| $Q_d(t)$ | Water demand flow rate (m$^3$/s) |
| $Q_c(t)$ | Water consumption flow rate (m$^3$/s) |
| $Q_p(t)$ | Pump flow rate (m$^3$/s) |
| $Q_{p,max}$ | Maximum flow rate that can be pumped from a borehole (m$^3$/s) |
| $r$ | Rate of satisfaction of the water demand |
| $s$ | Water source |
| $S_t$ | Area of the base of the tank (m$^2$) |
| $SEI$ | Socio-economic impact |
| $t$ | Time |
| $T_a(t)$ | Ambient temperature (°C) |
| $T_{pv}(t)$ | PV modules temperature (°C) |
| $TDH(t)$ | Total dynamic head (m) |
| $V_{pv}\ (t)$ | Voltage of the PV array (V) |
| $V_t$ | Tank volume (m$^3$) |
| $V_c$ | Volume consumed at the PVWPS (m$^3$) |
| $V_d$ | Volume demanded at the PVWPS (m$^3$) |
| $w_i$ | Weighting coefficient of the socio-economic impact function |
| $yOPEX$ | Yearly operational cost ($) |
| $\alpha$ | Coefficient relating two impact indicators |
| $\beta_i$ | Regression coefficient of the demand model |
| $\eta_{stc}$ | Efficiency of the PV modules in standard test conditions (STC) (%) |
| $\phi_{bef}$ | Prediction rate before installation of the PVWPS |
| $\phi_{aft,PVWPS}$ | Prediction rate at the PVWPS |
| $\gamma$ | Coefficient of loss on the maximum power related to PV modules temperature (°C$^{-1}$) |
| $\mathcal{I}$ | Impact indicator |
| $\mathcal{I}_d$ | Distance impact indicator |
| $\mathcal{I}_{dia}$ | Diarrhea impact indicator |
| $\mathcal{I}_{ee}$ | Extraction easiness impact indicator |
| $\mathcal{I}_{wc}$ | Water cost impact indicator |
| $\mathcal{I}_{wq}$ | Water quality impact indicator |
| $\kappa_n$ | Aquifer losses coefficients (s/m$^2$) |
| $\lambda$ | Azimuth of the PV array (rad) |
| $\mu_n$ | Borehole losses coefficients (s$^2$/m$^5$) |
| $\nu$ | Pipe pressure losses coefficient (s$^2$/m$^5$) |
| $\theta$ | Tilt of the PV array (rad) |
| $\pi_i$ | Predictor of the water demand |
| $\pi_d$ | Distance predictor |
| $\pi_{ee}$ | Extraction easiness predictor |
| $\pi_{pwq}$ | Perceived water quality predictor |
| $\pi_{tcw}$ | Time collecting water predictor |
| $\pi_{wc}$ | Water cost predictor |

| | |
|---|---|
| $\Pi$ | Number of predictors of the water demand |
| $\rho$ | Probability that a given household attends a given water source |
| $\sigma$ | Season (dry or wet) |
| $\zeta$ | Albedo of the surrounding environment |

# Conversion rate

All the prices are expressed in US dollars ($) and the rates retained are the ones on the 23/08/2018:

1 XOF (currency in Burkina Faso) = $0.00177

1 € = $1.16

# Introduction

# Introduction

In sub-Saharan Africa, more than 300 million people do not have access to potable water sources and most of them live in rural areas. Photovoltaic water pumping systems (PVWPS) can improve access to potable water, especially in rural villages that are not connected to the electricity grid.

The objective of this PhD thesis is to propose a new methodology for the optimal design of PVWPS for domestic water access in rural villages. The proposed methodology aims at determining the sizings of the PVWPS and its positions in the village that maximize the positive impact of the system on socio-economic development (e.g. use of water of better quality, decrease in the distance to collect water) and minimize its life-cycle cost. The first main originality is the introduction of the position of the PVWPS in the village as an optimisation variable. This is particularly relevant given that many rural villages in sub-Saharan Africa are extended and that households of the same village often have an uneven access to potable water sources. Therefore there may be positions of the PVWPS that are more favourable for the village as a whole. The second main originality is the inclusion of the socio-economic impact as an objective function of the optimisation. Indeed, institutions that finance these systems aim at maximising their positive socio-economic impact.

This methodology was developed in collaboration with researchers from various disciplines, i.e., electrical engineering (GeePs and SATIE laboratories), environmental policy (Imperial College London), econometrics (Colorado State University) and hydrology (Stanford University), and in association with the company DargaTech based in Burkina Faso. Besides, this methodology is applied to a rural village in Burkina Faso, where technical and socio-economic data have been collected since September 2017.

Chapter I presents the literature review. Chapter II describes the case study village and the experimental data collected. Chapter III presents the interdisciplinary model. Chapter IV presents the formulation of the optimisation problem and the results and proposes an improved procedure for the design and installation of PVWPS.

# Chapter I Literature review

# Chapter I Literature review

In the first section of this chapter, we discuss the low access to improved domestic water sources and the low grid coverage in sub-Saharan Africa. In the second section, we compare the main energy sources for pumping domestic water in off-grid areas. In the third section, we present the conventional way to design PVWPS. In the fourth section, we detail the main gaps that had been identified in the literature reviewed in the previous sections and relate those to the objectives of this PhD thesis.

# I.1 The water-energy nexus in rural areas of sub-Saharan Africa

## *I.1.1 Domestic water access*

The most common alternatives for water extraction in poor rural areas of developing countries are gathering water from an open well with a bucket and a rope, and hand pumps [1]. An open well is a hole sunk by hand in the ground, about 5-10 meters deep, used to collect water by throwing a bucket into it [1]. A hand pump is set on a drilled deep borehole and therefore allows to extract groundwater [1].

The water that is extracted from open wells with a bucket and a rope is not potable notably because it is exposed to contamination through mud [2]. This is the main reason why these sources are categorized as "unimproved". Figure I-1 shows that these unimproved sources are nevertheless the only ones available to a large share of the population in sub-Saharan Africa. Drinking water from unimproved water sources is responsible for diseases such as diarrhea and trachoma [3, 4]. For instance, according to [4], in Cameroon children living in a household with no access to potable water are 1.3 times more likely to get diarrheal diseases than those living in households with an easy access to potable water.

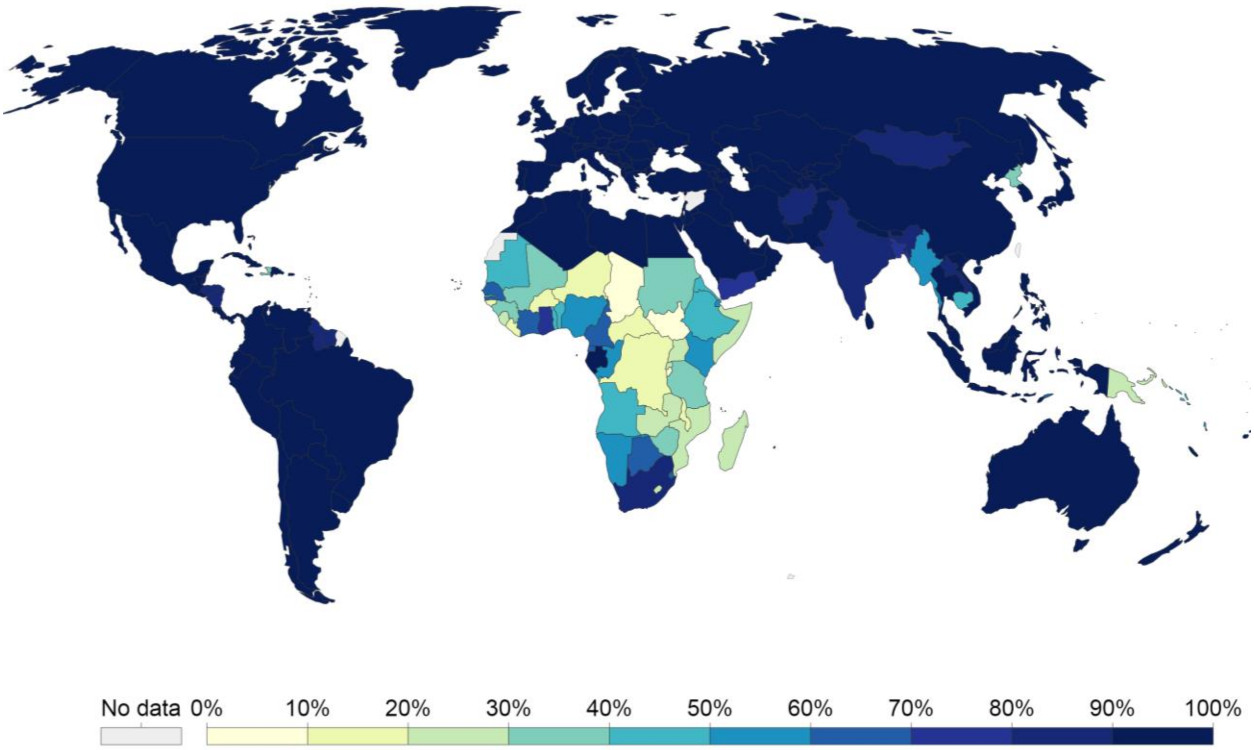


*Figure I-1 – Share of rural population with access to improved water sources, 2015 [5].*

Contrarily to open wells, hand pumps provide potable water as they extract water from aquifers and they are sealed to prevent contamination [2]. However, like for open wells, the pumped flow rate of hand pumps is limited by human strength, water extraction is hard and time consuming, which is responsible for significant queuing times [6, 7, 8]. Finally, hand pumps do not allow to reach deep aquifers (typically groundwater levels deeper than 50 m [9]) and require regular maintenance due to moving parts [2].

In comparison to the alternatives described above, electrified water pumping systems appear as more promising for providing water for domestic use, i.e., drinking, cooking, personal hygiene and laundry.

Indeed, despite their higher initial cost [1], they allow to reach deeper aquifers and they provide higher flow rates. Consequently the queuing time at the system is reduced, which allows to free time so to enable people to undertake other activities [10, 11]. In addition, electrified water pumping systems allow to lower the physical hardness of water collection [10, 11]. Finally, they can be a stepping stone toward the installation of piping systems that deliver water to households individually [12, 13]. Nevertheless, as electrified pumping systems provide the opportunity to extract larger volumes of water than hand pumps, increased attention has to be paid to the effect of pumping on groundwater resources in order to preserve their sustainability [9].

### *I.1.2 Electricity access*

Figure I-2 presents the share of the population of each country with access to electricity in 2015. A close observation to Figure I-1 and Figure I-2 points out that, in general, countries where access to improved water sources is the lowest are also the ones where the electricity access is deficient. In addition, national grid extension in the affected countries has proved to be too slow to reach remote rural areas in the near future [14, 15]. Other energy sources, such as off-grid solar energy systems, are a viable alternative to provide energy services in rural areas [16], and in particular electrified water pumping.

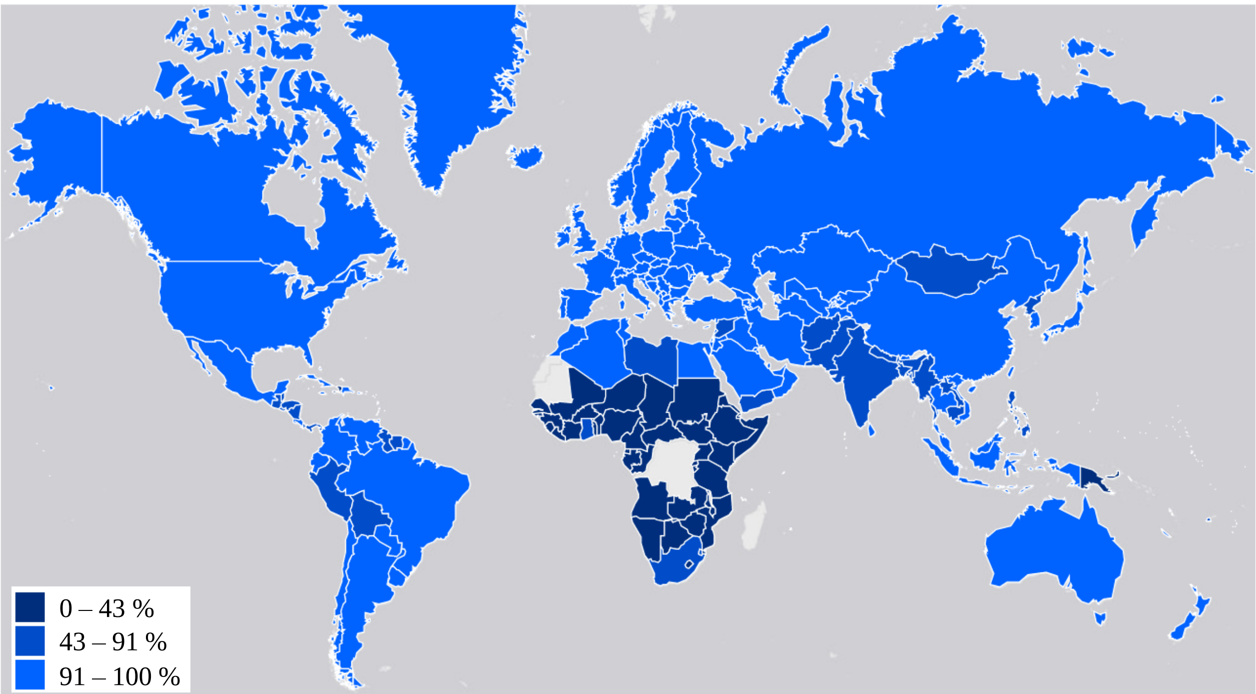


*Figure I-2 – Share of rural population with access to electricity, 2015 [17].*

## I.2 Electrified water pumping technologies for off-grid areas

The most often used energy sources for providing electrified water pumping in off-grid areas are photovoltaic energy and diesel [18]. Table I-1 compares photovoltaic water pumping systems (PVWPS) to diesel water pumping systems.

*Table I-1 – Comparison between diesel and photovoltaic energy for water extraction.*

| | Diesel pumping system | PVWPS |
|---|---|---|
| Storage | Not required | Electrical or water storage required |
| Capital cost | Low [1, 19] | High [1, 11, 19] |
| Operation cost | High [19] | Low [20, 21] |
| Lifetime | Short [19] | Long (typically 20 years) [19, 22, 23] |
| Greenhouse gases emissions | High [24, 25] | Low [24, 25] |
| Maintenance | Frequent maintenance required [1, 19] | Reduced maintenance needs [19, 26, 27] |
| Local impact | Noise, toxic fumes [28, 29] | |
| Reliability of supply | Intermittent supply in fuels in many regions [19] | Variability of solar resource [30] |

Despite their higher capital cost [1, 11, 19], PVWPS have become competitive in comparison to diesel pumps in off-grid rural areas in terms of life cycle cost [31, 32]. In several cases, they are even more economically viable [19, 33]. However, the high capital cost still represents a challenge for financing PVWPS [1, 11, 19].

Regarding greenhouse gases (GHG) emissions, life cycle analyses were carried out to evaluate the GHG emissions from PVWPS and the reduction in GHG emissions achieved when replacing diesel pumps by PVWPS. Some studies consider only $CO_2$ and other studies also take into account the other greenhouse gases (e.g. $CH_4$). In the latter case, results are given in kg of $CO_2$ equivalent ($CO_2$eq). In Table I-2, we present the results of these studies in terms of emissions per kW, as 1 kW is a typical size for a PVWPS for domestic water access [34, 35].

*Table I-2 – GHG emissions from PVWPS and their GHG emissions mitigation potential.*

| Reference | Location | Size of the system considered (kW) | PVWPS emissions | Emissions reduction for the replacement of a diesel pump by a PVWPS |
|---|---|---|---|---|
| [25] | China | 3.4 | 294 kg$CO_2$/kW/year | NC |
| [24] | Algeria | 1 | NC | 4 kg$CO_2$/kW/year |
| [36] | India | 1.8 | NC | 1160 kg$CO_2$/kW/year |
| [37] | Bangladesh | 2 | NC | 500 kg$CO_2$eq/kW/year |
| [38] | Saudi Arabia | 20 | NC | 1200 kg$CO_2$eq/kW/year |

NC: not considered.

The figures in Table I-2 can be compared to other figures of merit such as the average yearly GHG emissions per capita in the OECD countries: 11700 kgCO2eq/capita/year [39]. We observe that, for domestic water access, the impact of the implementation of new PVWPS and of the replacement of diesel pumps by PVWPS in terms of GHG emissions is restricted. This is mainly due to the fact that a low power PVWPS (typically 1 kW) can allow to deliver a very high value energy service, i.e. water provision for dozen of households [34]. We will therefore not consider GHG emissions from PVWPS in this PhD thesis.

Another key advantage of PVWPS in comparison to diesel pumps is their long lifetime [19, 22, 23] and their reduced maintenance needs [19, 26, 27], which is particularly important in rural areas [40]. Moreover,

PVWPS do not emit toxic fumes [29] and are less noisy [28], reducing their effect on the local operator. PVWPS are therefore a good candidate for development projects, as considered in this thesis. Nonetheless, thanks to their quicker installation [19], diesel pumps may be a more suitable for emergency and temporary projects, following earthquakes for instance.

## I.3 Conventional PVWPS design

We define the design of a PVWPS for domestic water access in a rural village as the determination of its:

- *Architecture,* i.e., the choice and the disposition of the components.
- *Position,* i.e., the geographical location in the village.
- *Sizing,* i.e., the size of the components.

### *I.3.1 Architecture*

In order to be able to fulfil the water needs and to deal with the variability of the climatic conditions, a storage component is always required in PVWPS. The two mains possibilities for providing storage are: storing electrical energy produced by the PV array in batteries, or storing pumped water in a tank [31] (see Figure I-3). However, batteries wear out quickly in the harsh conditions considered (dust, temperature) and therefore have to be replaced frequently [41]. When batteries are effectively replaced, this increases the operation cost [42]. In addition and more importantly, batteries are not always replaced in these isolated areas, which jeopardizes the sustainability of the whole PVWPS [41]. As the architecture with water tank is more reliable than the one with battery, it is the most commonly used for providing domestic water in isolated areas [31, 41]. In this thesis, the architecture with water tank will thus be considered.

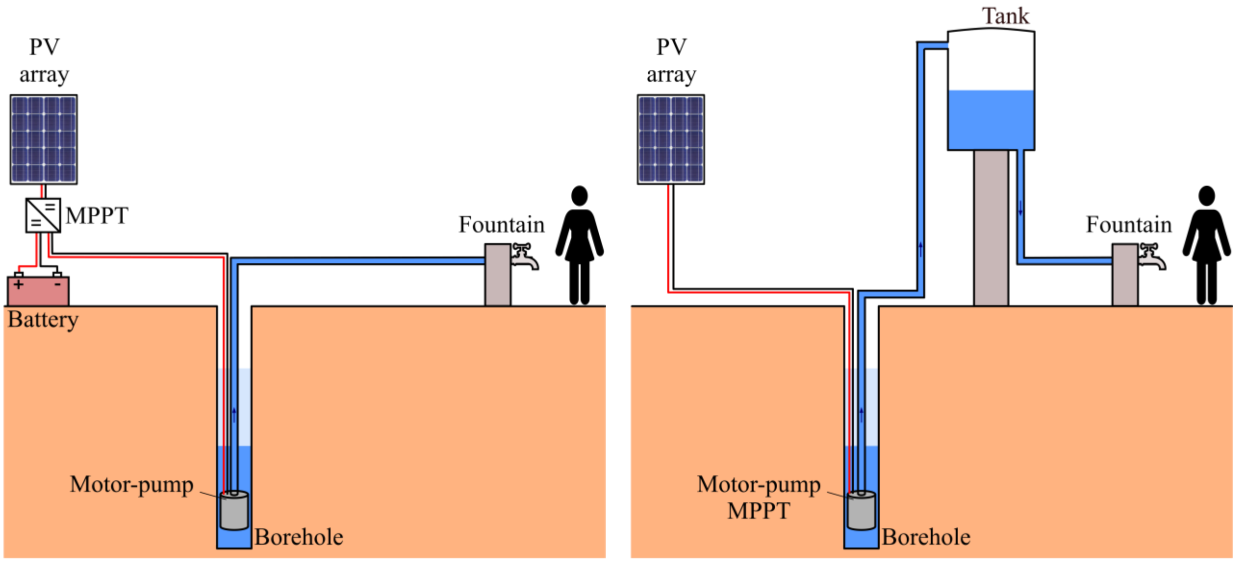


*Figure I-3 – Schematic layout of PVWPS with battery storage (left) and water tank storage (right) – adapted from [31, 43, 44], MPPT: maximum power point tracker.*

### *I.3.2 Position*

Setting the position of a PVWPS, and of a water source in general, can be separated into two main phases [45]:

- The proposition of a position by decision makers. This is referred to as '**positioning**' in this thesis.
- The validation or invalidation of the proposed position through geophysical, hydrological and water quality analyses. This is referred to as '**position validation**'. If the position proposed initially is invalidated, the decision maker suggests another position (i.e. back to the **positioning** phase).

**Positioning**

The positioning of PVWPS and of water sources in general is a relatively undocumented topic and no scientific article on the subject was encountered. The few documents of the grey literature on this topic mention that the position may be proposed by the financing institution and/or village authorities [46, 47] and that the following elements should be considered when proposing a position:

1. The position should be away from potential contaminations sites (e.g. latrines, burial sites, municipal garbage dump) [46].
2. The position should be safe [46].
3. Reports on local geophysical studies and on the characteristics of existing wells of the village should be examined, if there are any [45].
4. The position should be accessible by the households [46].

Regarding element 3, it is difficult to implement in isolated areas of developing countries due to the scarcity of geophysical and hydrology data [46, 48]. In addition, an element that is not mentioned is that the new water point should be installed in the vicinity of households which have the worst access to water (e.g. households that only have access to open wells).

Finally, we observe that, no support tool is provided for the application of the mentioned elements and therefore for the positioning of the water source. As a consequence, the decision maker may decide on a position that is not the most favourable for the village as a whole. This non-optimal choice may be due to the inability of the decision maker to grasp the whole situation of the village or may be done on purpose by the decision maker, who may not be acting in the interest of the whole village. A support tool may help the decision maker to decide on the optimal position for the PVWPS. It may also allow a separate institution to verify that the position proposed by the decision maker is the most favourable for the whole village.

**Position validation**

Firstly, geophysical studies are performed to detect the presence of water around the proposed position, noted $(Lat_1, Lon_1)$ [45]. If geophysical studies suggest the presence of water at a position $(Lat_S, Lon_S)$, next to $(Lat_1, Lon_1)$, a borehole is drilled at the position $(Lat_S, Lon_S)$. If water is indeed encountered at $(Lat_S, Lon_S)$ while drilling, three tests are then performed [45, 49]:

- *pumping tests* which consist in pumping water at different flow rates while monitoring the water level in the borehole. The purpose of these tests is to determine the maximum flow rate that can be extracted from the borehole.
- *physico-chemical tests* which consist in measuring the physico-chemical parameters of the water, such as pH, temperature, alkalinity, electrical conductivity, arsenic concentration.
- *bacteriological tests* which consist in measuring the bacteriological parameters of the water such as the concentration of thermotolerant coliform and of faecal streptococci.

If the decision maker considers that the maximum pumped flow rate, determined from the pumping tests, is sufficient to meet the needs of the inhabitants and that the water quality is satisfying, the position is validated and the PVWPS is installed at $(Lat_S, Lon_S)$.

### *I.3.3 Sizing*

Several studies have been performed to determine the optimal sizing of PVWPS for domestic water access. We have summarized the objective function(s), variables and constraint(s) considered in these optimisations in Table I-3.

*Table I-3 – PVWPS optimal sizing in the literature.*

| Reference | Objective function(s) | Variables | Constraint(s) |
|---|---|---|---|
| [50] | Life-cycle cost,<br>probability of not fulfilling the water consumption | PV array peak power,<br>tank volume | None |
| [51] | Life-cycle cost,<br>probability of not fulfilling the water consumption,<br>excess in pumped water in comparison to the consumption | PV array peak power,<br>tank volume | None |
| [52] | Life-cycle cost,<br>probability of not fulfilling the water consumption | PV array peak power,<br>tank volume | None |
| [53] | Probability of not fulfilling the water consumption | PV array peak power,<br>tank volume | None |

We observe that previous studies have mostly aimed at minimising the life-cycle cost of the PVWPS [50, 51, 52] and at minimising the probability of not fulfilling the water consumption of the inhabitants [50, 51, 52, 53]. The variables considered are the peak power of the PV array and the volume of the water tank [50, 51, 52, 53]. To our best knowledge, no study considers the motor-pump reference as an optimisation variable. It may be interesting to do so as the motor-pump is at the centre of the energy conversion chain (see Figure I-3). Therefore, from now on, we define “sizing” a PVWPS as determining the peak power of the PV array, the motor-pump reference and the tank volume.

In addition, it is noticeable that the position of the PVWPS in the village is not taken into account in the above studies on sizing [50, 51, 52, 53]. It is considered that the PVWPS should meet the water consumption of the whole village, no matter what is its position. This approach may be valid for small villages where all the inhabitants go to only one water source. However, a large share of sub-Saharan Africa rural villages are extended (area of several $km^2$) and the inhabitants of the same village go to different water sources [54, 55]. For these villages, it is rational thus to assume that the water demand, i.e. the load curve, to the newly installed PVWPS depends on its position in the village. This should be reflected in the sizing, which varies with the load curve at the PVWPS, and should therefore depend on the position of the PVWPS in the village.

## I.4 Literature gaps and research objectives

We see in section I.3.3 that the positioning and the sizing of the PVWPS should be coupled. This means that the water demand, i.e. the load curve, at a new PVWPS should be predicted, for any position in the village, and this predicted water demand should be used for sizing the PVWPS. Some econometrics models have investigated the water demand in rural villages and the first idea could be to use the output of these models as an input for sizing the PVWPS. For instance, [56] studied the determinants of the demand for different water sources (e.g. public sources, private wells) in Sri Lanka and similar studies were performed in Kenya [55], Honduras [57] and Philippines [58]. However, to our knowledge, current studies do not go as far as predicting the load curve at water sources. In addition, they focus on existing sources and they do not look at adding a new source, that may in addition be of a different type (e.g. adding a PVWPS in a village where there are only open wells). These elements highlight that considering the position of the PVWPS in the village also requires to adapt existing water demand models.

We also observe that none of the studies on the optimal design of PVWPS seek to maximize the positive impact on socio-economic development (e.g. use of water of higher quality, decrease in distance to collect water), while it is the main objective of the institutions that finance these systems [59, 60]. Some studies have been working on the evaluation of the socio-economic impact of energy systems. For instance, [61] developed an approach and model which compares several energy technologies for rural electrification over a wide range of criteria and forecasts social, human, financial and environmental impacts of energy supply on the population. In addition, [62] proposed a model to evaluate energy planning options (e.g. combined heat and power plants, energy saving) over technical, economic and social criteria (e.g. consistence of installation and maintenance requirements with local technical know-how, cost of primary energy saved). However, we did not find a similar methodology for investigating the socio-economic impact of electrified water pumping systems, like PVWPS. In addition and more importantly, the above articles on energy systems do not relate the design variables of the system (e.g. position, size of each component) to the values of the considered criteria. This prevents to find the optimal design, i.e. the optimal value of the design variables, vis-à-vis the socio-economic criteria. This also highlights the need to develop models that relate design variables to the socio-economic impact of the system.

*The aim of this PhD thesis is to develop a methodology to determine the PVWPS sizings and positions in a village that both maximize the positive impact on socio-economic development and minimize the lifecycle cost of the PVWPS.* This is fulfilled in three main steps:

- **Chapter II.** A PVWPS is designed and installed in the conventional way in a rural village of sub-Saharan Africa. On the one hand, this allows to understand in detail the current situation regarding PVWPS and to design a methodology that builds on this current situation. On the other hand, this allows to collect data to apply the developed methodology and to validate the proposed models.
- **Chapter III.** We build an interdisciplinary model that links the sizing and position of the PVWPS to its socio-economic impact and its life-cycle cost. The interdisciplinary model is composed of 4 sub-models: demand, technical, impact and economic.

- **Chapter IV.** We define an optimisation problem to determine the PVWPS sizings and positions that maximize the positive impact on socio-economic development and minimize the life-cycle cost of the PVWPS, and then we present the results.

To summarize, in Chapter II, we learn from the design and installation of a PVWPS in the conventional way. Then, in Chapter III and Chapter IV, we use the knowledge acquired to propose an improved design and installation methodology (i.e. present how we could have designed and installed the conventionally set PVWPS more optimally).

# Chapter II Experimental setup

# Chapter II Experimental setup

In the frame of this PhD thesis, we raised funds and organized the installation of a PVWPS in the rural village of Gogma in Burkina Faso. The PVWPS was designed and installed in 2017, following the conventional way described in section I.3. The first reason for installing this PVWPS was to improve our understanding of the current situation regarding PVWPS and to propose a methodology for the optimal design of PVWPS (see Chapter III and Chapter IV) that builds on this current situation. Other reasons were to gather data for applying the proposed methodology and to be able to compare model results to experimental measurements.

In section II.1, we present the characteristics of the village of Gogma and the PVWPS installed and in section II.2 we describe the data collected.

# II.1 Case study village and PVWPS

## *II.1.1 The village of Gogma, Burkina Faso*

Burkina Faso is a Sub-Saharan country of West Africa (Figure II-1) with a population of 19 million and a Human Development Index of 0.42, the $7^{th}$ lowest in the world in 2017 [63]. The rural village of Gogma (GPS coordinates: $Lat$: 11.73°; $Lon$: - 0.58°) is a village of ~2 km×2 km located in the "Centre-East" region of Burkina Faso (see Figure II-2). The closest town to Gogma is the town of Garango which is 15 km away.

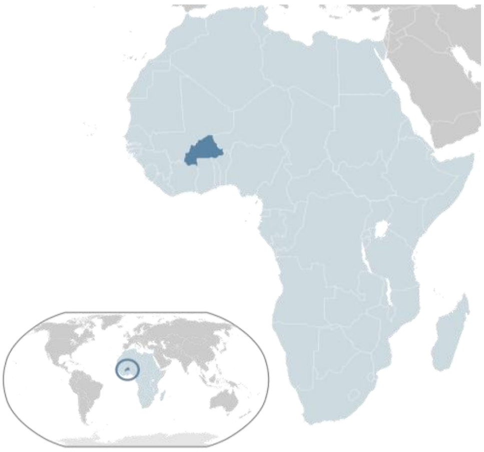

*Figure II-1 – Location of Burkina Faso. Source: Wikipedia.*

*Figure II-2 – Centre-East region in Burkina Faso. Source: Wikipedia.*

The village counts with 1100 inhabitants who live in 125 households. The 125 households are themselves grouped into 41 "household gatherings" such that shown in Figure II-3. The vast majority of people in Gogma work in agriculture and live on less than $1/capita/day. Households do not have access to electricity. We have identified 4 types of domestic water uses: drinking, cooking, personal hygiene and laundry. Water for these uses is collected from 22 sources divided into 3 categories: 16 open wells from which water is extracted with a bucket and a rope (see Figure II-4), 5 hand pumps (see Figure II-5) and 1 PVWPS (Figure II-8 and Figure II-9).

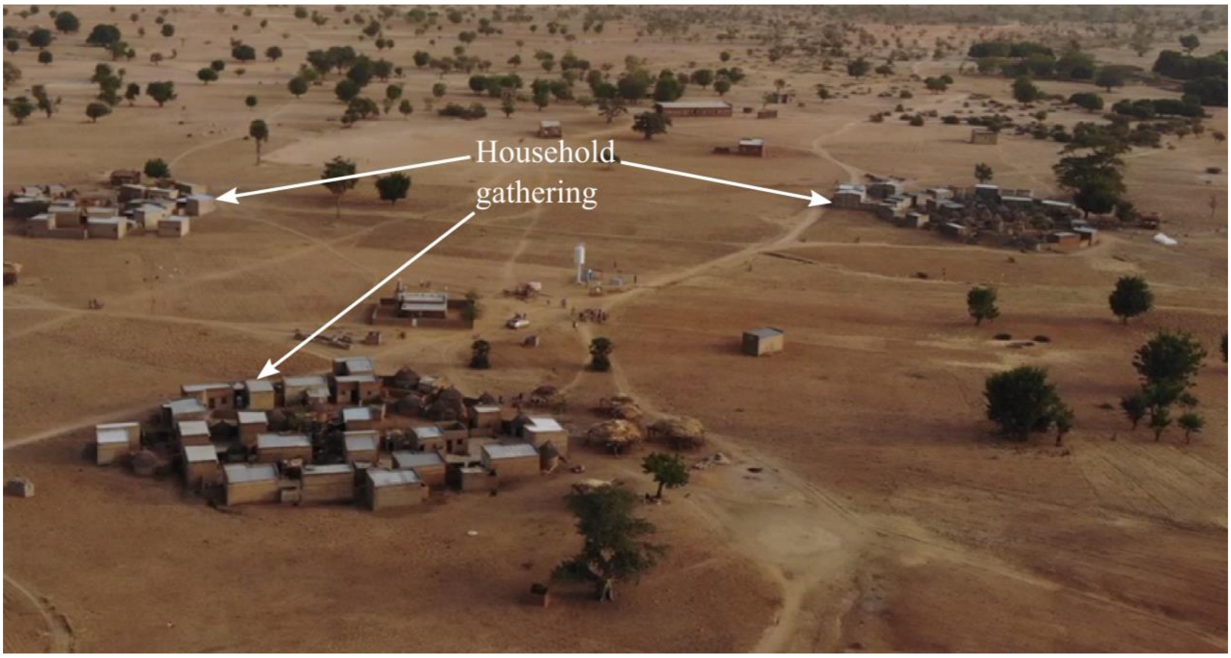


*Figure II-3 – Household gatherings.*

*Figure II-4 – Open well.*

*Figure II-5 – Hand pump.*

## *II.1.2 PVWPS*

### *II.1.2.1 Design and installation*

The installation of the PVWPS in Gogma followed up on the demand from the local authorities of Gogma to the NGO Respublica [64]. The local authorities asked for the installation of an improved water source in an area of Gogma where only open wells were available. Funding for the PVWPS was provided through a donation from Respublica and a crowdfunding organized by the association Eau Fil du Soleil [65]. Eau Fil du Soleil was created by several members of our research group in 2017 and aims at promoting science initiatives in relation to PVWPS in developing regions [66]. The design and installation of the PVWPS was coordinated by the company DargaTech [67], based in Ouagadougou and specialised in photovoltaic systems. The data that were collected during the design and the installation of the PVWPS are presented in section II.2.

The design and installation of the PVWPS were performed according to the following steps:

**Step 1, beginning of September 2017**: the local authorities looked for potential areas to avoid (e.g. burial sites and unsafe areas, see section I.3.2), i.e. areas where the PVWPS should not be installed. No particular area to avoid was encountered.

**Step 2, beginning of September 2017**: the local authorities of Gogma highlighted the position where they would like the PVWPS to be installed.

**Step 3, 18 September 2017**: geophysical measurements, performed by the company Institut Superieur d'Application des Géosciences (ISAG), highlighted a suitable position to drill ($Lon$ = -0.5722° and $Lat$ = 11.7244°) next to the position proposed by the local authorities.

**Step 4, 3 November 2017**: a borehole was drilled by the company Sogedaf. The drilling machine was rent to SAIRA international. Water was found at -14 m (water strike level). Then, due to the pressure of the ground over the aquifer, the water level in the borehole went up to -6 m (static water level). The good execution of the drilling was controlled by a third party called a "drilling controller".

**Step 5, 5 – 8 November 2017**: 4 step pumping tests and 1 long pumping test were performed by Sogedaf. Sogedaf highlighted that the maximum flow rate that can be withdrawn from the borehole $Q_{p,max}$ is equal to 1.8 $10^{-3}$ $m^3/s$. The pumping tests were also controlled by the "drilling controller". Physico-chemical tests were performed by the laboratory Aina. They showed that the water is suitable for drinking in terms of physico-chemical quality.

**Step 6, November 2017**: the PVWPS was sized by the company DargaTech. The peak power of the PV array and the tank volume were determined through analytical calculations. The motor-pump was selected from the Grundfos catalogue [68], notably because of the high quality of Grundfos motor-pumps. The PV modules and the tank were bought in Ouagadougou and the motor-pump was imported from France.

**Step 7, December 2017 – January 2018**: the PVWPS was installed by DargaTech in three phases:

(a) *2 - 8 December 2017*: civil engineering was performed to lay the foundations of the water tank, build the borehole head and the fountain. 4 employees from DargaTech and 2 inhabitants of the village participated in this civil engineering work.

(b) *8 January 2018*: the water tank was installed by 5 employees from DargaTech.

(c) *14 January 2018*: the PV array and the motor-pump were installed by 4 employees of DargaTech and the welder from Garango. A signpost was also put in place next to the fountain with the rules of use of the PVWPS (e.g. do not do laundry next to the fountain, do not wash motor bikes next to the fountain)

**Step 8, 14 January 2018***:* the PVWPS was opened for consumption to the inhabitants.

**Step 9, 27 February 2018***:* bacteriological tests were performed by the laboratory Aina at the PVWPS. They showed that the water is suitable for drinking in terms of bacteriological quality. Based on physico-chemical (step 5) and bacteriological tests results, the water at the PVWPS is therefore potable.

**Step 10, 27 February 2018***:* following the bacteriological tests results, the PVWPS was kept open for consumption by local authorities of Gogma.

The analysis of the different steps and a semi-structured interview with Arouna Darga, the CEO of DargaTech, allowed to determine the procedure for the design and installation of PVWPS which is presented in Figure II-6. According to this interview, this procedure is standard in Burkina Faso.

It is interesting to observe that the bacteriological test is not performed at step 5, at the same time as physico-chemical tests, but after the installation of the PVWPS. Indeed, Arouna Darga explained that the components of the PVWPS (e.g. pipes, tank, fountain) may also be source of bacteriological contamination which explains why the bacteriological test is performed after the installation of the PVWPS. In addition, Arouna Darga specified that these bacteriological tests are not always performed or that they may be performed a few months after the opening of the PVWPS (as in the case of the PVWPS of Gogma). Besides, according to Arouna Darga, negative bacteriological water quality tests (i.e. non potable water) are extremely rare for sealed boreholes in rural areas. He also added that, if the bacteriological tests were to be negative, the opening of the PVWPS to consumption would depend on the situation in the village. For instance, if there are only non-potable sources (e.g. open wells) in the village, the PVWPS may still be opened.

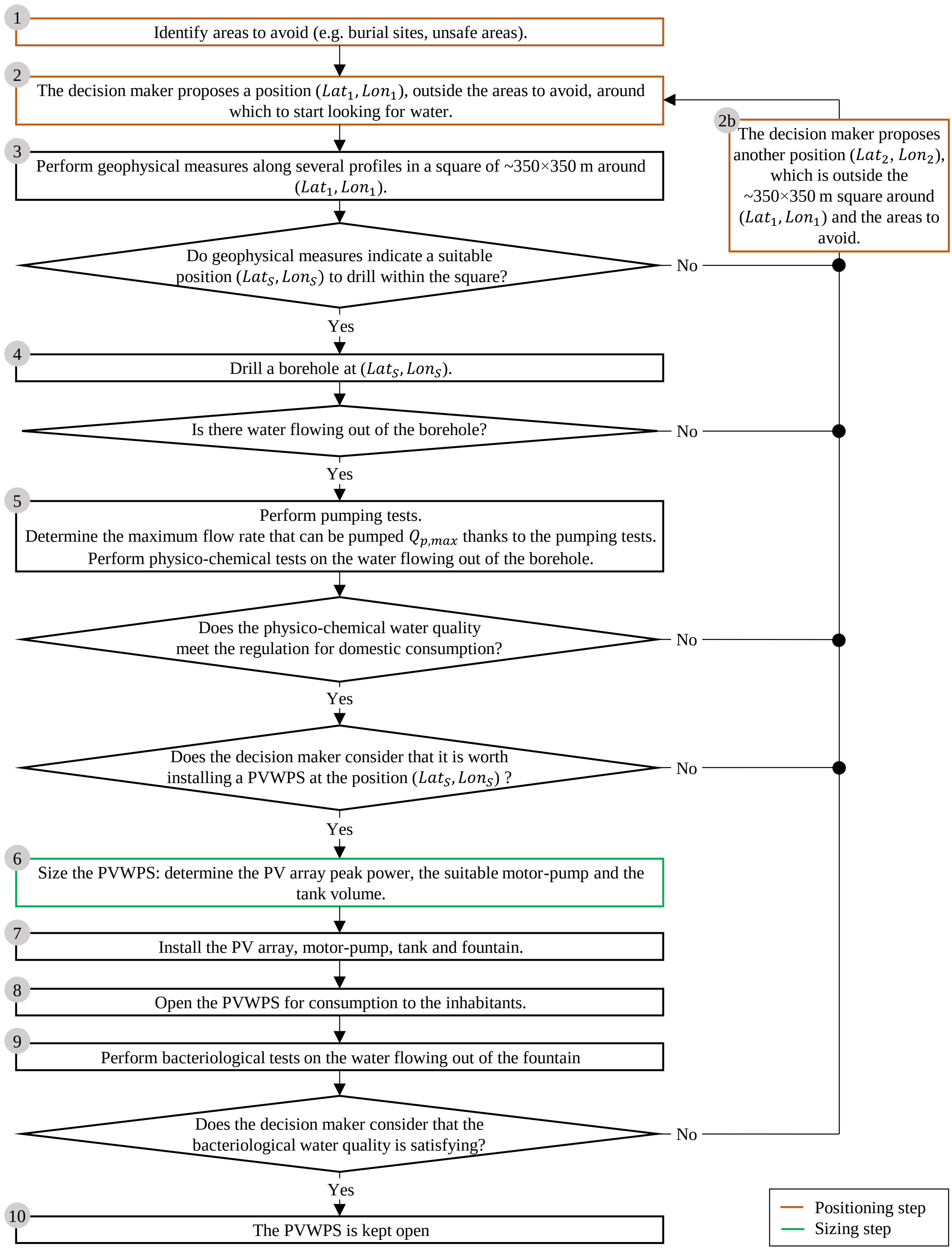


*Figure II-6 – Conventional procedure for the design and installation of a PVWPS.*

### *II.1.2.2 Technical description*

The architecture of the PVWPS is presented in Figure II-7. The components that are encompassed in this architecture are:

- A PV array.
- A motor-pump with a maximum power point tracking (MPPT) controlled converter, which tracks the best operating point of the PV array. This whole set is immersed in the borehole and is called “motor-pump” in the rest of the manuscript.
- A controller which starts and stops the motor-pump according to two set points of the water level in the tank, which is obtained by a float switch.
- A water tank.
- A pipe assembly PA1 which links the motor-pump to the tank.
- A fountain at which inhabitants collect water by using 3 taps.
- A pipe assembly PA2 which links the tank to the fountain.

The water collected at the fountain is used for 4 types of domestic uses: drinking, cooking, personal hygiene and laundry. Most of the users take water back home for drinking, cooking and personal hygiene and do the laundry next to the fountain.

Figure II-8 and Figure II-9 show pictures of this PVWPS. A video of the village and of the PVWPS is also available at the following link: https://youtu.be/VrjM0edKVsI. Table II-1 summarizes the features of the PVWPS. In the rest of the thesis, we refer to the PVWPS that was installed as the “current PVWPS of Gogma”.

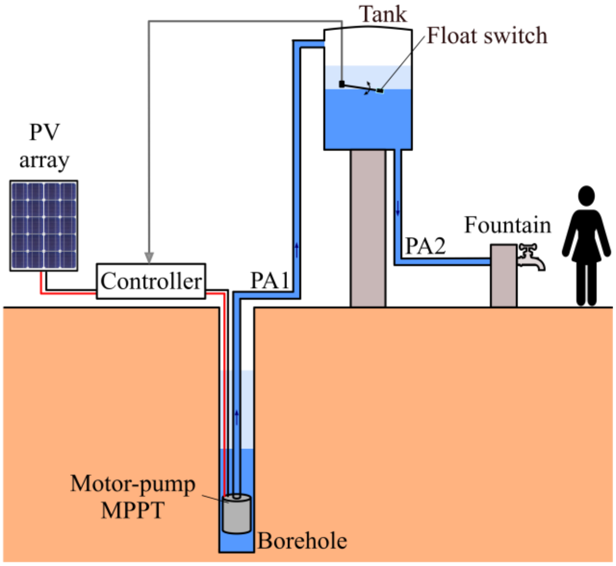


*Figure II-7 – Architecture of the PVWPS.*

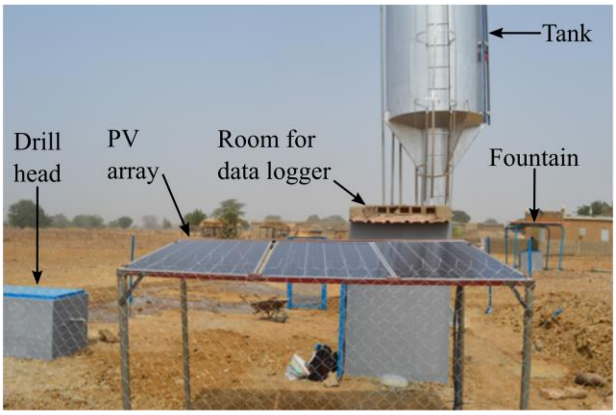


*Figure II-8 – Picture of the PVWPS of Gogma.*

*Figure II-9 – Overview of the PVWPS.*
*On the left: the fountain where the inhabitants collect water.*
*On the right: the PV array and the water tank surrounded by a wire netting.*

*Table II-1 – Features of the current PVWPS of Gogma.*

| | |
|---|---|
| **PV array: 3 multicrystalline silicon modules in series** | |
| Surface of the PV array | 3.9 $m^2$ |
| Tilt $\Theta$ | 0.19 rad (11°) |
| Azimuth λ | π rad (180°) |
| **Borehole** | |
| Distance from the ground level to the bottom of the borehole | 56 m |
| Interior diameter of the borehole | 0.11 m |
| **Motor-pump: Grundfos SQFlex 5A-7** [69] | |
| Distance from the ground level to the motor-pump | 30 m |
| Maximum power input $P_{max}(MP)$ | 1400 W |
| Maximum pumping height | 50 m |
| Maximum pump flow rate | 2.5 $10^{-3}$ $m^3/s$ |
| **Tank: cylindrical made of steel** | |
| Height between the ground level and the bottom of the tank $H_{t,b}$ | 4.2 m |
| Volume of the cylinder $V_t$ | 11.4 $m^3$ |
| Base surface of the cylinder $S_t$ | 3.3 $m^2$ |
| Height of the cylinder $H_{t,t}$ | 3.5 m |
| **Controller: Grundfos CU 200** [70] | |
| **Pipe assembly PA1: 4 pipes of different diameters and materials** | |
| Total length | 47 m |
| **Fountain** | |
| Number of taps | 3 |
| **Pipe assembly PA2: 1 pipe** | |
| Total length | 21 m |

## II.2 Data collection

In Gogma, since September 2017, we have been collecting data from the following disciplines: energy systems, social sciences, geography, hydrology and geophysics. The collected data are summarized in Table II-2 and further detailed in the following sections. In Table II-2, we also specify:

- The data that have been collected during the procedure of design an installation of the PVWPS (labelled as '**Conventional procedure**') and the ones that have been collected in addition, specifically for research purposes (labelled as '**Research**').
- If data were collected by our research group or through specialized companies based in Burkina Faso.
- The collection period, i.e. the total period over which data have been collected (note that the data are not necessarily collected full-time during the collection period).
- The collection time, i.e. the time required to collect the data in number of work days of one data collector (we consider that the collector works 8 hours per day).
- The collection cost. When the data collection was performed by a company, we use the bill from the company. When then data collection was performed by our research group, we estimate data collection cost by multiplying the collection time by the daily cost of a data collector, estimated to $160/day.
- The sub-model(s) where data is (are) used. Indeed, the interdisciplinary model presented in Chapter III, is composed of 4 sub-models (demand, technical, impact and economic) and the collected data may be used in one or several of these sub-models as input and/or for experimental validation.

The considerations on the collection period, time and cost allow to quantify the investment in time and money required to collect each type of data.

*Table II-2 – Summary of collected data.*

| Type | Description | Collected by | Collection period (Collection time for 1 data collector) | Data collection cost | Sub-model where data is used (see Chapter III) |
|---|---|---|---|---|---|
| On-field observations | Observations on living conditions and water access. **Research** | Research group | 18 Sept 2017 – Present (10 days) | $1600 | Demand, Impact |
| GIS (geographic information system) mapping | GPS positions of the households, water sources, important points of the village (shops, mosques, church, …). **Research** | Research group | 18 Sept 2017 – 10 Nov 2017 (3 days) | $480 | Demand, Impact |
| Geophysical measures | Detection of the presence of water along 4 profiles of 150 m long by using electromagnetic methods. **Conventional procedure** | Institut Superieur d'Application des Géosciences (ISAG) [71] | 18 Sept 2017 (1 day) | $386 | |
| Account books of water sources | The account book of a source specifies the households that attend this source and the cost for collecting water at the source. **Research** | Research group | 03 Oct 2017 – 20 June 2018 (1 day) | $160 | Demand, Impact |
| Household surveys | Survey on the living conditions and water access. Two surveys are performed: one before the installation of the PVWPS and one after. **Research** | Survey before installation: Research group<br><br>Survey after installation: company Best Sigma | Survey before installation: 03 Oct 2017 – 21 Oct 2017 (10 days)<br><br>Survey after installation: 27 Oct 2018 to 6 Nov 2018 (10 days) | $3200 | Demand, Impact |
| Pumping tests | 4 step pumping tests, of 2 hours each, at 4 different pump flow rates. 1 long pumping test of 47 hours at a given flow rate. **Conventional procedure** | Sogedaf | 05 Nov 2017 – 09 Nov 2017 (3 days) | 4 step pumping tests: $511<br><br>Long pumping test: $2050 | Technical |
| Water quality tests | 1 physico-chemical test at the PVWPS.<br>1 bacteriological test at the PVWPS.<br>**Conventional procedure**<br><br>21 bacteriological tests for the other 21 water sources for domestic water in Gogma.<br>**Research** | Laboratoire Aina [72] | 7 Nov 2017 – 27 Feb 2018 (2 days) | 1 physico-chemical test at the PVWPS = $141<br><br>1 bacteriological test at the PVWPS = $21<br><br>21 bacteriological tests for the other sources = $441 | Impact |
| PVWPS monitoring | Continuous technical data collection on the operation of the PVWPS. **Research** | Research group | 14 Jan 2018 – Present (10 days[2]) | Hardware and installation[1] = $2000<br><br>Data collection and processing = $1000 | Demand, Technical |

[1] The development time and cost of the data logger is not included. The development time is estimated to 3 months and the development cost to $50000.

### *II.2.1 On-field observations*

In total 8 months were spent in Gogma by members of our research group, split at different moments during the last 3 years. This allowed us to perform 250 on-field observations. For each observation, the following elements were specified:

- Content.
- Is it something that was observed with the eyes or is it something that was said by someone. For the latter case, the name of the person was written down.
- Location.
- Day and time of the day.

The following key information were gathered through on-field observations:

- Households do not need to pay to collect water at open wells.
- Most of the inhabitants perceive the water at sealed boreholes (hand pumps and PVWPS) as potable and perceive the water at open wells as non-potable.
- Inhabitants perceive water extraction at PVWPS as easy.
- Most of the households collect water in the morning and in the evening but it seems that they collect more water in the evening than in the morning.
- Inhabitants sometimes use their bike to carry water.
- In the household surveys, inhabitants reported to use ~20 L/capita/day for personal hygiene. According to our on-field observations, we think that it is overestimated.
- Inhabitants sometimes make several return journeys to collect water.

### *II.2.2 GIS mapping*

The GPS coordinates of the households, water sources and important locations in the village have been collected. We went to each location and used the mobile application "GPS Satellite" [73]. The coordinates obtained are represented on the satellite picture in Figure II-10**.**

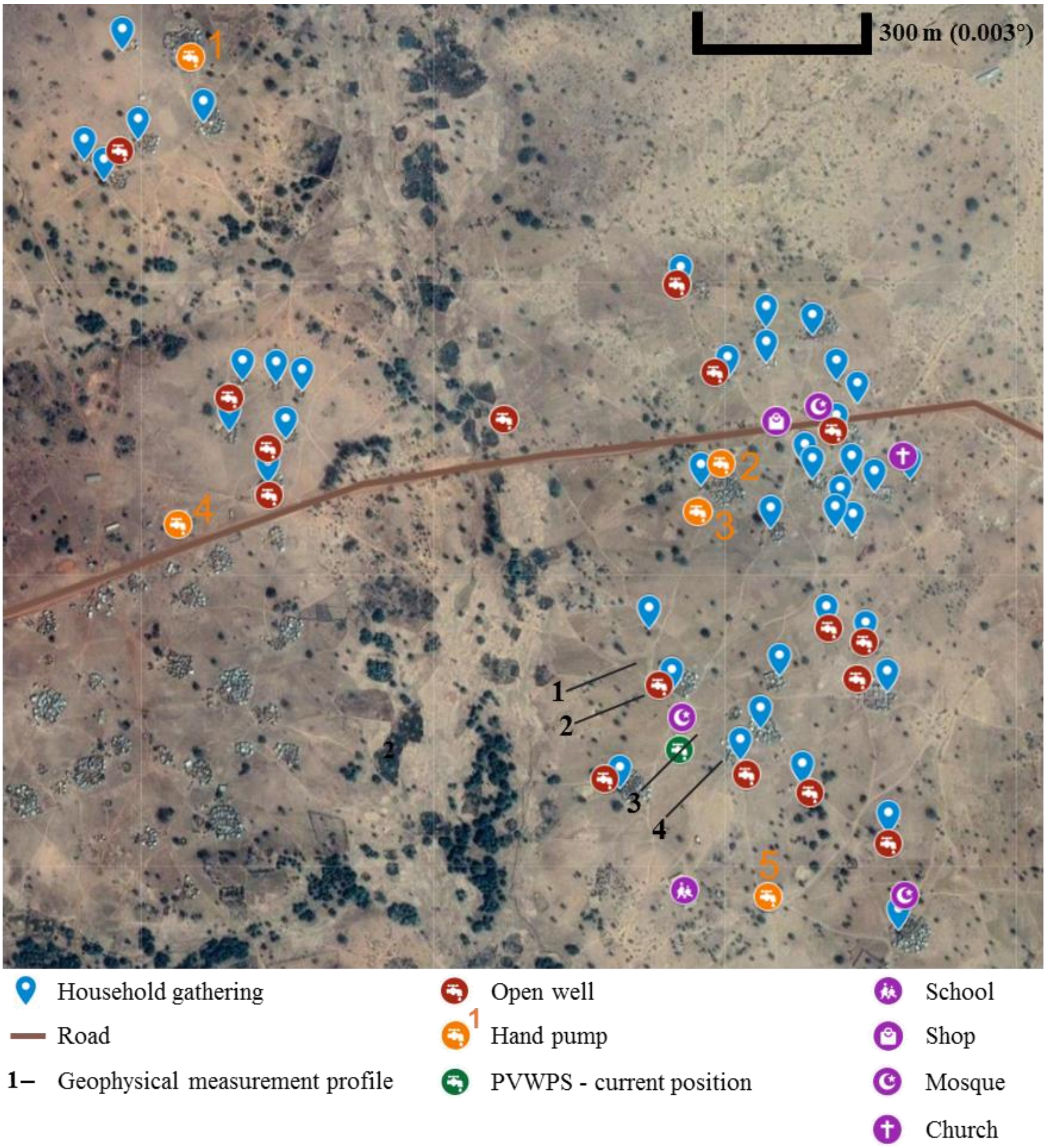


*Figure II-10 – GIS mapping of Gogma.*
*Data collected between the 18 September 2017 and the 10 November 2017.*

### *II.2.3 Geophysical measures*

The geophysical study was realized by the Institut Superieur d'Application des Géosciences (ISAG) by using the very low-frequency electromagnetic method [74]. Geophysical measurements were performed along 4 profiles of 150 m each, which corresponds to scanning a square of ~350×350 m. These profiles are represented in Figure II-10. Measurements along profiles 1, 2 and 4 did not suggest the presences of water along those profiles. On profile 3, there is a specific position that suggested the presence of water. It is at this position that the borehole for the current PVWPS was drilled.

Typically, performing measurements in a square of 350×350 m (i.e. 0.12 $km^2$) takes half a day and costs ~$500. It would therefore be very costly and time consuming to perform geophysical measurements over an entire village of several square kilometres (e.g. Gogma has an area of 4 $km^2$). In addition, it is important to have in mind that these geophysical measurements only provide information about the level of the top of the aquifer, which is not equal to the static water level in the borehole that will be drilled in the case of a confined aquifer [49]. Besides, geophysical measurements do not provide information about the response of the water level in the borehole to water pumping nor about the water quality [49]. This explains why geophysical measurements and groundwater exploration are performed only after the positioning of the PVWPS, i.e. after a position is proposed by the decision maker (see Figure II-6).

### *II.2.4 Account books of water sources*

Account books of the 5 hand pumps and of the PVWPS were accessed by our research group. There is one account book for each hand pump and one account book for the PVWPS. The account book specifies which households go to this source and the cost to collect water at this source. We also remind that we determined that open wells are free of charge through on-field observations (section II.2.1). The cost for each source is given in Table II-3. The hand pumps numbers correspond to the ones presented in Figure II-10.

It is interesting to note that households have to pay annually for hand pumps and monthly for the PVWPS. In addition, we observe that the yearly amount paid for water at hand pumps and at the PVWPS does not depend on the quantity of water consumed.

*Table II-3 – Water sources costs.*

| Source type/number | Price |
|---|---|
| Open wells | $0/year |
| Hand pump 1 | $2.1/year |
| Hand pump 2 | $1.3/year |
| Hand pump 3 | $0.9/year |
| Hand pump 4 | $0.9/year |
| Hand pump 5 | $0.9/year |
| PVWPS | $0.9/month i.e. $10.8/year |

Data collected between 3 October 2017 and 20 June 2018.

### *II.2.5 Household surveys*

#### *II.2.5.1 Description*

Two rounds of household structured surveys were performed. The first round took place in October 2017, before the installation of the PVWPS. The second round took place in October/November 2018, after the installation of the PVWPS. The households surveyed were the same for both survey rounds. 88 households were selected randomly to be surveyed from the 125 households in Gogma[2]. The main points covered by the survey are presented in Table II-4 and all the questions of the survey are available in Appendix A. The survey duration was about 45 minutes. The survey was designed drawing on existing surveys on water and

[2] 90 households were in fact surveyed but 2 are not considered because survey answers for these households are not complete, notably regarding their choice of water source.

electricity access in developing countries (e.g. survey of the SURE-DSS tool [61]). Surveying a large share of the households in Gogma (~70%) and selecting these households randomly allowed us to survey both households that started going to the PVWPS after its installation, and others that did not. Answers to the second round of surveys showed that 22 of the 88 surveyed households go to the PVWPS both during the dry and the wet season.

In this PhD thesis, we use answers to the first survey round as inputs for the demand and impact models (see sections III.2 and III.4) and answers to the second survey round to compare the results of the demand model to experimental measurements (see sections III.2). In the future, comparing the results of the first and second survey rounds may allow us to quantify some local impacts of the installation of the PVWPS of Gogma. This is notably with this in mind that we performed both survey rounds at the same moment of the year (October/November).

*Table II-4 – Themes covered by the household survey.*

| Theme | Description | Survey section (see Appendix A) |
|---|---|---|
| Time and position | Time of survey and GPS position of the surveyed household. | a |
| Household demographic situation | Age, gender, level of education and economic activity of all household members. | a |
| Economic assets | - Number of houses owned and materials of the floor, walls and roof of each house.<br>- Number of phones.<br>- Number of motor bikes and bicycles. | a |
| Access to services | Access to internet, electricity, gas cooking. | a |
| Agricultural activities | Number of fields, quantities of the different crops grown, use of crops grown (self-consumption or selling in the market). | b |
| Livestock | Number and type of the animals owned. | b |
| Health | List of diseases and symptoms contracted by each member of the household in the last month, and associated medical expenses. | c |
| Women’s schedule | Time allocated for their different activities of the day. | d |
| Safety | Perception of the safety in the village (robbers, snakes …) | e |
| Water use | For the dry season and the wet season:<br>- source where water is collected.<br>- daily quantity of water collected for each water use.<br>- time at which water is collected. | f |
| Water sources | For each water source used by the household:<br>- availability of water at the source during the dry season and the wet season.<br>- perception about the water quality at the source<br>- perception about the difficulty to extract water at the source .<br>- cost of using the source.<br>- time spent queuing and extracting water. | f |
| Income and sparings | Income from different sources of revenues (crop and animal sales, sales at shop, wages earned, money received from government, money received from family), and amount of money spared. | g |

First survey round (before installation of the PVWPS): 3 October 2017 to 21 October 2017, second survey round (after the installation of the PVWPS): 27 October 2018 to 6 November 2018.

### *II.2.5.2 Data cleaning*

The answers to questions on ‘water use’ and ‘water sources’ (section F of the survey) will be the most used in this thesis. We observe that ~30% of the households go to different sources between the dry season and the wet season. This is mostly due to the fact that some open wells are not available during the dry season because they are dry. Therefore, some households go to an open well during the wet season but have to go

to a different water source during the dry season. Seasonality will thus be considered in the interdisciplinary model (see Chapter III).

In addition, ~15% of the households go to different sources for different uses for a given season. For instance, for the dry season the household may go to two sources for drinking, cooking and hygiene but may go to a third one for laundry. In this case, we consider the source(s) used for drinking as the destination(s), as drinking is the most critical use in terms of water quality. Finally, ~15% of the households go to two sources for drinking, instead of one, for a given season. In this case, we select randomly one of both sources as the final destination. We made these assumptions, and therefore did not consider that households may use different sources for different uses and that they may use different sources for drinking in the interdisciplinary model (and more specifically in the demand model) because we did not understand the motivation behind these behaviours of the households. This could be the object of future work.

### *II.2.6 Pumping test*

Two types of pumping tests were performed at the PVWPS just after the borehole drilling, in November 2017, by the company Sogedaf.

Firstly, 4 step pumping tests were performed for 4 different flow rates (2.8 $10^{-4}$, 8.3 $10^{-4}$, 1.7 $10^{-3}$ and 1.8 $10^{-3}$ $m^3/s$). For each step pumping test, the water level in the borehole $H_b$ was monitored, with a water level meter [75], during one hour of pumping at a given flow rate and during one additional hour when there was no pumping (recovery phase). Figure II-11 presents the water level in the borehole $H_b$ measured during the 4 step pumping tests. Secondly, a 47 h pumping test was performed. The water level in the borehole $H_b$ was monitored during 36 hours of pumping at a flow rate of 1.8 $10^{-3}$ $m^3/s$ and during an additional 11 hours when there was no pumping (recovery phase). The results are given in Figure II-12.

On these pumping tests we observe that the static water level, i.e. the water level in the borehole when there is no pumping, is equal to -6 m at this time of the year. The decrease of $H_b$ from this static water level while pumping corresponds to the dynamic behaviour of the water level in the borehole. Following these measurements, Sogedaf highlighted that the maximum flow rate that can be pumped from the borehole $Q_{p,max}$ is equal to 1.8 $10^{-3}$ $m^3/s$. However, Sogedaf did not explain the choice of this value for $Q_{p,max}$ and did not model the response of the water level in the borehole $H_b$ to pumping.

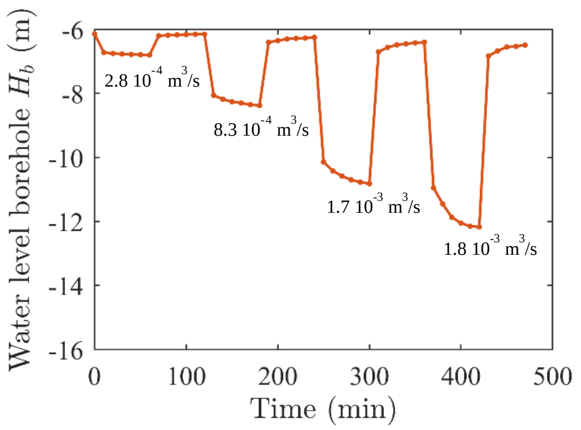


*Figure II-11 – Water level in the borehole measured during the step pumping tests. Test performed on 5 November 2017 by Sogedaf.*

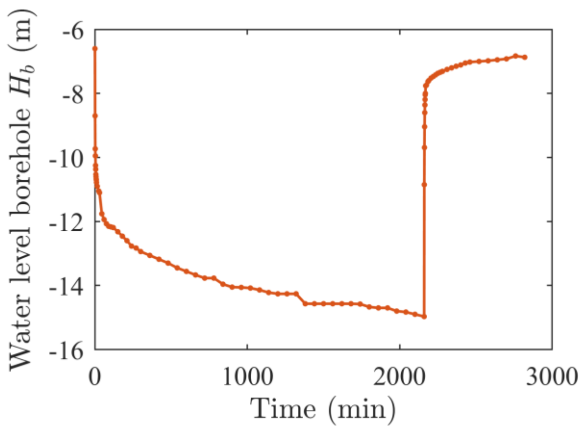


*Figure II-12 – Water level in the borehole measured during the long pumping test (pump flow rate: 1.8 $10^{-3}$ $m^3/s$). Test performed on 8 and 9 November 2017 by Sogedaf.*

## *II.2.7 Water quality data*

All the water quality tests were performed by the Laboratoire Aina [72].

### *II.2.7.1 Physico-chemical tests*

The physico-chemical tests were performed only at the PVWPS. They took place during the pumping tests on 7 November 2017. Laboratoire Aina measured the physico-chemical parameters of the water amongst which the pH, temperature, alkalinity, electrical conductivity, arsenic concentration. These measurements were compared to the physico-chemical quality standards for drinking water in Burkina Faso. The physico-chemical quality of water fulfilled the requirements for consumption.

### *II.2.7.2 Bacteriological tests*

Bacteriological tests on all the open wells and hand pumps were performed on 14 November 2017 and the test on the PVWPS was performed on 27 February 2018. For each source, Laboratoire Aina measured the concentration of total coliform, thermotolerant coliform and faecal streptococci. The results of the water quality tests are summarized in Table II-5.

*Table II-5 – Results of bacteriological tests performed by Laboratoire Aina [72].*

| Source | Number of sources | Concentration of total coliform (CFU/100mL) | Concentration of thermotolerant coliform (CFU/100mL) | Concentration of faecal streptococci (CFU/100mL) |
|---|---|---|---|---|
| Open well | 16 | Mean: 441; Std: 482; Min: 0; Max: 1688 | Mean: 222; Std: 311; Min: 0; Max: 800 | Mean: 377; Std:264; Min: 44; Max: 816 |
| Hand pump | 5 | Mean: 0; Std: 0; Min: 0; Max: 0 | Mean: 0; Std: 0; Min: 0; Max: 0 | Mean: 0; Std:0; Min: 0; Max: 0 |
| PVWPS | 1 | Mean: 0; Std: 0; Min: 0; Max: 0 | Mean: 0; Std: 0; Min: 0; Max: 0 | Mean: 0; Std: 0; Min: 0; Max: 0 |

Std: standard deviation. Numbers higher than zeros are in red.
Tests performed on 14 November 2017 and on 27 February 2018.

According to international recommendations, in drinking water, there should be 0 CFU/100mL total coliform [76], 0 CFU/100mL thermotolerant coliform [76] and 0 CFU/100mL faecal streptococci [77]. Therefore, according to Table II-5, water from all open wells is not suitable for drinking in terms of bacteriological quality and water from all hand pumps and from the PVWPS is suitable (see Table II-5).

Therefore, the bacteriological tests show that the water at open wells is not potable, which was expected based on the literature (see section I.1.1).

We did not perform physico-chemical tests at the hand pumps of the village for budgetary reasons (~\$140 for each test, see Table II-2) and because these physico-chemical tests were already performed when the hand pumps were installed and they showed that the water is suitable for drinking in terms of physico-chemical quality (otherwise the hand pumps could not have been opened to consumption). Consequently, in Gogma, the water from the hand pumps and from the PVWPS is potable, which was expected based on the literature (see section I.1.1).

The comparison of the water quality tests results to the water quality perceived by the households, which is obtained through the surveys (see section II.2.5) and on-field observations (see section II.2.1), shows that households have a good perception of water quality: in general, they know that the water at open wells is not potable (i.e. low water quality) and that the water at sealed boreholes (hand pumps and PVWPS) is potable (i.e. high water quality).

### *II.2.8 Monitoring of the PVWPS of Gogma*

The quantities measured in the frame of the monitoring of the PVWPS of Gogma are presented in Table II-6. In this table, the pump flow rate $Q_p$ is the flow rate extracted from the borehole and is measured thanks to a flow meter set on PA1 (see Figure II-7). The consumption flow rate $Q_c$ corresponds to the water collected by the inhabitants at the fountain. This flow rate is the amount of water retrieved from the water tank and is measured by setting up a flow meter on PA2.

Most of the quantities of Table II-6 have been collected since January 2018 thanks to a data logger that we developed. The data logger is powered by external PV modules (different from the ones of the PVWPS) and the recorded data are collected by using a USB stick. This data logger was conceived with the idea of minimizing its cost in order to encourage its use for monitoring other PV water pumping installations. The architecture and a picture of the data logger are shown in Figure II-13. The data logger permits to collect data with a time step of ~2.2 s and the recording rate is equal to the frequency of acquisition. In February 2019, an independent hydrostatic pressure sensor was added to measure the water level in the borehole $H_b$. The water level in the borehole is measured with a time step of 1 minute. For convenience, all the measured data were rescaled to an equally spaced temporal resolution of 1 min by nearest interpolation for this PhD thesis.

*Table II-6 – Data monitored by the data logger.*

| Measured data | Type of sensor | Model of sensor | Location of sensor | Frequency (Samples/min) | Sensor accuracy | Period of data collection |
|---|---|---|---|---|---|---|
| Irradiance on the plane of the PV modules ($G_{pv}$) | Calibrated photovoltaic cell & Data logger | Solems RG100 | On the plane of the PV modules | 27 | ± 10% | 14 Jan 2018 - present |
| Ambient temperature ($T_a$) | Platinum resistance thermometer & Data logger | RS Pro PT1000 | In the shadow, next to the PV modules | 27 | ± 0.05% | 14 Jan 2018 - present |
| PV modules temperature ($T_{pv}$) | Platinum resistance thermometer & Data logger | RS Pro PT1000 | On the back of a PV module | 27 | ± 0.05% | 14 Jan 2018 - present |
| Voltage of the PV array ($V_{pv}$) | Voltage transducer & Data logger | LEM LV 25P | At the output of the PV array | 27 | ± 0.9% | 14 Jan 2018 - present |
| Current from the PV array ($I_{pv}$) | Current transducer & Data logger | LEM LA 55P | At the output of the PV array | 27 | ± 0.9% | 14 Jan 2018 - present |
| Pump flow rate ($Q_p$) | Turbine flow sensor & Data logger | HaiHuiLai YF-DN40 | On PA1 | 27 | ± 5% | 14 Jan 2018 - present |
| Consumption flow rate ($Q_c$) | Turbine flow sensor & Data logger | HaiHuiLai YF-DN40 | On PA2 | 27 | ± 5% | 14 Jan 2018 - present |
| Water level in the borehole ($H_b$) | Hydrostatic pressure sensor | DCX-22 SG | In the borehole | 1 | ± 0.1% | 8 Feb 2019 - present |

Data collected from 14 January 2018.

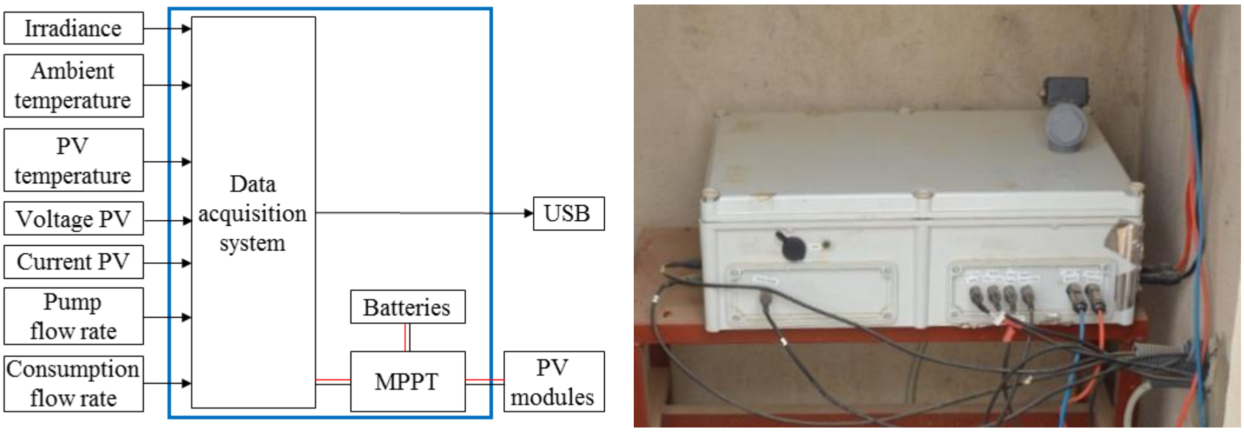


*Figure II-13 – Data logger developed for monitoring the PVWPS of Gogma.*

Figure II-14 presents an example of data collected by the data logger on the 19 February 2019. The interruptions in the pump flow rate profile (at 9h43 and 13h55) correspond to the moments at which the water level in the tank $H_t$ has reached the stop level $H_{t,s}$, which means that the tank is full. When water pumping is interrupted, the PV modules are in open circuit. As the water level in the tank can be directly deduced from the pump and the consumption flow rate, which are both measured, it is also considered as measured. Moreover, in order to avoid a shift of this measured water level in the tank, which may come

from the uncertainty on the flow meters measurements, we reset the measured water height to $H_{t,s}$ each time the tank is full. During the whole record history of the PVWPS, the water level in the tank has always remained higher than 0 m. This means that the sizing of the PVWPS is such that all the households that wish to go to the PVWPS are able to collect water there. The PVWPS is said to be 'oversized'.

To our best knowledge, it is the first time that experimental measurements have been collected on a PVWPS for domestic water access in a rural village and on a PVWPS located in sub-Saharan Africa [78], and we have the objective of monitoring the PVWPS of Gogma during its whole lifetime. This unique database can therefore help to study the performance and the sustainability of photovoltaic water pumping in sub-Saharan Africa and for domestic water access.

More generally, this database can also be used for other studies related to photovoltaic systems in rural villages in sub-Saharan Africa. For instance, we used it for the detection of cleaning interventions on photovoltaic modules by using machine learning algorithms [79]. In addition, the monitoring of the PVWPS and the development of the data logger was at the origin of the "Axo" project, which focuses on the potential of big data for PVWPS in rural areas [80]. Finally, we built a second data logger, that is installed on a photovoltaic water pumping pilot at the University of Paris-Saclay. The pilot and the associated data logger are notably used for teaching projects on energy conversion, testing motor-pumps from manufacturers and training students that will undertake humanitarian work in developing countries.

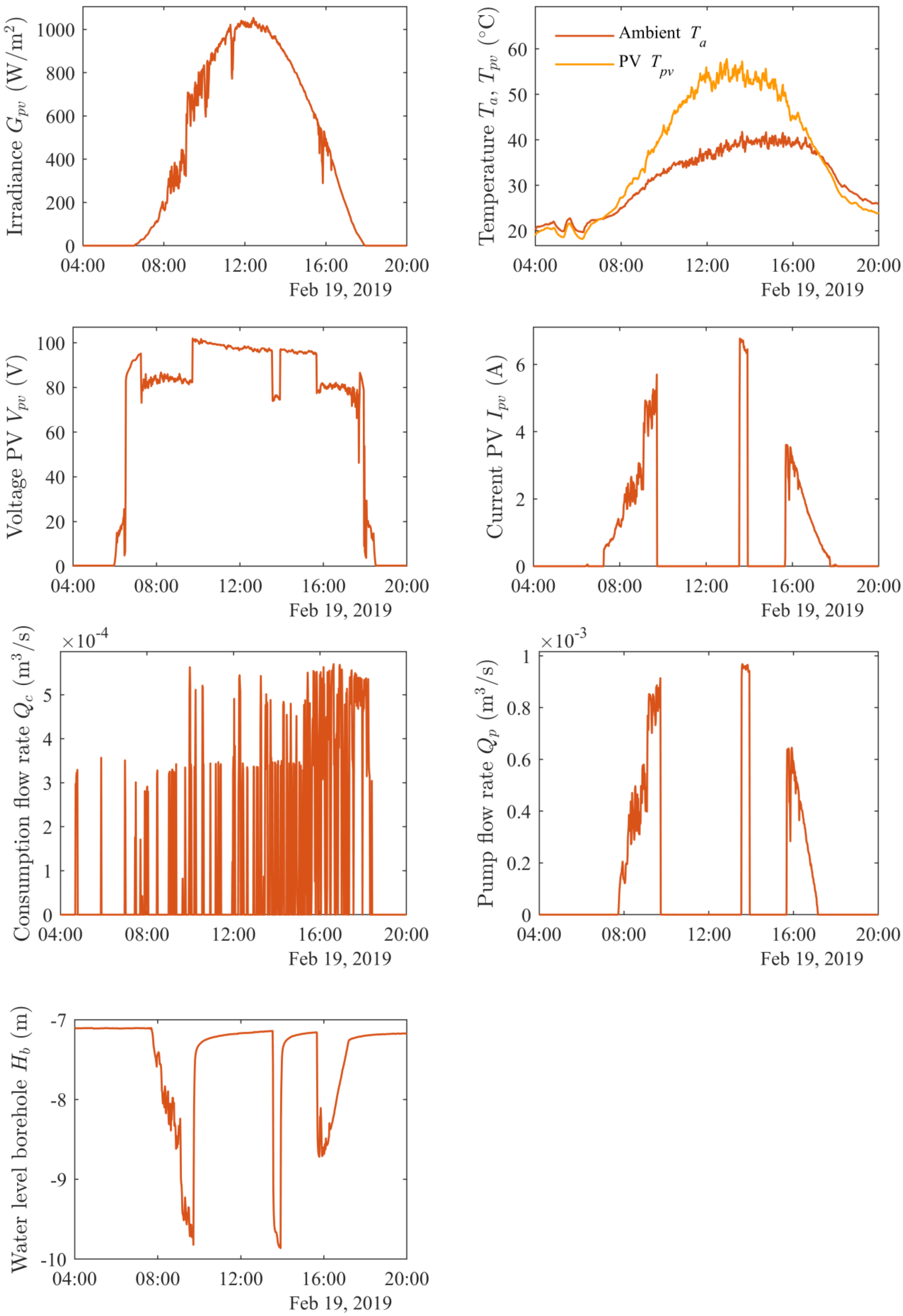


*Figure II-14 – Example of data collected by the data logger.*

## II.3 Partial conclusion

In this chapter, firstly, we presented the rural village of Gogma in Burkina Faso where we installed a PVWPS. We highlighted the complexity of the global water situation in Gogma where 125 households collect water at 22 sources. We detailed the conventional procedure that was followed for installing the PVWPS and we provided a technical description of the system (architecture, components).

Secondly, we described the experimental data that we have been collecting in Gogma. The following data were collected:

- On-field observations were performed during the 8 months of fieldwork of members of our research group.
- The GPS coordinates of the households, water sources and important points of the village were gathered.
- Geophysical measures were performed, before the installation of the PVWPS, in order to detect the presence of water.
- The cost to collect water at each source was determined through the account books of the sources.
- 88 randomly selected households were surveyed both before and after the installation of the PVWPS.
- Pumping tests were undertaken to quantify the effect of water pumping on groundwater resources.
- Bacteriological analyses were performed for all water sources of the village in order to quantify their quality.
- The operation of the PVWPS has been monitored continuously since January 2018 thanks to a data logger that we have built and installed.

# Chapter III Interdisciplinary model

# Chapter III Interdisciplinary model

In this PhD thesis, we aim at performing an optimisation to determine the sizings and the positions of the PVWPS that minimize its life-cycle cost and maximise its positive socio-economic impact. To do so, the first step is to build a model that relates the optimisation variables, which are associated to the sizing and the position of the PVWPS, to the objective functions of the optimisation, which are the life-cycle cost of the PVWPS and its socio-economic impact. The proposed interdisciplinary model is presented in this chapter. Then, in Chapter IV, we will show how this model is used for the optimisation.

In section III.1, we present an overview of the interdisciplinary model and introduce the different sub-models that compose it. Then, from section III.2 to section III.5 we detail the sub-models: the demand model in section III.2, the technical model in section III.3, the impact model in section III.4 and the economic model in section III.5.

## III.1 Overview

The block diagram of the interdisciplinary model is presented in Figure III-1. The 4 sub-models (demand, technical, impact and economic) are shown on this diagram.

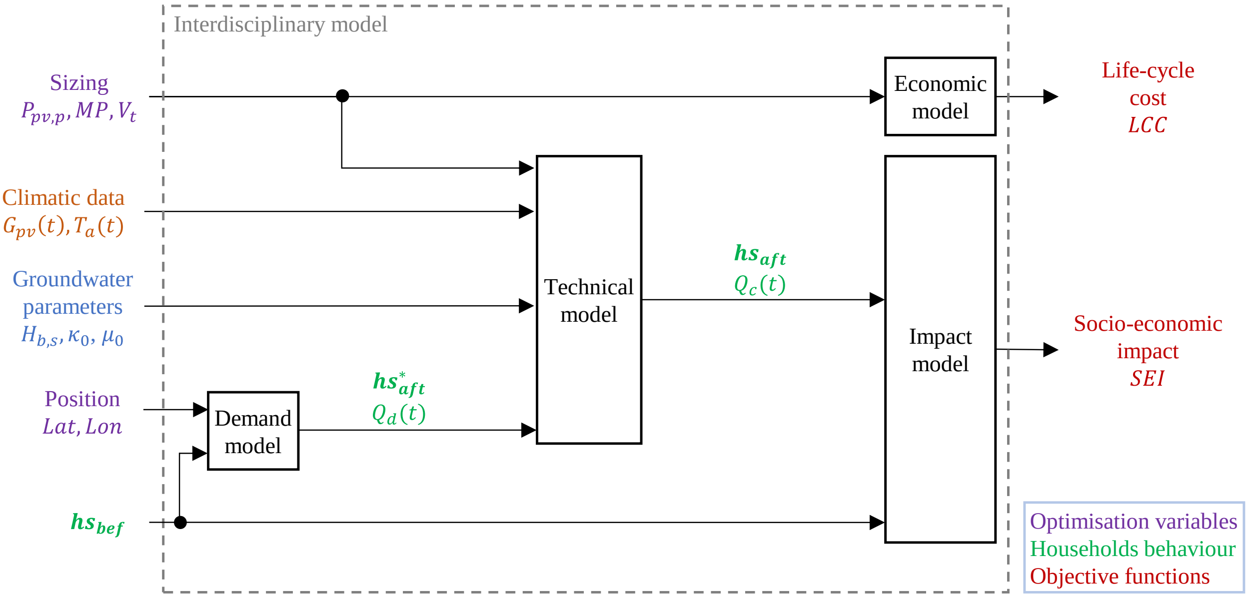


*Figure III-1 – Block diagram of the interdisciplinary model.*
*$\boldsymbol{hs_{bef}}$: water sources where the households go before the installation of the PVWPS, $\boldsymbol{hs^*_{aft}}$: water sources where the households wish to go after installation of the PVWPS, $Q_d$: water demand at the PVWPS, $\boldsymbol{hs_{aft}}$: water sources where the households effectively go after installation of the PVWPS, $Q_c$: water consumption at the PVWPS.*

The inputs of the interdisciplinary model can be grouped into 4 categories:

1. *Optimisation variables*. We distinguish two types of optimisation variables: (1) the sizing variables of the PVWPS and (2) the position of the PVWPS in the village, which is given by its longitude $Lon$ and its latitude $Lat$. These sizing variables include the peak power of the PV array in standard test conditions (STC) $P_{pv,p}$, the reference of motor-pump $MP$ and the volume of the water tank $V_t$. These particular three sizing variables are chosen based on the existing literature (see section I.3.3) and on a sensitivity analysis that we performed in article [81], which showed that these three variables have the highest influence on the operation of PVWPS.
2. *Climatic data*. Climatic data are composed of the irradiance on the plane of the PV array $G_{pv}$ and the ambient temperature $T_a$.
3. *Groundwater parameters*. The groundwater parameters are the static water level in the borehole $H_{b,s}$ (i.e. the water level in the borehole when there is no pumping) and the aquifer losses coefficient $\kappa_0$ and the borehole losses coefficient $\mu_0$. $\kappa_0$ and $\mu_0$ characterize the dynamic behaviour of the water level in the borehole. The parameters $H_{b,s}$, $\kappa_0$ and $\mu_0$ depend on the groundwater resources in the considered village.
4. *Water sources where the households go before installation of the PVWPS*: $\boldsymbol{hs_{bef}}$. More specifically, $\boldsymbol{hs_{bef}}$ is a vector, of length the number of households in the village $n_v$, which specifies, for each household, the water source where it goes before the installation of the PVWPS.

The outputs of the interdisciplinary model are the two objective functions of the optimisation: the life-cycle cost $LCC$ of the PVWPS and its socio-economic impact $SEI$.

In Figure III-1, $\boldsymbol{hs}_{\boldsymbol{aft}}^{*}$ is a vector of length $n_v$ which indicates, for each household, the water source where it *wishes to go after* the installation of the PVWPS and $Q_d(t)$ is the corresponding *water demand* at the PVWPS. $\boldsymbol{hs}_{\boldsymbol{aft}}$ is a vector of length $n_v$ which indicates, for each household, the water source where it *effectively goes after* the installation of the PVWPS and $Q_c(t)$ is the corresponding *water consumption*. If the PVWPS is 'oversized', all the households that wish to go to the PVWPS can go there ($\boldsymbol{hs}_{\boldsymbol{aft}} = \boldsymbol{hs}_{\boldsymbol{aft}}^{*}$) and the water consumption is equal to the water demand ($Q_c(t) = Q_d(t)$). If the PVWPS is 'undersized', all the households that wish to go to the PVWPS cannot go there ($\boldsymbol{hs}_{\boldsymbol{aft}} \neq \boldsymbol{hs}_{\boldsymbol{aft}}^{*}$) and the water consumption is not equal to the water demand, ($Q_c(t) \neq Q_d(t)$).

Regarding the four sub-models:

- The *demand model* is an econometric model which predicts the water sources where the households wish to go after installation of the PVWPS from the position of the PVWPS in the village and the water sources where the households go before installation of the PVWPS.
- The *technical model* allows to identify the households that can effectively go to the PVWPS amongst the households that wish to go to the PVWPS. This model considers the climatic conditions, the groundwater parameters and the sizing of the PVWPS. It simulates the different stages of the energy conversion chain within the PVWPS.
- The *impact model* permits to evaluate the socio-economic impact $SEI$ associated with the changes in water sources between before and after the installation of the PVWPS.
- The *economic model* allows to determine the life-cycle cost $LCC$ of the PVWPS from the values of the sizing variables. The model takes into account the capital and operational costs and the time value of money.

These four sub-models are further detailed in the following sections.

For the case of Gogma, some open wells are not available during the dry season because they are dry. Therefore, some households go to an open well during the wet season but have to go to a different water source during the dry season (see section II.2.5.2). Consequently, the vectors $\boldsymbol{hs}_{\boldsymbol{bef}}$, $\boldsymbol{hs}_{\boldsymbol{aft}}^{*}$ and $\boldsymbol{hs}_{\boldsymbol{aft}}$ are not the same between the dry season and the wet season. In addition, the demand, technical and impact models are evaluated once for the dry season and once for the wet season. For the application of the model to Gogma, we consider that the dry season lasts from 1 December 2017 to 30 June 2018 and that the wet season lasts from 1 July 2018 to 30 November 2018.

## III.2 Demand model

The block diagram of the demand model is shown in Figure III-2. During the first step (section III.2.1) we determine, for each household, the water source where it wishes to go after the installation of the PVWPS $\boldsymbol{hs^*_{aft}}$ from the position of the PVWPS in the village $(Lat, Lon)$ and the water source choice of each household before installation of the PVWPS $\boldsymbol{hs_{bef}}$. During the second step (section III.2.2), we determine the evolution of the water demand $Q_d$ at the PVWPS from $\boldsymbol{hs^*_{aft}}$. Our demand model builds on the related MSc thesis project undertaken by Vitali Caplain in 2018 [82]. To the best of our knowledge, it is the first model that predicts the water demand profile at water sources of a rural village, considers the inclusion of a new type of water source and accounts for the seasonality in the water demand.

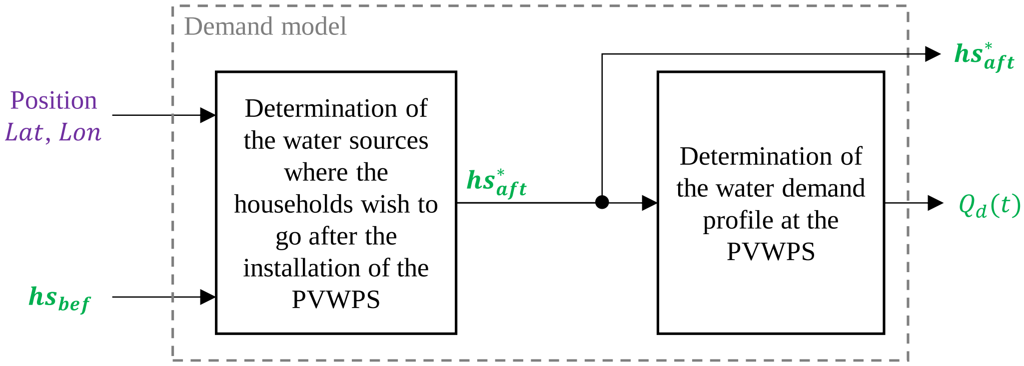


*Figure III-2 – Block diagram of the demand model.*
*$\boldsymbol{hs_{bef}}$: water sources where the households go before the installation of the PVWPS, $\boldsymbol{hs^*_{aft}}$: water sources where the households wish to go after the installation of the PVWPS, $Q_d$: water demand at the PVWPS.*

### *III.2.1 Determination of the water sources where the households wish to go after installation of the PVWPS*

In section III.2.1.1, we use the data collected in the household survey regarding water source choice before the installation of the PVWPS $\boldsymbol{hs_{bef}}$ to build an econometric model that predicts the choice of water source of each household. In section III.2.1.2, this model will then be applied to predict the water sources where the households wish to go after the installation of the PVWPS $\boldsymbol{hs^*_{aft}}$.

#### *III.2.1.1 Building the regression using the water source choice before installation of the PVWPS*

In this section, we consider only the surveyed households $\boldsymbol{h_{sur}}$ and the water sources that were there before the installation of the PVWPS (i.e. 16 open wells and 5 hand pumps for Gogma).

The probability $\rho(h, s)$ that the household $h$ goes to the water source $s$ is obtained by a linear regression:

$$\rho(h, s) = \beta_0 + \sum_i \beta_i \cdot \pi_i(h, s) \tag{1}$$

where $\beta_i$ are the regression coefficients and $\pi_i$ are the predictors of the water source choice ($\pi_i(h, s)$ is the value of the predictor $\pi_i$ for the household $h$ and the source $s$). The main advantage of the linear regression is that the regression coefficients $\beta_i$ obtained are easy to interpret. In addition, we also tried a logistic regression without significant improvement in the prediction accuracy [82].

**Firstly**, we identify the potential predictors $\pi_i$ of the water source choice through a literature review:

- *Distance household-source ($\pi_d$).* The distance between the household and the water source is negatively correlated to the likelihood of choosing the water source [83].
- *Water cost ($\pi_{wc}$).* The lower the cost of water at a source, the higher the will to use the source [84].
- *Perceived water quality ($\pi_{pwq}$).* The lower the perceived quality of the water from the source, the lower the will to use the source [84].
- *Extraction easiness ($\pi_{ee}$).* People are more likely to choose a water source if water collection at this source is easy [85].
- *Time collecting water ($\pi_{tcw}$).* The time collecting water is equal to the sum of the time spent queuing and of time spent extracting water. The time collecting water at a given source is negatively correlated to the likelihood of choosing the source [83].

**Secondly**, each predictor is quantified for the considered village. The methods of quantification of the predictors for Gogma are presented in Table III-1. Thanks to the data collected through GIS mapping (sections II.2.2) and water sources account books (section II.2.4) and household surveys (section II.2.5), it is possible to compute the value of each predictor $\pi_i$ for each household $h$ and water source $s$: $\pi_i(h, s)$.

*Table III-1 – Quantification of predictors in the case of Gogma.*

| Predictor | Method of quantification | Possible values |
|---|---|---|
| Distance household-source ($\pi_d$) | For each household, we calculated the straight line distance between the household and the water sources of Gogma from GPS coordinates. The choice of the straight line distance is justified in [86]. | Euclidean distance in meters |
| Water cost ($\pi_{wc}$) | The cost for collecting water at each source was obtained through account books and on-field observations. For a given source $s$, the water cost is the same for all households $h$. | Monthly cost in $ |
| Perceived water quality ($\pi_{pwq}$) | In the survey, each household was asked about how it perceives the water quality at the source it uses. It could choose between: 0 (high quality) and 1 (low quality). However, we do not know how the households perceives water quality at a source where it does not go. We extrapolate missing data by looking at the answers of the households that go to this source (we take the average of their answers). | 0 (high perceived quality) – 1 (low perceived quality) |
| Extraction easiness ($\pi_{ee}$) | In the survey, each household was asked about the arduousness to collect water at the source it uses. It could choose between: 0 (not arduous), 1 (arduous), 2 (very arduous). Missing data are extrapolated in the same way as for the perceived water quality. | 0 (not arduous) – 2 (very arduous) |
| Time collecting water ($\pi_{tcw}$) | In the survey, each household was asked about the time it takes to collect water at the source it uses. Missing data are extrapolated in the same way as for the perceived water quality. | Time in minutes |

**Thirdly**, we select the predictors to include in the model. We remind that the final objective and the originality of the demand model is to predict which households wish to go to a water source of a new type, i.e. the PVWPS (see section I.4). According to this objective, we propose to add an original step in the design of the demand model. This step consists in analysing the risks of using some predictors, knowing that they will be used to predict demand at a source of a new type. In the case of Gogma, we found the following risks associated with using the predictors $\pi_{tcw}$, $\pi_{wc}$ and $\pi_{ee}$:

- *For the predictor $\pi_{tcw}$ (time collecting water), it is difficult to assume an accurate value for the time collecting water at the PVWPS*. Indeed, this value depends on many unknown factors such as the attendance at the PVWPS and the management scheme adopted at the PVWPS.
- *For the predictor $\pi_{wc}$ (water cost) and the predictor $\pi_{ee}$ (extraction easiness), the value of the predictor for the PVWPS is expected to be out of the range of the values of the predictor for the water sources available before the installation of the PVWPS*. More specifically, for the predictor $\pi_{wc}$, water collection at open wells is free and it costs ~\$1/year at hand pumps, but it costs ~\$11/year at the PVWPS (see section II.2.4). For the predictor $\pi_{ee}$, extraction is 'very hard' at open wells ($\pi_{ee}$~2) and 'hard' at hand pumps ($\pi_{ee}$~1) but it is expected to be 'easy' at the PVWPS ($\pi_{ee}$~0) (see section II.2.1). Consequently, as the determination of the regression coefficients $\beta_i$ is performed only with the water sources available before the installation of the PVWPS, there is a large risk of error when using these $\beta_i$ coefficients to predict the households that wish to go to the PVWPS. In other words, we do not know how the households would react to a source for which water collection would cost \$11/year or for which water extraction would be 'easy' ($\pi_{ee}$~0), because this type of source was not considered for the identification of the $\beta_i$ coefficients of the model.

On the contrary, for the predictor $\pi_{pwq}$ (perceived water quality), we can reliably assume that the perceived water quality at the PVWPS will be high (~0). Indeed, according to on-field observations, inhabitants have a high perception of the water quality at sealed boreholes like the PVWPS (see section II.2.1). Besides, the values of $\pi_{pwq}$ used for the identification are within 0 and 1, as $\pi_{pwq}\sim1$ for open wells and $\pi_{pwq}\sim0$ for hand pumps. Thus, the perceived water quality at the PVWPS ($\pi_{pwq}$~0) is within the range of perceived water quality used for the identification ($\pi_{pwq}$ between 0 and 1).

We also analyse the multicollinearity between predictors. Indeed, if two predictors are correlated, they may not be both required in the prediction model and therefore it may be possible not to use some of the predictors, which are associated with some risk when the PVWPS will be added to the available sources. We compute the multicollinearity matrix for each season by using the values of the predictors for each association household/source. The results are given in Table III-2. The small differences in correlation coefficients between the dry and wet seasons come from the fact that some open wells are not available during the dry season. According to [87], two predictors are strongly correlated if the correlation coefficient between these two predictors is not within -0.4 and 0.4. In Table III-2, we write in red the values of the correlation coefficients that are not within -0.4 and 0.4.

*Table III-2 – Multicollinearity matrix for Gogma.*

| | Distance household-source ($\pi_d$) | Water cost ($\pi_{wc}$) | Perceived water quality ($\pi_{pwq}$) | Extraction easiness ($\pi_{ee}$) | Time collecting water ($\pi_{tcw}$) |
|---|---|---|---|---|---|
| Distance household-source ($\pi_d$) | | | | | |
| Water cost ($\pi_{wc}$) | Dry: 0.14<br>Wet: 0.13 | | | | |
| Perceived water quality ($\pi_{pwq}$) | Dry: -0.09<br>Wet: -0.08 | Dry: -0.90<br>Wet: -0.91 | | | |
| Extraction easiness ($\pi_{ee}$) | Dry: -0.01<br>Wet: -0.03 | Dry: -0.61<br>Wet: -0.70 | Dry: 0.65<br>Wet: 0.76 | | |
| Time collecting water ($\pi_{tcw}$) | Dry: -0.15<br>Wet: -0.12 | Dry: 0.43<br>Wet: 0.49 | Dry: -0.57<br>Wet: -0.63 | Dry: -0.41<br>Wet: -0.44 | |

In red: values of the correlation coefficients that are not within -0.4 and 0.4.

Results indicate that the predictor $\pi_d$ (distance household-source) is not strongly correlated with any other predictor. However, we observe that there are signs of correlation between the predictors $\pi_{wc}$ (water cost), $\pi_{pwq}$ (perceived water quality), $\pi_{ee}$ (extraction easiness), and $\pi_{tcw}$ (time collecting water). Therefore, given the risk analysis performed above, we propose to consider the predictors $\pi_d$ and $\pi_{pwq}$, instead of other possible combinations of predictors (e.g. $\pi_d/\pi_{wc}$, $\pi_d/\pi_{ee}$ …). Equation (1) therefore becomes:

$$\rho(h,s) = \beta_0 + \beta_d \cdot \pi_d(h,s) + \beta_{pwq} \cdot \pi_{pwq}(h,s) \quad (2)$$

where $\pi_d(h,s)$ is the distance between the household $h$ and the source $s$ and $\pi_{pwq}(h,s)$ is the perception of household $h$ of the water quality at the source $s$. $\beta_d$ and $\beta_{pwq}$ are the regression coefficients associated to the $\pi_d$ and $\pi_{pwq}$ predictors respectively.

**Fourthly**, we identify the $\beta_i$ coefficients. For this identification, the values of the probability $\rho(h,s)$ are needed (see equation (1)). For this purpose, we use the data collected on the households $\boldsymbol{h_{sur}}$ (i.e. households part of the survey pool). Indeed, thanks to these data we know the source to which each household goes. We therefore deduce the 'measured' values of $\rho(h,s)$ as following: for the household $h$, for the source $s$ where it goes we set $\rho(h,s) = 1$ and, for all the other water sources we set $\rho(h,s) = 0$. We identify the $\beta_i$ coefficients by using the data of 70% of the households $\boldsymbol{h_{sur}}$. The 70% of households are selected randomly. Then, we predict the source choice of the remaining 30% of the households thanks to the values of the predictors and the identified $\beta_i$ coefficients (see equation (1)). The predicted source choice of the household $h$ is the one that maximizes $\rho(h,s)$. The predictions are compared to the real source choice of the households before the installation of the PVWPS. For each household, either the regression predicts the real source choice and it is a success; or it does not predict the real source choice and it is a failure. Dividing the number of successes, i.e. when the prediction matches the real source choice, by the number of predictions gives us the 'prediction rate before the installation of the PVWPS' $\phi_{bef}$. For instance, if we were to randomly select the source choice of Gogma's households, the prediction rate $\phi_{bef}$ would be equal to 1/21=5%, as there were 21 sources before the installation of the PVWPS.

In the case of Gogma, we identify the regression coefficients and we compute the prediction rate $\phi_{bef}$ separately for the dry season and the wet season, as the source choice depends on the season (see

section III.1). Additionally, $\boldsymbol{h_{sur}}$ contains 88 households for Gogma. Therefore, the values of the $\beta_i$ coefficients and of $\phi_{bef}$ depend on the 70% of the households selected for identifying the $\beta_i$ coefficients and of the 30% of the households selected for computing $\phi_{bef}$. To mitigate this problem, we perform the following sequence 1000 times:

- Select 70% of the 88 households randomly. Determine the values of $\beta_0$, $\beta_d$ and $\beta_{pwq}$ with the data from these 70% of households.
- Use the remaining 30% of household to compute the prediction rate $\phi_{bef}$.

Then, the final value of $\beta_0$ is the average of the 1000 values of $\beta_0$ obtained (same for $\beta_d$ and $\beta_{pwq}$). The final prediction rate is the average of the 1000 prediction rates obtained. The final values encountered for $\beta_0$, $\beta_d$ and $\beta_{pwq}$ and for the prediction rate $\phi_{bef}$ are given in Table III-3. In addition, for all of the 1000 repetitions, the p-values of the 'distance household-source' predictor and of the 'perceived water quality' predictor are smaller than 0.01. This shows that both predictors have statistical significance [88].

*Table III-3 – Values of the regression coefficients and of the prediction rate before installation of the PVWPS – case of Gogma.*

| season | $\beta_0$ | $\beta_d$ ($m^{-1}$) | $\beta_{pwq}$ | Prediction rate before installation of the PVWPS $\phi_{bef}$ |
|---|---|---|---|---|
| dry | 0.28 | -0.00015 | -0.13 | 62% |
| wet | 0.24 | -0.00013 | -0.09 | 48% |

The coefficient $\beta_d$ is negative. This means that the higher the distance $\pi_d(h, s)$ between the household $h$ and the source $s$, the lower the probability $\rho(h, s)$ that the household $h$ chooses the source $s$. The coefficient $\beta_{pwq}$ is also negative. This means that the worse the perception that the household $h$ has of the water quality at the source $s$ ($\pi_{pwq}(h, s)$ close to 1), the lower the probability $\rho(h, s)$. These results on the distance and the perceived water quality are consistent with the literature.

### *III.2.1.2 Integrating the PVWPS*

In order to be able to predict the choice of water source of all the households of the village after the installation of the PVWPS $\boldsymbol{hs^*_{aft}}$, we have to integrate the PVWPS and the households that are not part of $\boldsymbol{h_{sur}}$ (i.e. not part of the survey pool).

*We first focus on the integration of the PVWPS.* We need to be able to compute the value of each predictor $\pi_i$ for an household $h$ and the PVWPS: $\pi_i(h, PVWPS)$. For Gogma, the distance between the PVWPS, located at the position ($Lat$, $Lon$), and any household $h$ of the village can be computed from the GPS coordinates (see section II.2.2). In addition, as justified in section III.2.1.1, we consider that all the households perceive the water quality at the PVWPS as high: $\pi_{pwq}(h, PVWPS) = 0, \forall h$.

Consequently, thanks to the application of equation (2), we can predict the source where each household wishes to go, for any position ($Lat$, $Lon$) of the PVWPS in the village. For the households that are predicted not to wish to go to the PVWPS, we do not keep the prediction of the model in $\boldsymbol{hs^*_{aft}}$. Instead we consider that these households remain using the same water source where they used to go before the installation of the PVWPS.

It is possible to propose a first validation of the prediction of the households that wish to go to the PVWPS thanks to the available data. Indeed, for the position of the current PVWPS (see Figure II-10), we can predict the households that wish to go to the PVWPS and we also know the households that in reality go to the PVWPS, thanks to the account book of the PVWPS (see section II.2.4) and the household surveys (see section II.2.5). Moreover, as the current PVWPS is oversized, all the households that wish to go there are able to do so (see section II.2.8). In order to compare the prediction to the reality we distinguish four cases presented in Table III-4.

*Table III-4 – Four possibilities for the prediction result at the current PVWPS of Gogma.*

| Prediction from the model | Reality as per surveys and account books | Success or failure of the prediction |
|---|---|---|
| Household wishes to go to the PVWPS | Household wishes to go to the PVWPS | Success |
| Household wishes to go to the PVWPS | Household does not wish to go to the PVWPS | Failure |
| Household does not wish to go to the PVWPS | Household wishes to go to the PVWPS | Failure |
| Household does not wish to go to the PVWPS | Household does not wish to go to the PVWPS | Not relevant |

As the current PVWPS is oversized, all the households that wish to go there are able to do so.

We define the prediction rate at the PVWPS as: $\phi_{aft,PVWPS} = \frac{number\ of\ successes}{number\ of\ successes + number\ of\ failures}$. We obtain a prediction rate at the PVWPS $\phi_{aft,PVWPS}$ of 91% for the dry season and of 91% for the wet season. This means that we predict with more than 90% accuracy, the households that wish to go to the PVWPS. We can expect the accuracy of the model to be similar for other positions of the PVWPS in the village. Indeed, the identification of the $\beta_i$ regression coefficients was performed by using data in the whole village and not only near the position of the current PVWPS. The prediction rate at the PVWPS $\phi_{aft,PVWPS}$ is the most relevant metric for our study because it influences the interdisciplinary model output $SEI$ (socio-economic impact), contrarily to $\phi_{bef}$.

Finally, in Table III-5, we also present the results of the prediction rates $\phi_{bef}$ and $\phi_{aft,PVWPS}$ for the other sets of predictors that we could have selected (see section III.2.1.1). For the combinations of predictors $\pi_d/\pi_{wc}$, $\pi_d/\pi_{ee}$ and $\pi_d/\pi_{tcw}$, the values of $\phi_{aft,PVWPS}$ are lower than the values of $\phi_{bef}$. This result is aligned with the choice of the combination $\pi_d/\pi_{pwq}$ instead of the combinations $\pi_d/\pi_{wc}$, $\pi_d/\pi_{ee}$ and $\pi_d/\pi_{tcw}$ that was made in section III.2.1.1.

*Table III-5 – Prediction success rates for several combinations of predictors.*

| Predictors considered | Prediction success rate before the installation of the PVWPS $\phi_{bef}$ | Prediction success rate at the PVWPS $\phi_{aft,PVWPS}$ |
|---|---|---|
| Distance household-source / Water cost ($\pi_d/\pi_{wc}$) | Dry: 52%<br>Wet: 45% | Dry: 25%<br>Wet: 25% |
| Distance household-source / Perceived water quality ($\pi_d/\pi_{pwq}$) | Dry: 62%<br>Wet: 48% | Dry: 91%<br>Wet: 91% |
| Distance household-source / Extraction easiness ($\pi_d/\pi_{ee}$) | Dry: 64%<br>Wet: 57% | Dry: 36%<br>Wet: 37% |
| Distance household-source / Time collecting water ($\pi_d/\pi_{tcw}$) | Dry: 49%<br>Wet: 48% | Dry: 0%<br>Wet: 0% |

*We now focus on the integration of the households that are not part of* $\boldsymbol{h_{suv}}$ *(i.e. not part of the survey pool).* We use the GPS coordinates of these households. For each of these households, we suppose that it behaves

in the same way as the household of $\boldsymbol{h_{suv}}$ that is the closest geographically, both before and after the installation of the PVWPS. We also consider that it has the same values of $\rho(h, s)$.

### *III.2.2 Determination of the water demand profile at the PVWPS*

In the previous section, we predicted the households that wish to go to the PVWPS. In this section, we determine the water demand profile at the PVWPS, i.e. the evolution of the water demand flow rate $Q_d$ at the PVWPS over the day.

For this purpose, we use the information on the daily water quantity collected and the time at which water was collected before the installation of the PVWPS, that were gathered through the survey. In addition we make the following assumptions:

- Each household that wishes to go to the PVWPS collects the same daily water quantity as it used to at its previous water source. This assumption is based on the fact that no piping system is installed along with the PVWPS and that households therefore still have to walk to the fountain of the PVWPS to collect water.
- Each household that wishes to go to the PVWPS collects water at the same time as it used to at its previous water source.

We acknowledge that these assumptions merit further investigation in future works, notably because the habits of the inhabitants may evolve with the installation and over the lifetime of the PVWPS.

For the position of the current PVWPS of Gogma, we simulate the water demand curve at the PVWPS for the dry season (in blue in Figure III-3) and for the wet season (in blue in Figure III-4). The difference in the simulated demand curve between the dry season and the wet season is due to the following factors. Firstly, the vector $\boldsymbol{hs^*_{aft}}$ varies from one season to another. Secondly, the time at which water is collected, which is reported in the surveys, also varies from one season to another for certain households.

For the position of the current PVWPS of Gogma, we can compare the simulated demand curve to the measures of the demand flow rate performed by the data logger of the current PVWPS[3] (see section II.2.8). For a given season, we determine the hourly averaged daily demand profile from the measured demand flow rate as following: for each hour $i \in [1, 24]$, the average demand flow rate for this hour is the average of the flow rates measured at this hour for all the days of the season[4]. The measured daily average demand profile for the dry season is represented in red in Figure III-3 and the one for the wet season is in Figure III-4. In Table III-6 we also give the daily integrals of the simulated and measured demand profiles for both seasons. Results indicate that the daily water quantity is overestimated by a factor of 1.52 to 2.05.

---

[3] Actually, it is the consumption flow rate $Q_c$ that is measured. However, as the current PVWPS of Gogma is oversized, the demand flow rate and the consumption flow rate are equal ($Q_d$ = $Q_c$).
[4] For the dry season, which last from 1 December 2017 to 30 June 2018, we use the data from the monitoring system acquired between 14 January 2018 and 30 June 2018. Indeed, we started acquiring data with the monitoring system on 14 January 2018.

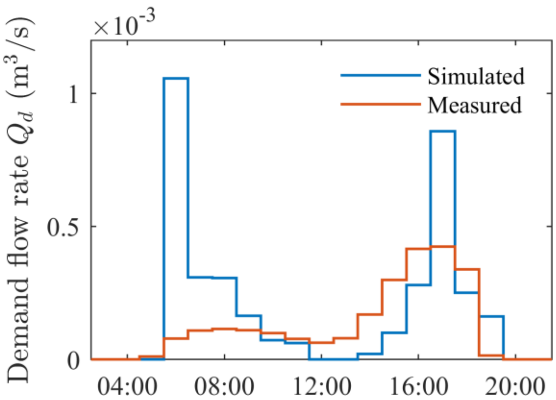


*Figure III-3 – Demand flow rate profile simulated by the demand model and measured by the data logger (i.e. flow meter data) – dry season.*

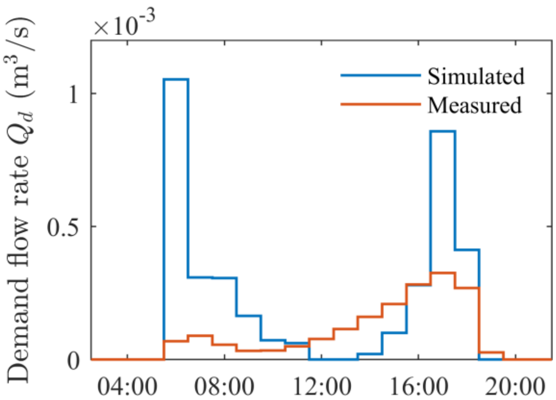


*Figure III-4 – Demand flow rate profile simulated by the demand model and measured by the data logger (i.e. flow meter data) – wet season.*

*Table III-6 – Daily integrals of the simulated and measured demand profiles for both seasons.*

| Season | Daily integral of the simulated water demand profile ($m^3$) | Daily integral of the measured water demand profile ($m^3$) |
|---|---|---|
| Dry | 13.1 | 8.6 |
| Wet | 13.1 | 6.4 |

The differences between the simulated and measured demand (see Figure III-3, Figure III-4 and Table III-6) may be explained by the following elements:

- The error on the prediction success rate at the PVWPS $\phi_{aft,PVWPS}$, which is about 10% (see section III.2.1.2).
- Some households may not accurately estimate the daily water quantity that they use. According to our on-field observations (see section II.2.1), we think that households notably overestimated the water quantity used for personal hygiene, which represents ~50% of the domestic water use in the survey answers. In its literature review of water demand models, [54] highlighted that there are significant errors on households water consumption reported in surveys.
- Some households may not have reported accurately the times at which they collect water in the survey. Indeed, we observed through on-field observations that inhabitants of Gogma rarely wear watch and Ho et al. [86] reported that inhabitants who do not wear a watch often do not know the time accurately.
- Some households may also collect a share of the water at other sources, and notably water for personal hygiene at open wells. This may especially be the case during the wet season as all open wells are available and there is more water in open wells during this season. This could help to explain why the measured daily water demand at the PVWPS is lower during the wet season than during the dry season (see Table III-6).
- In the survey, we asked people about the quantity of water collected and the time at which they collected water. We then split equally the quantity of water collected between these times. In Gogma, the majority of households reported that they collect water in the morning and in the evening. This notably explains the two spikes in the simulated water demand in Figure III-3 and Figure III-4. However, when comparing the simulated water demand to the measured one, a possible

hypothesis may be that in reality people collect more water in the evening than in the morning. This was also suggested by on-field observations (see section II.2.1)

- Users of the PVWPS may have changed their habits and they may not use the PVWPS in the same way as they used their previous water source.

In the future, we will investigate the influence of these elements by completing the household survey and applying the demand model in other villages. We will also continue to compare model results, which are obtained from household survey answers, to flow meter data. Indeed, this comparison is original and relevant, in our opinion.

This will also allow us to gain more experience on this type of demand model. Indeed, as it is the first model that predicts the attendance at a source of a new type and load curves at sources, there is no point of comparison for the moment. Besides, in section IV.3, we investigate the effect of the difference between the simulated and measured demand on the optimisation results.

## III.3 Technical model

The block diagram of the technical model is shown in Figure III-5. The energy conversion model allows to determine the evolution of the water level in the tank $H_t$ from the sizing variables, the groundwater parameters, the climatic data and the water demand at the PVWPS $Q_d$. The beneficiaries identification model allows to determine the water consumption at the PVWPS $Q_c$ and the water sources where the households effectively go after the installation of the PVWPS $\boldsymbol{hs_{aft}}$ from the water level in the tank $H_t$, the water demand at the PVWPS $Q_d$ and the water sources where the households wish to go after the installation of the PVWPS $\boldsymbol{hs^*_{aft}}$.

In section III.3.1, we present the energy conversion model, apply it and validate it for the current PVWPS of Gogma. In section III.3.2, we present the generalization of the energy conversion model. In section III.3.3, we present the beneficiaries identification model.

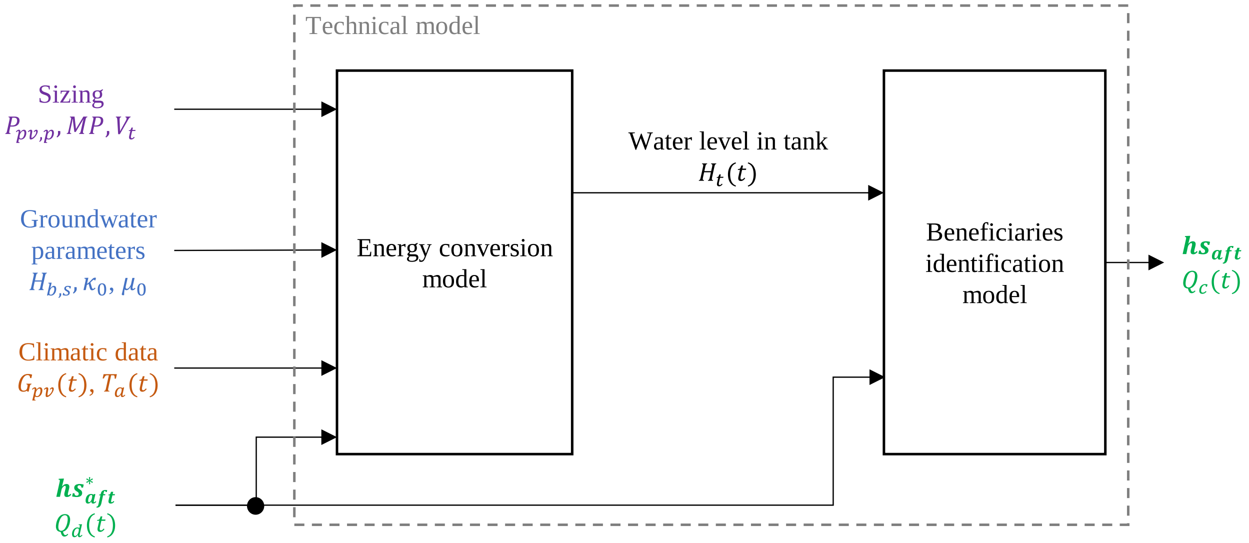


*Figure III-5 – Block diagram of the technical model.*
*$\boldsymbol{hs^*_{aft}}$: water sources where the households wish to go after installation of the PVWPS, $Q_d$: water demand at the PVWPS, $\boldsymbol{hs_{aft}}$: water sources where the households effectively go after installation of the PVWPS, $Q_c$: water consumption at the PVWPS.*

### *III.3.1 Energy conversion model – presentation and application to the current PVWPS of Gogma*

The block diagram of the energy conversion model is presented in Figure III-6. For clarity reasons, in this diagram, we only present on the arrows the time dependent quantities. The sizing variables and the groundwater parameters are inside the sub-models blocks and they are in purple and in blue respectively.

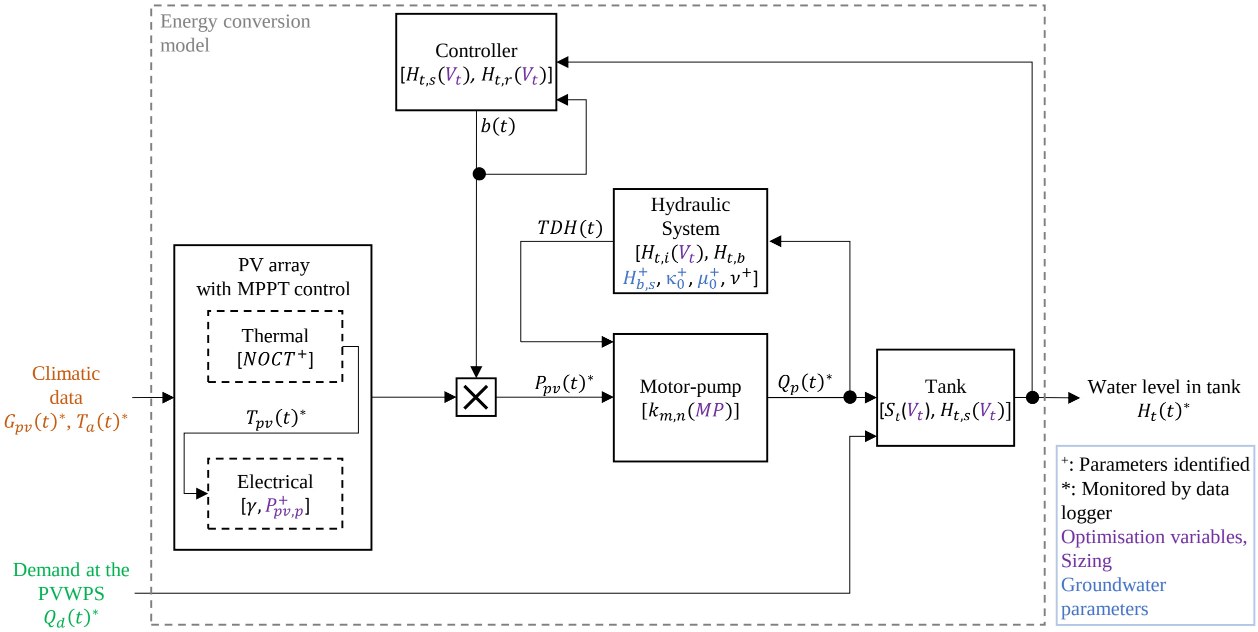


*Figure III-6 – Block diagram of the energy conversion model.*

In Figure III-6, we also present within square brackets, the parameters encompassed in each sub-model. We can distinguish three types of parameters:

- The groundwater parameters ($H_{b,s}$, $\kappa_0$ and $\mu_0$) which are in blue in Figure III-6.
- The parameters that are also optimisation variables, such as $P_{pv,p}$, or that are dependent on optimisation variables. This is for instance the case of the height between the bottom of the tank and the stop level $H_{t,s}$ which depends on the tank volume $V_t$.
- The remaining the parameters such as the nominal operating temperature cell $NOCT$.

In Figure III-7, we represent the heights that feature in the energy conversion model.

It is important to note that the inclusion of the water demand flow rate at the PVWPS $Q_d$ as an input of the energy conversion chain model is an original contribution. It allows to model the instantaneous operation of PVWPS which include a tank and a controller that stops and restarts the motor-pump depending on the water level in the tank [78], which are commonly used for domestic water access. It also permits to link the demand model to the technical one (see Figure III-1).

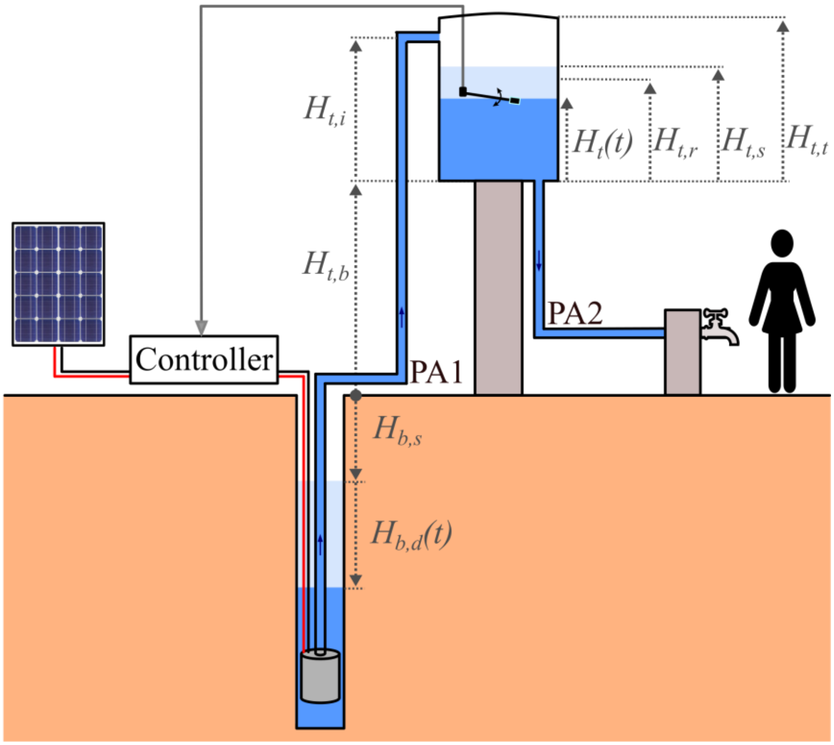


*Figure III-7– Definition of the heights.*
*The height datum is set at the ground level so $H_{b,s}$ and $H_{b,d}$ are negative.*

### *III.3.1.1 Sub-models*

In this section, we detail the sub-models of the energy conversion model. We also give the values of the parameters for the current PVWPS of Gogma. Some of the parameters were measured directly on the PVWPS or obtained from the literature. The other parameters are identified by performing regressions using the data acquired by the data logger (see section II.2.8) from 12 February 2018 to 18 February 2018 (identification set). The square of the multiple correlation coefficient $R^2$ is used to estimate the accuracy of identifications. We indicate the data acquired by the data logger and the parameters identified in Figure III-6.

#### III.3.1.1.1 Photovoltaic array

**Thermal model**

The PV array thermal model computes the temperature of the PV modules $T_{pv}$ using:

$$T_{pv}(t) = T_a(t) + \frac{NOCT - 20}{800} G_{pv}(t) \tag{3}$$

where $T_a$ is the ambient temperature and $G_{pv}$ is the irradiance on the plane of the PV array. The $NOCT$ (nominal operating cell temperature), generally specified by the manufacturer, corresponds to the temperature of the open circuited modules under the following conditions: irradiance on the plane of the modules of 800 W/m$^2$, ambient temperature of 20°C, wind velocity of 1 m/s and the modules are mounted such that their back side is open.

For the current PVWPS of Gogma, the $NOCT$ was not given in the datasheet of the PV modules. The $NOCT$ is therefore determined by identification. To do so, we perform a regression using equation (3) and the

experimental data of $T_{pv}$, $T_a$ and $G_{pv}$ from the identification set. The identification yields to a $NOCT$ of 32 °C ($R^2 = 0.98$). This is low compared to usual values for multicrystalline silicon PV modules, which are in the order of 43 °C to 45 °C [89]. This can be explained by a wind speed higher than 1 m/s and which is not taken into account in the thermal model. Indeed, we installed a complete weather station at the PVWPS in February 2019 in addition to existing sensors, and we measured an average wind speed of 6.6 m/s between February 2019 and August 2019. Besides, the PV modules are placed at 2 m above ground which favours cooling by convection.

Through a sensitivity analysis, we showed that the thermal parameters of PV modules ($NOCT$ and $\beta$) have a small impact on the output of the energy conversion model and on the optimal sizing of PVWPS [81]. Consequently, it is not indispensable to model the thermal behaviour of PV modules and, in this case, the ambient temperature $T_a$ is not required as an input to the energy conversion model.

**Electrical model**

For the PV array electrical model, considering that the maximum power point tracking of the PV array is correctly performed by the converter of the motor-pump, a simplified model is used [90, 91]:

$$P_{pv}(t) = \frac{G_{pv}(t)}{G_0} P_{pv,p} \left(1 + \gamma \left(T_{pv}(t) - 25\right)\right) b(t) \tag{4}$$

where $P_{pv}$ is the PV array output power (i.e. input power to the motor-pump), $G_0$ is the reference irradiance (1000 W/m$^2$), $P_{pv,p}$ is the peak power of the PV array in standard test conditions (STC), $\gamma$ is the coefficient of loss on the maximum power related to modules temperature and $b$ is the controller trigger signal. The signal $b$ allows to transfers ($b = 1$) or not ($b = 0$) the power of the PV array to the motor-pump depending on the water level in the tank $H_t$ (see section III.3.1.1.2).

For the PVWPS of Gogma, the soiling losses are neglected as the modules are cleaned at least twice a month by the person of the village who is responsible of maintaining the PVWPS. In addition, the PV modules were bought in Burkina Faso and the only documentation that was provided was a tag on the back of the modules. $\gamma$ was not given in the tag and is thus taken equal to -0.4%/°C, which is the standard value for multicrystalline silicon modules [90]. According to the tag, the total peak power of the PV array in STC $P_{pv,p}$ is equal to 750 $W_p$. Nevertheless, since in these regions the tag is not always reliable, it was preferred to determine the value of $P_{pv,p}$ by identification. A value of 620 $W_p$ was obtained ($R^2 = 0.96$).

III.3.1.1.2 Controller

The controller is modelled by a switch which transfers ($b = 1$) or not ($b = 0$) the power of the PV array to the motor-pump depending on the water level in the tank $H_t$. The value of $b$ is governed by the hysteresis function presented in Figure III-8, where $H_{t,s}$ is the water level in the tank for which the motor-pump stops (the tank is full) and $H_{t,r}$ is the level for which it restarts.

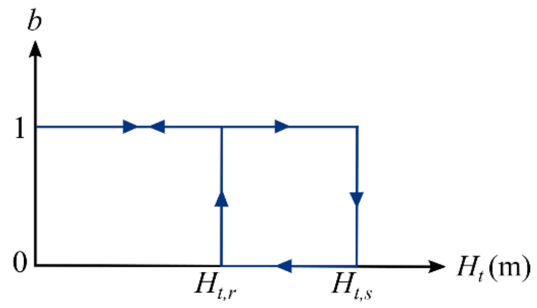


*Figure III-8 – Controller model.*

For the current PVWPS of Gogma, we measured $H_{t,s}$ = 3.3 m and $H_{t,r}$ = 3.0 m.

III.3.1.1.3 Tank

As the tank is sealed, it is considered that no water leaves the tank by evaporation. The height of water in the tank $H_t$ is thus expressed as:

$$H_t(t_0) = H_{t,s}$$
$$H_t(t) = \max\left(0,\ H_t(t_0) + \int_{t_0}^{t} \frac{Q_p(\tau) - Q_d(\tau)}{S_t}\, d\tau\right) \tag{5}$$

where $Q_p$ is the pump flow rate, $Q_d$ is the water demand flow rate and $S_t$ is the cylindrical tank base area[5]. The model is initialized at a time $t_0$ at which the tank is full and the water level in the tank is therefore equal to the stop level $H_{t,s}$.
For the current PVWPS of Gogma, we measured $S_t$ = 3.3 m$^2$.

III.3.1.1.4 Motor-pump

The characteristic of the motor-pump reference $MP$ provided by the manufacturer is used to build the motor-pump model. This characteristic links the total dynamic head $TDH$, the pump flow rate $Q_p$ and the input power $P_{pv}$. The points of the characteristic for which $Q_p > 0$ are fitted by a polynomial $P_a$ (the coefficients of $P_a$ are noted $k_{m,n}$). The pump flow rate is thus given by:

$$Q_p(t) = \max\left(0, P_a\left(P_{pv}(t), TDH(t)\right)\right) \tag{6}$$

The motor-pump SQFlex 5A-7 [69] is used in the current PVWPS in Gogma. We use a 4$^{th}$ order polynomial $P_a^{4,4}$ for fitting the characteristic of this motor-pump. The coefficients $k_{m,n}$ of the polynomial are given in Appendix B. Figure III-9 presents the points from the datasheet and the surface obtained by fitting. The fitting is very accurate ($R^2$ = 1.00).

[5] Taking the maximum between '0' and the second member '$H_t(t_0) + \int_{t_0}^{t} \frac{Q_p(\tau)-Q_d(\tau)}{S_t} d\tau$' allows to make sure that the water level in the tank $H_t$ never becomes negative when the PVWPS is undersized (see section III.3.2.3).

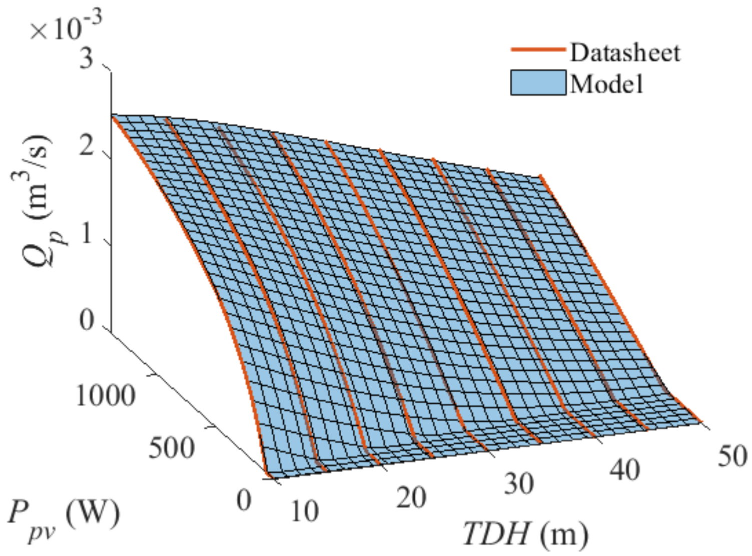


*Figure III-9 – Model of the motor-pump SQFlex 5A-7.*

III.3.1.1.5 Hydraulic system

The model of the hydraulic system allows to compute the total dynamic head $TDH$ between the motor-pump and the tank. The total dynamic head $TDH$ between the motor-pump and the tank is given by [92]:

$$TDH(t) = -\left(H_{b,s} + H_{b,d}(t)\right) + H_{t,b} + H_{t,i} + H_{pa1}(t), \;\; \forall P_{pv} \tag{7}$$

where $H_{b,s}$ is the static water level (height between the ground level and the water level in the borehole when there is no pumping; $H_{b,s}$<0), $H_{b,d}$ is the drawdown (height between the static water level and the water level in the borehole when there is pumping; $H_{b,d}$<0), $H_{t,b}$ is the height between the ground level and the bottom of the tank, $H_{t,i}$ is the height between the bottom of the tank and the tank input (independent of the water level in the tank) and $H_{pa1}$ is the additional head due to pressure losses in pipe assembly 1. These heights are shown in Figure III-7. $H_{b,d}$ and $H_{pa1}$ can be expressed as function of $Q_p$ only (see equation (8) and (9)) and equation (7) holds for any value of $P_{pv}$. Equation (7) therefore represents the equation of a surface versus variables $Q_p$ and $P_{pv}$, which is called the hydraulic system surface.

For the PVWPS of Gogma, we measured $H_{t,b}$ = 4.2 m and $H_{t,i}$ = 3.4 m.

**Drawdown model**

It is considered that the drawdown $H_{b,d}$ depends on the pump flow rate $Q_p$ and of its square $Q_p^2$ [93] and that the drawdown at a time $t$ also depends on the flow rates at previous times [94]. Based on this, we propose the following expression for the drawdown $H_{b,d}$:

$$H_{b,d}(t) = -\sum_{n=0}^{N} \kappa_n Q_p(t - n\,\Delta T) - \sum_{n=0}^{N} \mu_n Q_p(t - n\,\Delta T)^2 \tag{8}$$

where $\kappa_n$ are coefficients that represent the aquifer losses, $\mu_n$ are coefficients that represent the borehole losses and $\Delta T$ is a time difference. The values chosen for $N$ and $\Delta T$ depend on the data availability, the accuracy required for the model and the speed of the drawdown response.

For the current PVWPS of Gogma, $\kappa_n$ and $\mu_n$ were identified from the step drawdown tests that were performed before the installation of the PVWPS, at the moment of the borehole drilling in November 2017 (see section II.2.6). Regressions of $H_{b,d}$ against $Q_p$ and $t$ with a $\Delta T$ of 10 minutes for different values of $N$ were tried [78, 94]. In the end, a model with only $\kappa_0$ and $\mu_0$ was selected. Indeed the aquifer response is fast and the statistical significance of the following coefficients ($\kappa_1, \mu_1, \kappa_2, \mu_2 \ldots$) is low. The values obtained for $\kappa_0$and $\mu_0$ are:

$$\kappa_0 = 2.0\ 10^3\ \mathrm{m}^{-2}\ \mathrm{s}; \mu_0 = 5.8\ 10^5\ \mathrm{m}^{-5}\ \mathrm{s}^2\ (\mathrm{R}^2 = 0.97)$$

Figure III-10 presents the drawdown measured during the 4 step pumping tests and the drawdown simulated by the model.

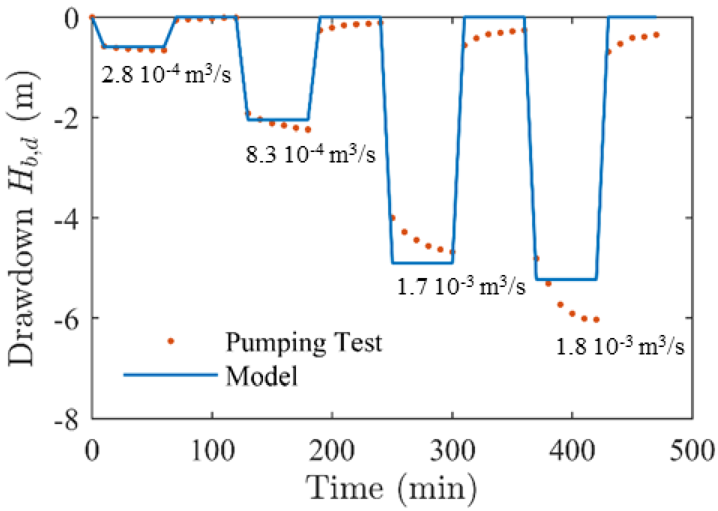


*Figure III-10 – Drawdown measured during the pumping tests and simulated by the model.*

As we have demonstrated in [95], the main advantage of the developed data-driven drawdown model is that, contrarily to existing models, it is not based on assumptions that are rarely met (e.g. homogenous and isotropic aquifer) and can be applied for all types of aquifers.

**Pipe model**

The additional head due to losses in pipe assembly 1 $H_{pa1}$ evolves quadratically with the pump flow rate $Q_p$ [96]:

$$H_{pa1}(t) = \nu Q_p(t)^2 \tag{9}$$

where $\nu$ is a constant. These losses occur along the length of the pipes and at junctions (elbows, curvatures, diameter changes between pipes and pipe output) [96].

In the case of the current PVWPS of Gogma, $\nu$ and $H_{b,s}$ are determined by identification by using equations (7) and (9) and data acquired by the monitoring system. As $TDH$ is not measured directly, it is obtained from $P_{pv}$ and $Q_p$ by fitting the motor-pump characteristic with another 4th order polynomial $P_b^{4,4}$ (see Appendix B for the values of the coefficients):

$$TDH(t) = P_b^{4,4}\left(P_{pv}(t), Q_p(t)\right), \forall Q_p > 0 \quad (\mathrm{R}^2 = 1.00) \tag{10}$$

By combining equation (7) and (10), the operating points of the PVWPS, which correspond to the intersection of the motor-pump surface and of the hydraulic system surface, can be found:

$$P_b^{4,4}\left(P_{pv}(t), Q_p(t)\right) = -\left(H_{b,s} - \kappa_0 Q_p(t) - \mu_0 Q_p(t)^2\right) + H_{t,b} + H_{t,i} + \nu Q_p(t)^2 \tag{11}$$

The values of $H_{b,s}$ and $\nu$ are identified by using the measured $P_{pv}$ and $Q_p$ from the identification set:

$$H_{b,s} = -\,4.9\ \mathrm{m}; \nu = 4.9\ 10^6\ \mathrm{m}^{-5}\ \mathrm{s}^2\ (\mathrm{R}^2 = 0.84)$$

The value of the static water level identified (-4.9 m) is close to the one measured during the step drawdown tests (see section II.2.6), which is of -6 m. The difference (1.1 m) may be due to measurement error, seasonal change, model inaccuracy or a combination of these factors. The value of $\nu$ is greater than usual values for this type of system, which corresponds to significant head losses due to the pipe assembly 1 (PA1) [96].

For installations for which pumping tests are not available, it is possible to determine the coefficients $(\kappa_n, \mu_n, H_{b,s}, \nu)$ from the intersection of the motor-pump surface and the hydraulic system surface only (equation (11) for the PVWPS of Gogma). However, as $\mu_0$ and $\nu$ are both coefficients for $Q_p(t)^2$, only the sum of $\mu_0$ and $\nu$ is obtained and not the individual values of the coefficients. This prevents to separate the contributions of the drawdown and the pipe losses to the total dynamic head. It would therefore not be possible to know if the drawdown goes below the level of the motor-pump.

#### III.3.1.1.6 Summary of the parameters value for the current PVWPS of Gogma

We summarise the parameters of the energy conversion model and their value for the current PVWPS of Gogma in Table III-7.

*Table III-7 – Parameters of the energy conversion model and value for the current PVWPS of Gogma.*

| Symbol | Description | Value for the current PVWPS of Gogma |
|---|---|---|
| $NOCT$ | Nominal operating cell temperature | 32 °C |
| $\gamma$ | Coefficient of loss due to PV modules temperature | -0.4%/°C |
| $P_{pv,p}$ | Peak power of the PV modules in standard test conditions (STC) | 620 $\mathrm{W_p}$ |
| $k_{m,n}$ | Coefficients of the polynomial which fit the characteristic of the motor-pump reference $MP$ | see Appendix B |
| $H_{t,s}$ | Height between the bottom of the tank and the stop level | 3.3 m |
| $H_{t,r}$ | Height between the bottom of the tank and the restart level | 3.0 m |
| $S_t$ | Area of the base of the cylindrical tank | 3.3 $\mathrm{m}^2$ |
| $H_{t,i}$ | Height between the bottom of the tank and the level at which water enters the tank | 3.4 m |
| $H_{t,b}$ | Height between the ground level and the bottom of the tank | 4.2 m |
| $H_{b,s}$ | Height between the ground level and the static water level in the borehole | -4.9 m |
| $\kappa_0$ | Aquifer losses coefficient | 2.0 $10^3$ $\mathrm{m}^{-2}$ s |
| $\mu_0$ | Borehole losses coefficients | 5.8 $10^5$ $\mathrm{m}^{-5}$ $\mathrm{s}^2$ |
| $\nu$ | Pipe pressure losses coefficient | 4.9 $10^6$ $\mathrm{m}^{-5}$ $\mathrm{s}^2$ |

### *III.3.1.2 Experimental validation*

In this section, we detail the experimental validation of the energy conversion model for the current PVWPS of Gogma. The validation is performed by using data from different periods than the identification set, called validation sets. The model validation is detailed for the first validation set which lasts from 19 February 2018 to 21 February 2018. Moreover, the results of the model validation are also given for two other validation sets of two weeks. The first one lasts from 16 May to 29 May 2018 and takes place during the dry season. The second one lasts from 29 July to 11 August 2018 and takes place during the wet season. To validate the model, we compare the model output, the water level in the tank $H_t$, to the measures of the data logger for each validation set.

Figure III-11 present the irradiance on the plane of the PV array $G_{pv}$ and the ambient temperature $T_a$ and the demand flow rate[6] $Q_d$ measured by the data logger for the validation set which last from 19 February to 21 February.

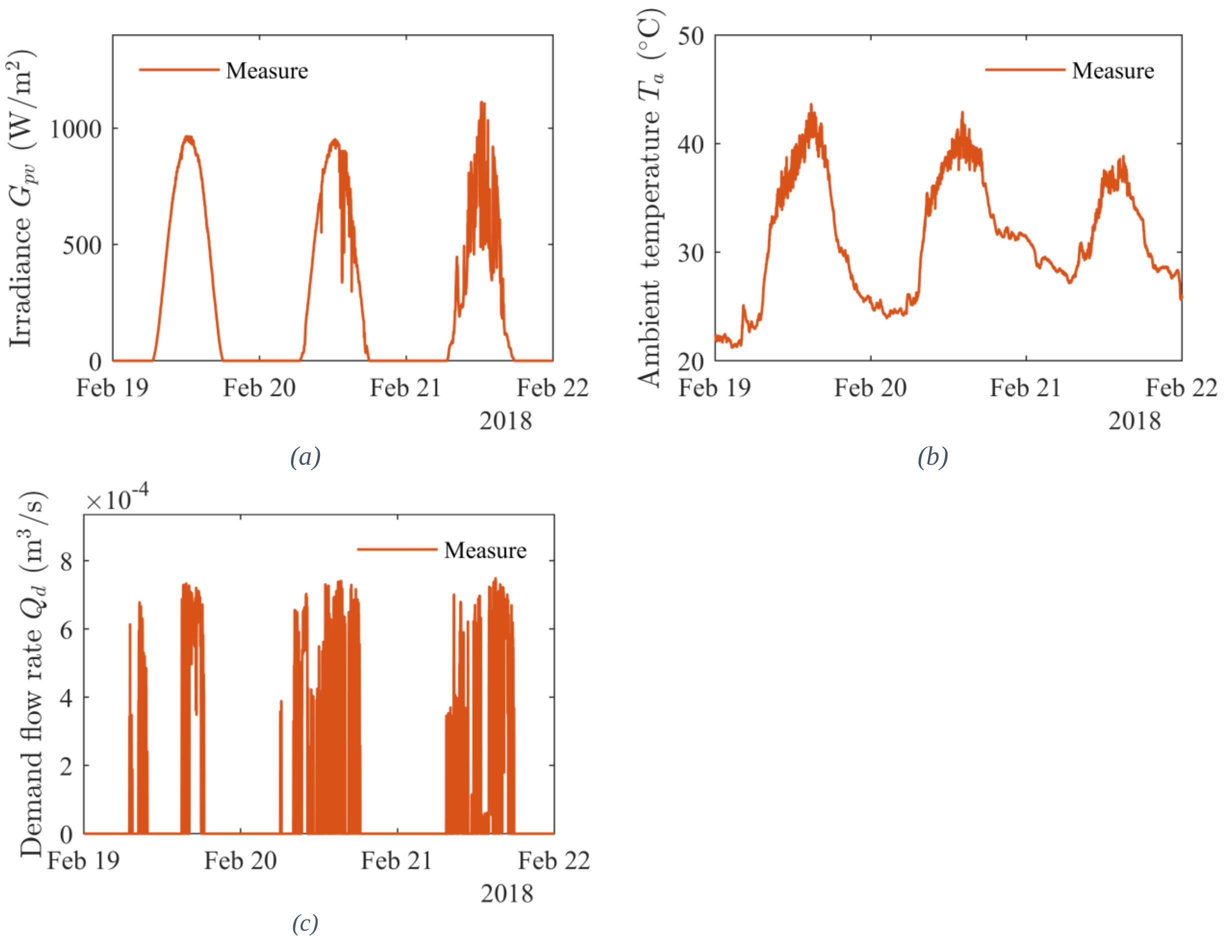


*Figure III-11 – Measured model inputs (a) irradiance (b) ambient temperature (c) demand flow rate.*

The computations for the model for the February validation set start on 19 February at 9h20 as the motor-pump has just stopped at this moment and the water level in the tank has just reached the stop level (see

[6] Actually, it is the consumption flow rate $Q_c$ that is measured. However, as the current PVWPS of Gogma is oversized, the demand flow rate and the consumption flow rate are equal ($Q_d$ = $Q_c$).

section III.3.1.1.3). Figure III-12 compares the measured water level in the tank $H_t$ to the one obtained from the model.

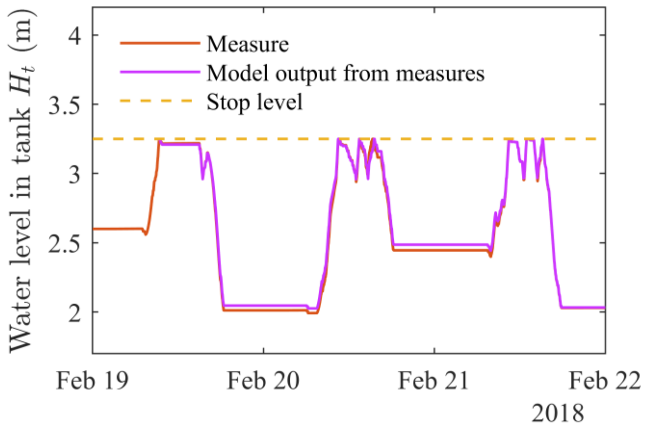


*Figure III-12 – Water level in the tank measured and simulated (model output).*

The root mean square error $RMSE$ between the measured and modelled height in the water tank is of 0.03 m. The $RMSE$ values are normalized by the height between the bottom of the tank and the stop level $H_{t,s}$, which is of 3.3 m, in order to obtain the normalized root mean square errors ($NRMSE$). For the validation period of February, the model allows to predict the water level in the tank with 1.0% error.

The same calculations were carried out for the two-week validation sets in May and July-August 2018. The $NRMSE$ for the May period is of 4.8%. The $NRMSE$ for the July-August period is 3.8%. Moreover, for all 3 validation periods, the absolute value of the difference between the instantaneous measured and modelled water heights in the tank does not durably increase along the validation period.

## *III.3.2 Energy conversion model – generalization*

### *III.3.2.1 Parameters values*

In order to generalize the PVWPS model, we need to determine the values of the parameters for other PVWPS than the current PVWPS of Gogma. We remind that the values of the parameters for the current PVWPS are given in Table III-7.

Firstly, for any PVWPS, we consider that the values of the parameters $NOCT$, $\gamma$, $\nu$ are the same as the ones for the current PVWPS of Gogma (see Table III-7).

Secondly, the peak power of the PV array $P_{pv,p}$ is both an optimisation variable and a parameter of the model which is used in equation (4). The energy conversion model can therefore be evaluated for any value of $P_{pv,p}$.

Thirdly, we can digitize the characteristic of any motor-pump reference $MP$ and determine the associated fitting coefficients $k_{m,n}$, in the same way as we did for the motor-pump SQFlex 5A-7 in section III.3.1.1.4. For this thesis, in addition to the SQFlex 5A-7 [69], we digitize the characteristic of the motor-pumps SQFlex 8A-5 [97], SQFlex 2.5-2 [98], SQFlex 1.2-2 [99], SQFlex 0.6-2 [100], SQFlex 11A-3 [98], SQFlex 8A-3 [99] and SQFlex 5A-3 [100].

Fourthly, we determine the values of the parameters $H_{t,i}$, $H_{t,s}$, $H_{t,r}$ and $S_t$ from the value of the tank volume $V_t$. For this purpose, we collected data from several tank manufacturers regarding the base radius $R_t$ and the height of the tank $H_{t,t}$ chosen for different tank volumes $V_t$. The results are presented in Figure III-13.

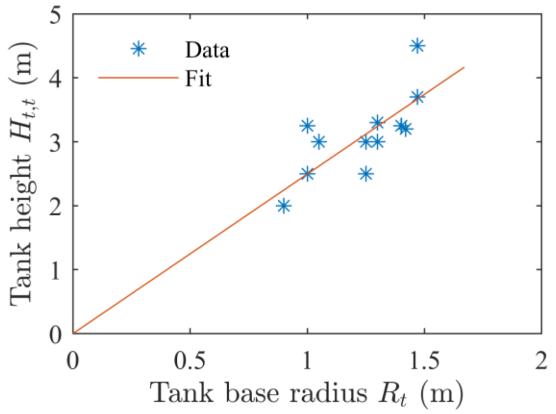


*Figure III-13 – Base radius $R_t$ and height $H_{t,t}$ chosen for different tank volumes $V_t$.*

We fit the collected data presented in Figure III-13 and we obtain the expression of $H_{t,t}$ as a function of $R_t$:

$$H_{t,t} = 2.49\ R_t\ (\mathrm{R}^2 = 0.61) \tag{12}$$

By using equation (12), $S_t = \pi R_t^2$ and $V_t = H_{t,t} \cdot S_t$ we obtain:

$$S_t = \pi \left(\frac{V_t}{2.49\ \pi}\right)^{\frac{2}{3}} \tag{13}$$

$$H_{t,t} = 2.49 \left(\frac{V_t}{2.49\ \pi}\right)^{\frac{1}{3}} \tag{14}$$

Following discussions with PVWPS installers, we also set $H_{t,i}$, $H_{t,r}$ and $H_{t,s}$ from $H_{t,t}$ as following:

$$H_{t,i} = H_{t,t} - 0.1\ \mathrm{m} \tag{15}$$

$$H_{t,s} = H_{t,t} - 0.2\ \mathrm{m} \tag{16}$$

$$H_{t,r} = H_{t,t} - 0.5\ \mathrm{m} \tag{17}$$

According to the definition of $H_{t,r}$ (equation (17)), $H_{t,t}$ has to be strictly higher than 0.5 m. When reinjecting this minimum value for $H_{t,t}$ into equation (14), we obtain a lower boundary for the tank volume $V_t$ of 0.1 m$^3$.

The only remaining parameters of the energy conversion model are the groundwater parameters ($H_{b,s}$, $\kappa_0$ and $\mu_0$). These parameters depend on the position of the PVWPS in the village ($Lat$, $Lon$). However, as presented in section II.2.3, it is not possible to determine the groundwater parameters from the position, without drilling a borehole and performing pumping tests (which is expensive: ~\$10$^4$ for drilling a borehole as shown in section III.5.1.2 and ~\$2.5 10$^3$ for performing pumping tests as shown in section II.2). In section IV.5, we will present the range of variation of the groundwater parameters and the influence of the

uncertainty on groundwater parameters on optimisation results. Until then, for any position in the village, the groundwater parameters are supposed equal to their values for the current PVWPS of Gogma (see Table III-7).

#### *III.3.2.2 Model inputs*

In order to provide results for the energy conversion model for different positions of the PVWPS ($Lat, Lon$) in the village, we use the water demand $Q_d$ simulated by the demand model (see section III.2.2). We assume that the daily evolution of the water demand is the same for every day of the season. For the dry season, it is given by the blue curve in Figure III-3. For the wet season, it is given by the blue curve in Figure III-4.

The simulated water demand $Q_d$, is obtained with a temporal resolution of 1 hour as it comes from survey responses (see section III.2.2). We therefore also use a temporal resolution of 1 hour for input climatic data, instead of 1 minute. In [104] and [105], we have shown that using a temporal resolution of 1 hour instead of 1 minute for water demand data and climatic data has a low impact on the energy conversion model output. Besides, using a temporal resolution of 1 hour allows to reduce computing time.

Finally, we use satellite climatic data as input from this point onward. Indeed, we showed that the loss of accuracy associated to the use of satellite data instead of measured ones does not exceed 3% [78]. Additionally, the use of satellite data permits the implementation of the energy conversion model in geographic areas where no local climatic measurements are available. In Appendix C, we present how the ambient temperature $T_a$ and the irradiance on the plane of the PV array $G_{pv}$ are obtained from satellite databases. For the case of Gogma, the satellite climatic data are the same for any position of the PVWPS in the village. Indeed, the whole village, which is of area ~2×2 km, is contained within one pixel of the satellite database, which is of area ~5×5 km [106]. We note that the average daily irradiance from satellite data are similar for the dry season (5.76 kWh/m$^2$) and the wet season (5.54 kWh/m$^2$). In addition, the average temperature from satellite data is 28.7 °C for the dry season and 26.2 °C for the wet season.

The satellite irradiance and temperature data for the period from 1 to 2 December 2017 (first two days of the dry season) are shown in Figure III-14 and Figure III-15. The simulated water demand for the same period and for the position of the current PVWPS is shown in Figure III-16.

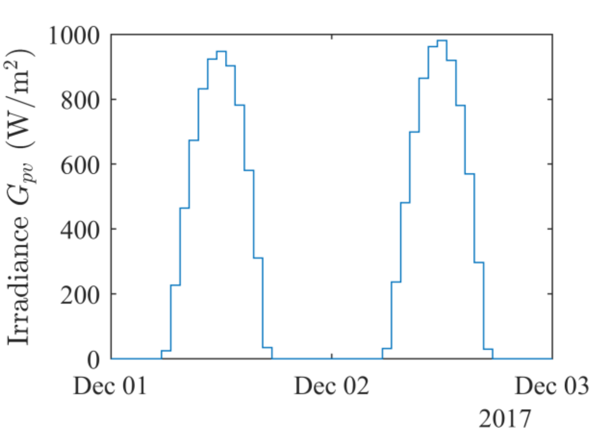


*Figure III-14 – Irradiance on the plane of the PV array from satellite data.*

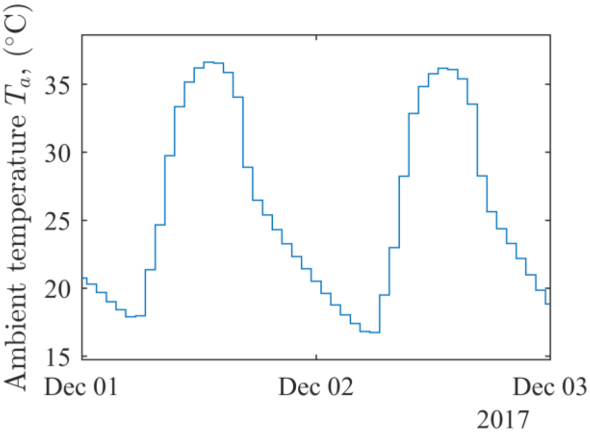


*Figure III-15 – Ambient temperature from satellite data.*

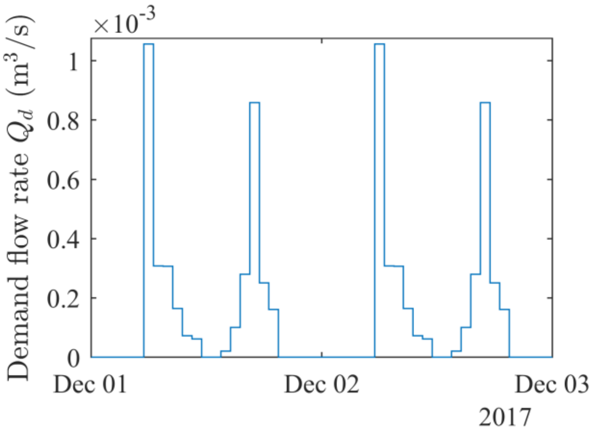


*Figure III-16 – Simulated water demand for the position of the current PVWPS*

### *III.3.2.3 Model results for undersized and oversized PVWPS*

We now simulate the energy conversion model for two sets of values of the sizing variables. This will allow us to illustrate the notion of oversized and undersized PVWPS.

Firstly, we simulate the energy conversion model for the period from 1 to 2 December 2017 for the following sizing of the PVWPS: $P_{pv,p}$ = 550 W$_p$, $MP$ = SQFlex 5A-7, $V_t$ = 17 m$^3$. The evolution of the water level in the tank $H_t$, the energy conversion model output, is presented in Figure III-18a. We observe that the water level in the tank $H_t$ never reaches 0 m, i.e. the tank is never empty. Additionally, when we simulate $H_t$ during the whole dry and wet seasons, we observe that it always remains higher than 0 m (not shown here). Consequently, the entire water demand $Q_d$ is fulfilled. In this case, the PVWPS is said to be 'oversized'.

Secondly, we simulate the energy conversion model for the following sizing of the PVWPS: $P_{pv,p}$ = 100 W$_p$, $MP$ = SQFlex 5A-7, $V_t$ = 8 m$^3$. The evolution of the water level in the tank $H_t$ for this sizing is presented in Figure III-19a. We observe that, for several periods of time when there is water demand at the system ($Q_d$ > 0 in Figure III-16), the water level in the tank $H_t$ is equal to 0 m, i.e. the tank is empty. This is notably the case in the evening on 1 December and in the morning and in the evening on 2 December. This means that the water demand during these periods of time is not fulfilled. In this case, the PVWPS is said to be 'undersized'.

### *III.3.3 Beneficiaries identification model*

Figure III-17 shows the block diagram of the beneficiaries identification model.

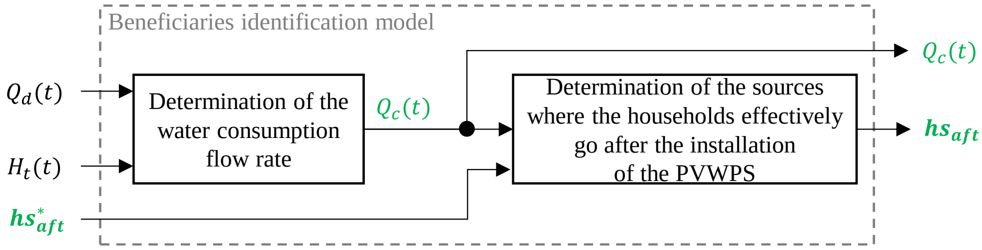


*Figure III-17 – Block diagram of the beneficiaries identification model.*
*$Q_d$: water demand at the PVWPS, $H_t$: water level in the tank, $\boldsymbol{hs^*_{aft}}$: water sources where the households wish to go after installation of the PVWPS, $Q_c$: water consumption at the PVWPS, $\boldsymbol{hs_{aft}}$: water sources where the households effectively go after installation of the PVWPS.*

#### *III.3.3.1 Determination of the water consumption flow rate*

We propose the following formula to determine the water consumption flow rate $Q_c$ from the water demand flow rate $Q_d$ and the water level in the tank $H_t$:

$$Q_c(t) = \begin{cases} Q_d(t) \text{ if } H_t(t) > 0 \\ 0 \text{ if } H_t(t) = 0 \end{cases} \tag{18}$$

In Figure III-18b and Figure III-19b we plot the consumption profiles obtained for the oversized and undersized systems considered in section III.3.2.3. We also superimpose the demand profile on these figures.

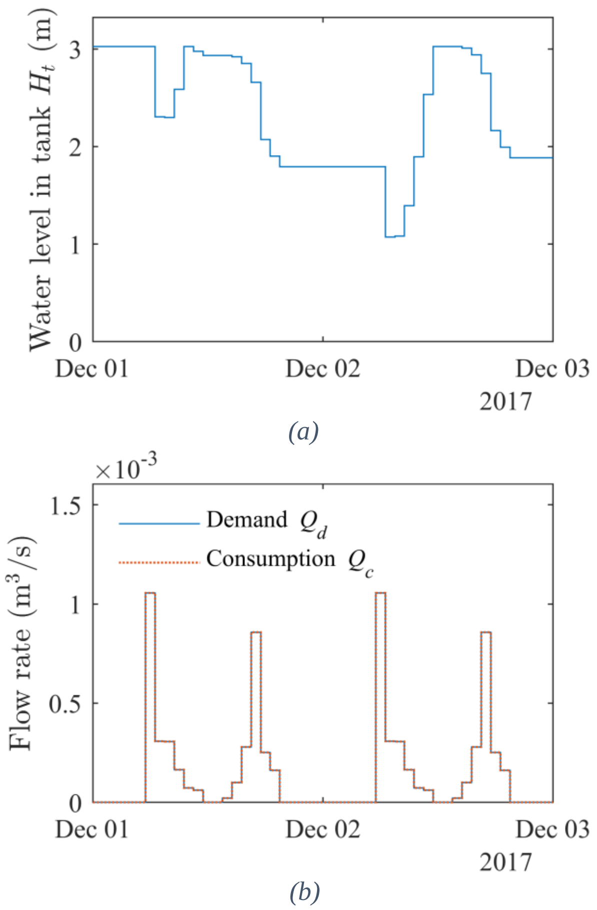


*Figure III-18 – Oversized PVWPS. (a) Water level in the tank (b) Demand and consumption flow rates.*

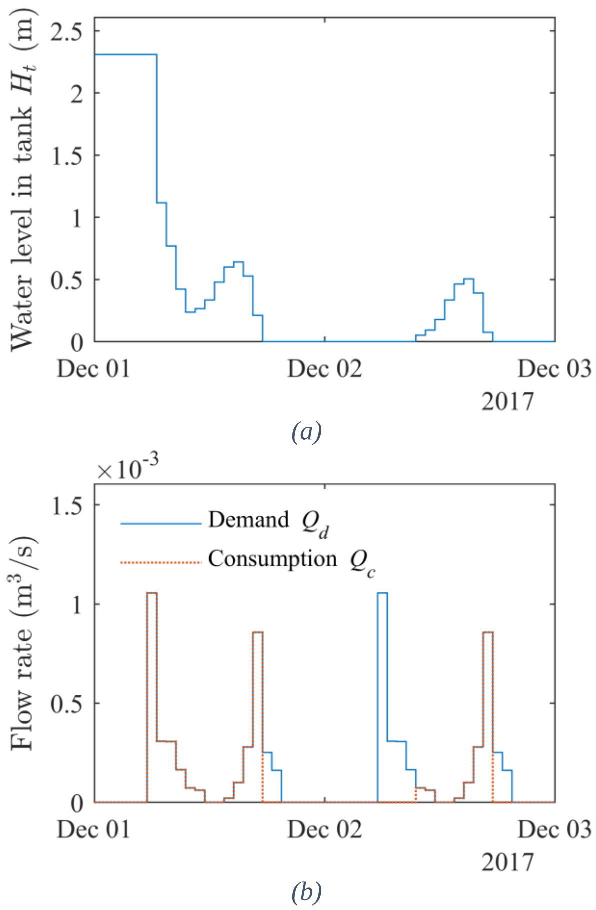


*Figure III-19 – Undersized PVWPS. (a) Water level in the tank (b) Demand and consumption flow rates.*

### *III.3.3.2 Determination of the sources where the households effectively go after installation of the PVWPS*

For each season ($\sigma \in$ {dry, wet}), we determine the volume demanded $V_d^\sigma$ and the volume consumed $V_c^\sigma$ from the water demand profile and the water consumption profile as following:

$$V_d^\sigma = \int_\sigma Q_d(t)dt \tag{19}$$

$$V_c^\sigma = \int_\sigma Q_c(t)dt \tag{20}$$

We can therefore define the rate of satisfaction of the water demand $r^\sigma$ as:

$$r^\sigma = \frac{V_c^\sigma}{V_d^\sigma} \tag{21}$$

Then, the number of households that effectively go to the PVWPS (i.e. number of consumers of the PVWPS) $n_c^\sigma$ is determined from the number of households that wish to go to the PVWPS (i.e. number of demanders of the PVWPS) $n_d^\sigma$ by:

$$n_c^\sigma = \mathrm{round}(r^\sigma \cdot n_d^\sigma) \tag{22}$$

In order to select the households that actually benefit from the PVWPS, we take the $n_c^\sigma$ households that have the highest probability to go to the PVWPS $\rho(h, PVWPS)$ amongst the $n_d^\sigma$ households that wish to go to the PVWPS. In addition, we consider that the $n_d^\sigma$ - $n_c^\sigma$ households that are not selected remain at the water source where they used to go before the installation of the PVWPS. This allows to deduce the vector $\boldsymbol{hs_{aft}}$ from the vector $\boldsymbol{hs_{aft}^*}$.

For instance, for the dry season and the current position of the PVWPS, $V_d^{dry}$ = 2778 m$^3$ and $n_d^{dry}$ = 36. For the oversized PVWPS, $V_c^{dry}$ = $V_d^{dry}$ and all the $n_d^{dry}$ households can attend the PVWPS ($n_c^{dry}$ = $n_d^{dry}$). For the undersized PVWPS, $V_c^{dry}$ = 427 m$^3$ and only $n_c^{dry}$ = 6 households can attend the PVWPS.

This is a first proposal to determine the number of consumers from the number of demanders in the case of an undersized system. This proposal could of course be refined in the future. It may notably be interesting to study households' behaviour in existing cases where PVWPS are undersized.

## III.4 Impact model

Thanks to the demand and technical models, we can predict the water sources where the households effectively go after the installation of the PVWPS $\boldsymbol{hs_{aft}}$. The impact model computes the socio-economic impact $SEI$ associated to the change in water sources of the households between before ($\boldsymbol{hs_{bef}}$) and after ($\boldsymbol{hs_{aft}}$) the installation of the PVWPS (see Figure III-20). The socio-economic impact is quantified thanks to several indicators.

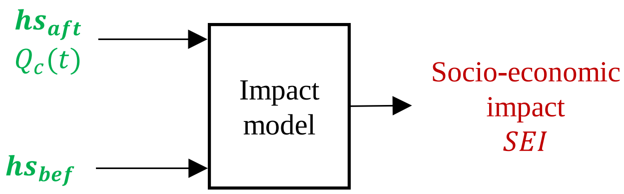


*Figure III-20 – Block diagram of the impact model.*

### *III.4.1 Indicators identification and ranking*

This section aims at identifying and ranking indicators that are related to the water source attended by a given household. To do so, we use the theory of change, which is a common tool in the impact evaluation literature [107, 108]. The proposed theory of change (see Figure III-21) presents the consequences of going to a given water source and each consequence is associated to an indicator. The proposed theory of change allows to have a better understanding of the socio-economic repercussions of investments in water infrastructures in rural sub-Saharan villages.

We distinguished two types of indicators: direct and indirect ones. Direct indicators correspond to attributes of the household-source couple ($h$, $s$). When an household changes of source, this is immediately associated with a change in these attributes. A change in these attributes may then trigger a change in other indicators, which are called 1st order indirect indicators. 1st order indirect indicator may themselves influence other indirect indicators, called 2nd order indirect indicators, so on and so forth.

Causal links between the indicators are represented by arrows in Figure III-21. In Table III-8, we present justifications for some of these causal links based on the literature. For the other causal links in Figure III-21, no references were encountered but we still represented these relations because they seem logical to us. Investigating these potential relations may represent future directions of research. For this purpose, similar methodologies as the one that we used in [109] to investigate the link between electricity access and willingness to pay for improved water access may be considered. Finally, the causal link between two indicators may be modelled by a coefficient $\alpha$ [110, 111]. This coefficient represents the magnitude to which a change in the value of the first indicator will impact the second indicator. For some of the causal links, we found results of studies that can allow to deduce a value for the coefficient $\alpha$. This is specified in Table III-8 by the "($\alpha$)" sign.

Finally, it is important to note that, the more indirect the indicator, the higher the influence of external factors on this indicator [107]. As a result, changes in indirect indicators may be more difficult to attribute to the change in water source than changes in direct indicators.

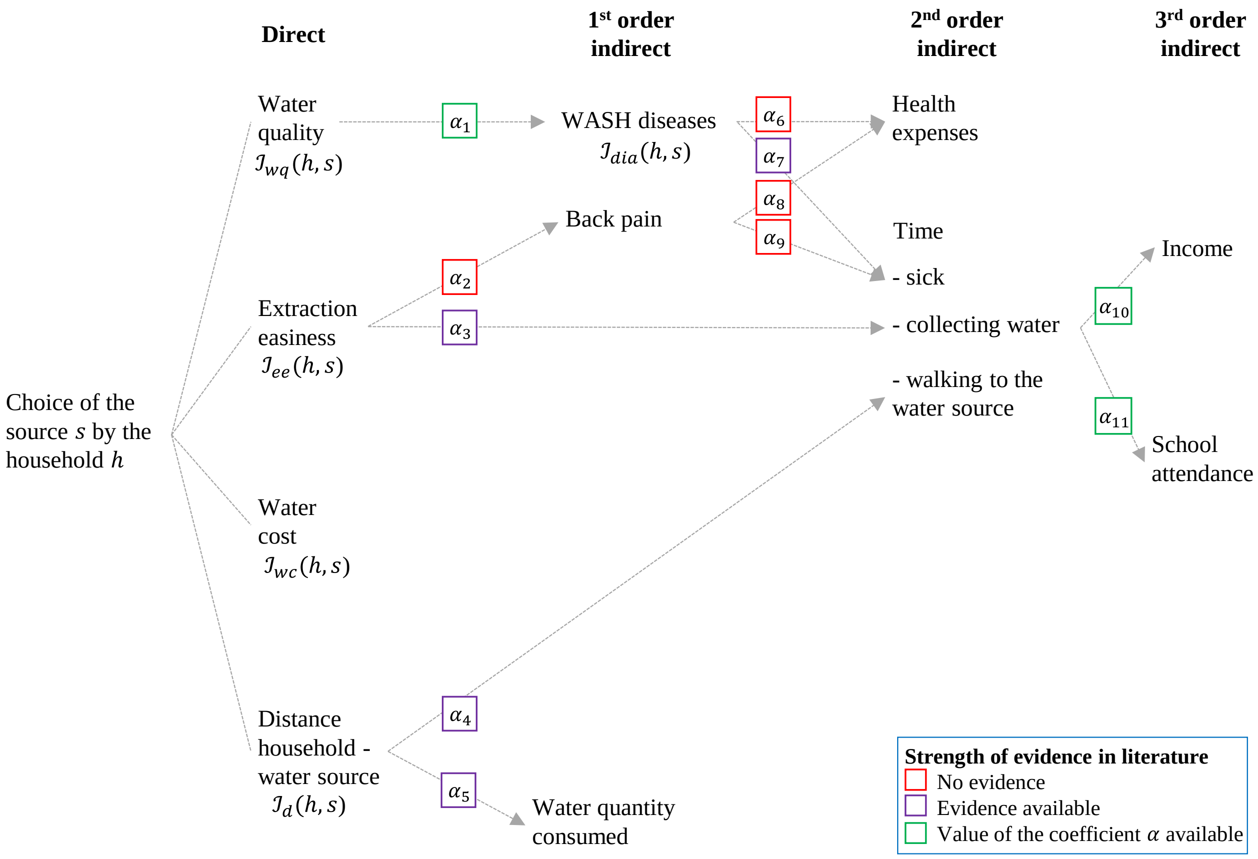


*Figure III-21 – Theory of change – effect of going to a water source. $\alpha$: causal link coefficient. WASH diseases: diseases related to water, sanitation and hygiene.*

*Table III-8 – Causal links between indicators of the theory of change.*

| Causal link n° | Input indicator | Output indicator | Justification from the literature |
|---|---|---|---|
| 1 | Water quality | WASH diseases | ➢ ($\alpha_1$) The percentage of reduction in diarrhea from water quality improvements is comprised between 12% and 47% [110].<br>➢ ($\alpha_1$) Water quality interventions trigger a 42% relative reduction in child diarrhea morbidity on average [112].<br>➢ ($\alpha_1$) A better access to safe water sources and better hygiene practices can decrease trachoma morbidity by 27% [113]. |
| 2 | Extraction easiness | Back pain | |
| 3 | Extraction easiness | Time collecting water | |
| 4 | Distance household - water source | Time walking to the water source | ➢ In Mozambique, Cairncross and Cuff [114] showed that women living in a village with a centrally located water source spent 106 minutes less to collect water per day than women living in a village who relied on a distant source.<br>➢ In Benin, Gross et al. [115] found that reduced walking distances from improved water access contributed to allow women to save 35 minutes per day. |
| 5 | Distance household - water source | Water quantity consumed | ➢ The higher the distance to collect water, the lower the water quantity consumed. According to [116], if the distance household-water source is:<br>o <250 m, the daily water consumption typically varies between 15 and 50 L/capita/day<br>o 250-1000 m, the daily water consumption typically varies between 10 and 30 L/capita/day<br>o >1000 m, the daily water consumption typically varies between 5 and 15 L/capita/day |
| 6 | WASH diseases | Health expenses | |
| 7 | WASH diseases | Time sick | ➢ Improving water, sanitation and hygiene services in schools can help to reduce the number of school days missed because of diarrhea [117]. |
| 8 | Back pain | Health expenses | |
| 9 | Back pain | Time sick | |
| 10 | Time savings | Income | ➢ ($\alpha_{10}$) In rural Kenya, Whittington et al. [111] computed that the value of the time saved from buying water to a vendor instead of collecting it was $0.38/hour.<br>➢ ($\alpha_{10}$) Churchill et al. [118] considered $0.125/hour as the value of the time of poor people.<br>➢ The percentage loss in gross domestic product due to diseases and productivity losses linked to water and sanitation is of 5% in developing countries [119].<br>➢ The Dutch ministry of foreign affairs raises awareness on the fact that the time saved from improved water access is often spent undertaking other unpaid work such as collecting firewood or unpaid agricultural labour. As a consequence, time savings may not allow a significant increase in income [120]. |
| 11 | Time savings | School attendance | ➢ ($\alpha_{11}$) In Ghana, reducing water collection time of 15 minutes allowed to increase girls school attendance by 8 to 12% [121].<br>➢ ($\alpha_{11}$) In Yemen, improved water supplies permitted to increase the percentage of girls enrolled in schools of 4 to 8% [120].<br>➢ In Tanzania, one third of water users groups reported that improved access to safe water supplies allowed to increase the time girls spend studying and school attendance [120].<br>➢ During the time when parents or siblings are sick, children skip class to take care of them. In addition, during the time when the teacher is sick, classes get cancelled [117]. |

## *III.4.2 Quantification of the indicators for each household*

### *III.4.2.1 Direct indicators*

When household $h$ attends a source $s$, we can compute the associated value of each direct indicator. The direct indicators, their methods of quantification and their range of variation in the case of Gogma are presented in Table III-9. Note that the lower the indicator, the better the living conditions of the household $h$.

*Table III-9 – Direct indicators.*

| Indicator | Quantification methods | Range of variation in Gogma $\mathcal{I}_{i,min}$ to $\mathcal{I}_{i,max}$ |
|---|---|---|
| Water quality $\mathcal{I}_{wq}$ | Based on the water quality tests performed, we determined that water from open wells is not potable and that water from hand pumps and the PVWPS is potable (see section II.2.7). We define the water quality variable as equal to 0 is the water is potable and 1 if the water is not potable. Note that, for a given source $s$, the water quality is the same for all households $h$. | 0 (potable water) to 1 (non-potable water) |
| Extraction easiness $\mathcal{I}_{ee}$ | For the PVWPS, we assume that water extraction at this source is 'not arduous' for all households, following on-field observations (see section II.2.1).<br>For the other sources, we know how households of the survey pool $\boldsymbol{h_{sur}}$ perceive water extraction at these sources (see Table III-1). In addition, we assumed that each household, that is not in $\boldsymbol{h_{sur}}$, goes to the same source as the household of $\boldsymbol{h_{sur}}$ that is the closest geographically (see section III.2.1.2). Thus, we also assume that it has the same perception of the extraction easiness at the source. | 0 (not arduous) to 2 (very arduous) |
| Water cost $\mathcal{I}_{wc}$ | The cost for collecting water at each source was obtained through account books and on-field observations. For a given source $s$, the water cost is the same for all households $h$. | \$0/month to \$0.89/month |
| Distance household-source $\mathcal{I}_{d}$ | We calculate the straight line distance between the household $h$ and the source $s$ from GPS coordinates. | 0 m to 983 m [7] |

The value of the direct indicator $i$ when the household $h$ chooses the source $s$ is noted $\mathcal{I}_i(h,s)$. Besides, before the installation of the PVWPS, the household $h$ attends the source $s_{bef}$ and, after the installation of the PVWPS, the household $h$ attends the source $s_{aft}$ (it is of course possible to have $s_{aft} = s_{bef}$). We define the variation of the direct indicator $i$ between before and after installation of the PVWPS, $\Delta\mathcal{I}_i(h)$, by:

$$\Delta\mathcal{I}_i(h) = -\left(\mathcal{I}_i(h, s_{aft}) - \mathcal{I}_i(h, s_{bef})\right) \tag{23}$$

We added the 'minus' sign at the beginning of equation (23) so that an improvement of the living conditions of the household $h$, i.e. $\mathcal{I}_i(h, s_{aft}) < \mathcal{I}_i(h, s_{bef})$, corresponds to a positive value of the indicator variation, i.e. $\Delta\mathcal{I}_i(h) > 0$.

[7] The distance household-source depends on the prediction of the demand model. In order to determine the maximum that this distance can reach ($\mathcal{I}_{d,max}$), we run 1000 times the demand model for random positions of the PVWPS in the village. We keep the maximum distance that a household is willing to travel to collect water, according to the model.

### *III.4.2.2 Indirect indicators*

The variation of the 1st order indirect indicators is deduced from the variation of the direct indicators thanks to the coefficients $\alpha$. The variation of the 2nd order indirect indicators is obtained from the variation of the 1st order indirect indicators in the same way, and so on for the 3rd order indirect indicators.

The first method to determine the value of a coefficient $\alpha$ is to extrapolate it from the literature. For instance, for the coefficient $\alpha_1$, according to [110], the percentage of reduction in diarrhea from water quality improvements is comprised between 12% and 47%. Therefore we consider a value of $\alpha_1$ equal to the mean between 12% and 47%, i.e. 35%. We also assume that a water quality improvement for the household $h$ corresponds to switching from a non-potable source to a potable one ($\Delta\mathcal{I}_{wq}(h)$ = 1) and that the percentage of reduction in diarrhea corresponds to the reduction of the percentage of household members affected by diarrhea, noted $\Delta\mathcal{I}_{dia}(h)$. $\Delta\mathcal{I}_{dia}(h)$ is thus given by:

$$\Delta\mathcal{I}_{dia}(h) = \alpha_1 \cdot \Delta\mathcal{I}_{wq}(h) \tag{24}$$

The first problem associated with this literature-based method is that studies are not available for all of the coefficients $\alpha$. For instance, for the theory of change of Figure III-21, studies were found for only 3 coefficients $\alpha$ ($\alpha_1$, $\alpha_{10}$, $\alpha_{11}$). In addition, we observe that only $\alpha_1$ can be used in our case as using $\alpha_{10}$ and $\alpha_{11}$ would require the knowledge of $\alpha_3$, $\alpha_4$, $\alpha_7$ and $\alpha_9$. The second problem is that the value used for the coefficient is not specific to the considered case study and was determined by using data from another case study. Indeed, the value of the coefficient may vary from one case study to another due to the fact that the socio-economic conditions are not the same.

The second method to determine the value of a coefficient $\alpha$ is to perform a regression between the two indicators that are related by the coefficient $\alpha$, using the data on the indicators collected in the village. For instance, for determining $\alpha_1$, one could perform a regression between the quality of the water source used and the percentage of household members affected by diarrhea. The main advantage of this method is that the value of $\alpha_1$ obtained is more accurate because it is specific to the considered case study. However, there are two main challenges for the application of this method. Firstly, it requires a complex analysis notably for identifying the control variables to include in the regression model and for demonstrating causality and not only correlation [122]. Secondly, for several coefficients, data that can be collected in one village only (~100 households) may not represent a large enough sample to accurately determine the coefficient [123]. In future works, it may be interesting to study which $\alpha$ coefficients may be determined with data from one village only, by using the household surveys performed in Gogma.

Following these considerations, in this thesis, we consider only the 4 direct indicators and the 1st order indirect indicator "WASH diseases". The "WASH diseases" indicator is itself restricted to "diarrhea", which is quantified from the "water quality" indicator using the coefficient $\alpha_1$ from the literature (see equation (24)), taken equal to 35%.

## *III.4.3 Socio-economic impact at the scale of the village*

The normalised variation of the indicator $i$, between before and after the installation of the PVWPS, at the scale of the village $\Delta\mathcal{I}_i(\boldsymbol{h})$ is given by:

$$\Delta\mathcal{I}_i(\boldsymbol{h}) = \frac{\sum_{k=1}^{n_v} \Delta\mathcal{I}_i(h_k)}{n_v \cdot \left(\mathcal{I}_{i,max} - \mathcal{I}_{i,min}\right)} \tag{25}$$

where $\boldsymbol{h}$ is a vector containing all the households of the village, $n_v$ is the number of households in the village, $\mathcal{I}_{i,min}$ and $\mathcal{I}_{i,max}$ are the minimum and maximum possible values of the indicator $i$ at the scale of the household. The minimum and maximum values of the direct indicators are given in Table III-9. The minimum of the diarrhea indicator is 0 and the maximum is $\alpha_1$ (0.35). Thanks to the normalisation by the denominator, for each indicator $i$, $\Delta\mathcal{I}_i(\boldsymbol{h})$ is a quantity without unit comprised between 0 and 1.

As presented in section III.1, the vectors $\boldsymbol{hs_{bef}}$ and $\boldsymbol{hs_{aft}}$, which are the inputs of the impact model, are not the same between the dry season and the wet season. Therefore, the variation of the indicators for each household $\Delta\mathcal{I}_i(h)$ (equations (23) and (24)) and the variation of the indicators for the whole village $\Delta\mathcal{I}_i(\boldsymbol{h})$ are computed for each season ($\sigma \in$ {dry, wet}). We define the socio-economic impact for the season $\sigma$, $SEI^\sigma$, as the weighted sum of the normalized variations of the indicators at the scale of the village:

$$SEI^\sigma = \sum_i w_i \cdot \Delta\mathcal{I}_i^\sigma(\boldsymbol{h}) \tag{26}$$

The weights $w_i$ are set by the decision maker depending on the indicators that he wants to favour. The socio-economic impact for the whole year $SEI$ is therefore equal to:

$$SEI = \frac{7}{12} SEI^{dry} + \frac{5}{12} SEI^{wet} \tag{27}$$

The coefficients $\frac{7}{12}$ and $\frac{5}{12}$ come from the fact that, in Gogma, the dry season lasts for 7 months and the wet season lasts for 5 months. Overall, we compare the values of the indicators for the dry season that follows the installation of the PVWPS to the ones for the dry season that precedes the installation of the PVWPS (same for the wet season). We do not consider the evolution of the indicators over the whole lifetime of the PVWPS (for instance the water cost $\mathcal{I}_{wc}$ at the PVWPS may change over the years). This will be the object of future work.

## III.5 Economic model

The economic model determines the life-cycle cost $LCC$ of the PVWPS for different values of the sizing variables $P_{pv,p}$, $MP$, $V_t$ (see Figure III-22). The model is presented in section III.5.1 and results are given in section III.5.2. Our economic model builds on the related MSc thesis project undertaken by Elvire Andre de la Fresnaye in 2018 [18].

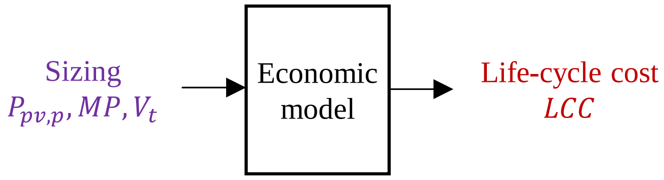


*Figure III-22 – Block diagram of the economic model.*

### III.5.1 Model

The life-cycle cost of the PVWPS is given by [50]:

$$LCC = CAPEX + OPEX \tag{28}$$

where $CAPEX$ is the capital cost and $OPEX$ is the total discounted operational cost over the lifetime of the PVWPS. $OPEX$ is given by:

$$OPEX = \sum_{j=1}^{L} \frac{yOPEX(j)}{(1+dr)^j} \tag{29}$$

where $yOPEX(j)$ is the yearly operational cost for year $j$, $dr$ is the discount rate and $L$ is the lifetime of the PVWPS. It is important to note that the lifetimes of all the components of the PVWPS also have to be determined in order to compute $yOPEX(j)$.

In section III.5.1.1, we determine the lifetimes of the PVWPS and of its components. The capital cost and the operational cost are determined in sections III.5.1.2 and III.5.1.3 respectively.

#### III.5.1.1 Lifetime

Data on the lifetime of the PVWPS and of its different components were collected through a literature review and through surveys with members of companies specialised in photovoltaic energy and PVWPS based in Burkina Faso (survey in Appendix D). The collected data are presented in Table III-10. In this table, we also specify the values selected in this thesis.

*Table III-10 – Lifetime of the PVWPS and of its components.*

| | Lifetime from the literature and surveys (years) | Selected lifetime (years) |
|---|---|---|
| PVWPS | ➢ **10** [124]<br>➢ **20** [20, 24, 125, 126, 127, 128, 129]<br>➢ **25** [34] | 20 |
| Borehole | ➢ **50** (Survey, A. Darga) (Survey, F. Lingani) | 50 |
| PV modules | ➢ **20** [20, 110]<br>➢ **25** [50] (Survey, F. Lingani)<br>➢ **30** (Survey, G. J. Balima) | 25 |
| PV modules structure | ➢ **50** (Survey, G. J. Balima) | 50 |
| Water level controller, float switch | ➢ **5** (Survey, A. Darga) | 5 |
| Motor-pump | ➢ **10** [34, 49, 128, 20] (Survey, F. Lingani) (Survey, G. J. Balima) | 10 |
| Tank | ➢ **20** [20]<br>➢ **50** (Survey, F. Lingani) | 30 |
| Fountain | ➢ **30** (Survey, A. Darga) | 30 |
| Fountain taps | ➢ **2** (Survey, A. Darga) | 2 |
| Pipes | ➢ **50** (Survey, G. J. Balima) | 50 |
| Wire fence | ➢ **20** (Survey, A. Darga) | 20 |
| Cables | ➢ **10** [20]<br>➢ **25** (Survey, F. Lingani)<br>➢ **30** (Survey, G. J. Balima) | 25 |
| Signpost | ➢ **20** (Survey, A. Darga) | 20 |

#### *III.5.1.2 Capital cost*

The capital cost is equal to:

$$CAPEX = CAPEX_{pv} + CAPEX_{MP} + CAPEX_t + CAPEX_f \tag{30}$$

where $CAPEX_{pv}$ is the PV modules capital cost, $CAPEX_{MP}$ is the motor-pump capital cost, $CAPEX_t$ is the tank capital cost and $CAPEX_f$ is the fixed capital cost. $CAPEX_{pv}$, $CAPEX_{MP}$ and $CAPEX_t$ depend on the sizing variables of the PVWPS ($P_{pv,p}$, $MP$, $V_t$), contrarily to $CAPEX_f$.

The capital cost $CAPEX_{MP}$ of each of the 8 references of motor-pumps $MP$ that we consider is available at [130]. Several local companies in Burkina Faso order their motor-pumps from Off-grid Europe. It is interesting to observe that, despite the fact that the 8 motor-pumps do not have the same performances, they all cost the same price: \$2.2 $10^3$.

Then, we determine the capital cost of the PV modules $CAPEX_{pv}$ as a function of the PV modules peak power $P_{pv,p}$ and the capital cost of the steel tank $CAPEX_t$ as a function of the tank volume $V_t$. For this purpose, we collected data on the capital cost of PV modules and of steel tanks for different PV modules peak powers and different tank volumes with the following methods:

- We included questions on the capital cost of PV modules and tanks in the survey to local companies (see Appendix D).
- Some local companies gave us quotations on PVWPS that they installed in the past.
- We asked several local companies to make us a quotation for installing a PVWPS in the village of Bidiga, which is situated at ~10 km from Gogma. For each company, we changed the system

specifications in terms of total dynamic head and daily water consumption in order to obtain quotations for PVWPS of different sizes.

The results of the data collection are presented in Figure III-23 for the PV modules and in Figure III-24 for the tank.

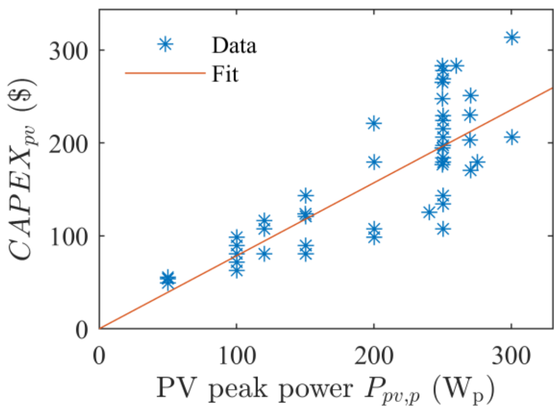


*Figure III-23 – Capital cost of the PV modules as a function of the PV modules peak power.*

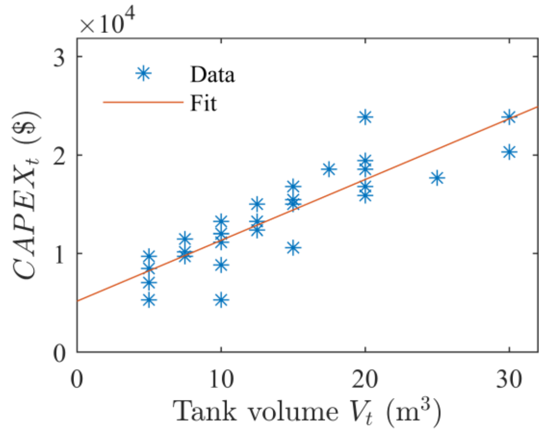


*Figure III-24 – Capital cost of the tank as a function of the tank volume.*

We fit the collected data presented in Figure III-23 and we obtain the expression of $CAPEX_{pv}$ as a function of $P_{pv,p}$:

$$CAPEX_{pv} = 0.79\ P_{pv,p} \quad (\mathrm{R}^2 = 0.64) \tag{31}$$

We do the same for the data of Figure III-24 for the tank:

$$CAPEX_t = 6.2\ 10^2\ V_t + 5.2\ 10^3 \quad (\mathrm{R}^2 = 0.78) \tag{32}$$

Finally, regarding the fixed capital cost $CAPEX_f$, we use the data for the current PVWPS of Gogma which are given in Table III-11. These information were provided by the NGOs Respublica and Eau Fil du Soleil which financed the PVWPS of Gogma.

*Table III-11 – Fixed capital cost breakdown.*

| Component | Cost (\$) |
|---|---|
| Borehole | $8.3\ 10^3$ |
| PV modules structure | $1.0\ 10^2$ |
| Water level controller, float switch | $4.2\ 10^2$ |
| Fountain | $1.3\ 10^3$ |
| Fountain taps | $5.0\ 10^1$ |
| Pipes | $1.9\ 10^3$ |
| Wire fence | $1.1\ 10^3$ |
| Other material (cables, glue, locks, signpost) | $7.2\ 10^2$ |
| Installation workforce | $1.4\ 10^3$ |
| **Total fixed capital cost $CAPEX_f$** | **$1.5\ 10^4$** |

In reality, there is a part of the borehole cost that depends on the depth of the borehole and therefore on the groundwater resources where the borehole is drilled. Consequently, the borehole cost varies with the

position ($Lat$, $Lon$) of the PVWPS in the village. However, we cannot take this variation into account because, as explained in section II.2.3, it is not possible to determine the groundwater resources for all positions in a village.

### *III.5.1.3 Operational cost*

The yearly operational cost is composed of a yearly replacement cost $yOPEX_{re}$ and of a yearly maintenance cost $yOPEX_{ma}$. We therefore have:

$$yOPEX(j) = yOPEX_{re}(j) + yOPEX_{ma}(j) \tag{33}$$

Firstly we estimate the yearly replacement cost $yOPEX_{re}$. According to the lifetime of the installed components presented in Table III-10, the only components that are replaced during the 20 years lifetime of the PVWPS are:

- the motor-pump $MP$ which is replaced every 10 years
- the fountain taps which are replaced every 2 years.
- the water level controller and the associated float switch which are replaced every 5 years

As a consequence, the yearly replacement cost $yOPEX_{re}$ for year $j$ is:

$$yOPEX_{re}(j) = \begin{cases} CAPEX_{fountain\ taps} \text{ if } j \in [2, 4, 6, 8, 12, 14, 16, 18] \\ CAPEX_{controller\ \&\ switch} \text{ if } j \in [5, 15] \\ CAPEX_{MP} + CAPEX_{fountain\ taps} + \ CAPEX_{controller\ \&\ switch} \text{ if } j \in 10 \\ 0 \text{ otherwise} \end{cases} \tag{34}$$

where $CAPEX_{fountain\ taps}$ is the capital cost of the fittings and taps for the fountain and $CAPEX_{controller\ \&\ switch}$ is the capital cost of the water level controller and the float switch.

Secondly we estimate the yearly maintenance cost $yOPEX_{ma}$. Data on the maintenance cost of PVWPS are scarce because PVWPS have been deployed in a large scale only in recent years [131, 132]. [50] considers a value of 1% of the capital cost for the yearly maintenance cost. Consequently, the variable maintenance cost $yOPEX_{ma}$ for year $j$ is:

$$yOPEX_{ma}(j) = \frac{CAPEX(j)}{100} \tag{35}$$

## *III.5.2 Results*

We compute the capital, operational, and life-cycle costs for the sizing of the current PVWPS of Gogma ($P_{pv,p}$ = 620 $W_p$, $MP$ = SQFlex 5A-7, $V_t$ = 11.4 $m^3$). The discount rate $dr$ considered for Burkina Faso is 5.6% [18]. The results for the current PVWPS of Gogma are given in Table III-12.

*Table III-12 – Capital, operational and life-cycle costs - current PVWPS of Gogma.*

| Cost | Value ($) |
|---|---|
| $\boldsymbol{CAPEX}$ | **3.0 $10^4$** |
| $CAPEX_{pv}$ | 4.9 $10^2$ |
| $CAPEX_{MP}$ | 2.2 $10^3$ |
| $CAPEX_t$ – variable part (6.2 $10^2$ $V_t$) | 7.1 $10^3$ |
| $CAPEX_t$ – fixed part | 5.2 $10^3$ |
| $CAPEX_f$ | 1.5 $10^4$ |
| $\boldsymbol{OPEX}$ | **6.0 $10^3$** |
| $\boldsymbol{LCC}$ | **3.6 $10^4$** |

We observe that the $CAPEX$ is 5 times higher than the $OPEX$. This prevalence of the $CAPEX$ over the $OPEX$ is characteristic of PVWPS [31]. In addition, the sum of $CAPEX_{pv}$, $CAPEX_{MP}$ and the variable part of $CAPEX_t$ is equal to \$9.8 $10^3$, i.e. one third of the $CAPEX$. This shows that the margin of cost reduction that can be achieved through the sizing variables ($P_{pv,p}, MP$ and $V_t$) is moderate.

## III.6 Partial conclusion

In this chapter, we described the proposed interdisciplinary model. This model links the sizing and the position of the PVWPS to its life-cycle cost and socio-economic impact.

The interdisciplinary model is composed of 4 sub-models:

- The demand model predicts the water demand at the PVWPS (i.e. the households that wish to go to the PVWPS) for any position of the PVWPS in the village.
- The technical model allows to identify the households that can effectively go to the PVWPS amongst the households that wish to go to the PVWPS.
- The impact model evaluates the socio-economic impact associated with the changes in water sources of the households between before and after the installation of the PVWPS.
- The economic model allows to determine the life-cycle cost of the PVWPS depending on its sizing.

Besides, we presented how the experimental data that we collected in Chapter II are integrated into each of these 4 sub-models and we compared the outputs of the demand and technical models to experimental measurements.

# Chapter IV Optimal design

# Chapter IV Optimal design

In Chapter III, we proposed an interdisciplinary model which links the sizing and the position of the PVWPS to its life-cycle cost and socio-economic impact. In section IV.1, we define an optimisation problem which aims at determining the sizings and the positions of the PVWPS which minimize its life-cycle cost and maximize its socio-economic impact. In section IV.2, we analyse an optimisation result for the case of Gogma, obtained for a socio-economic impact $SEI$ which considers all the direct indicators with weights all equal to one, and supposing that the groundwater resources are the same for all positions in Gogma. In section IV.3, we investigate the influence of the error in the demand model output on the optimisation results. In section IV.4, we study the influence of the indicators selected in the $SEI$ function on the optimisation results. In section IV.5, we investigate the effect of the groundwater resources on the optimisation results. Finally, in section IV.6, we propose an improved procedure for the design and installation of PVWPS, that includes the optimisation methodology developed.

## IV.1 Optimisation problem

The two objective functions of the optimisation are the life-cycle cost $LCC$ of the PVWPS, that we want to minimise, and its socio-economic impact $SEI$, that we want to maximise. The variables of the optimisation are the peak power of the PV array $P_{pv,p}$, the motor-pump reference $MP$, the tank volume $V_t$, the latitude $Lat$ and the longitude $Lon$ of the PVWPS. The motor-pump reference $MP$ is the only discrete variable and we remind that we have digitized the characteristic curves of 8 references of motor-pumps (see section III.3.2.1).

We add the constraint that, for each motor-pump reference $MP$, the total dynamic head $TDH$ must remain smaller than the maximum pumping height $H_{max}(MP)$ specified in the datasheet of the motor-pump:

$$TDH(t) < H_{max}(MP), \qquad \forall t \tag{36}$$

We also remind that we allow for undersized systems and the whole water demand $Q_d$ not to be fulfilled (see section III.3.3). In order not to consider undersized systems, the constraint that the water level in the tank remains higher than 0 m ($H_t(t) > 0, \forall t$) would need to be added.

Once the position of the PVWPS is set and the borehole is drilled, the maximum flow rate that can be pumped $Q_{p,max}$ can be determined from pumping tests. At this moment, we propose to set the constraint that the pump flow rate $Q_p$ must remain lower than $Q_{p,max}$. For sections IV.2 to IV.5, the position is not set so we do not implement this constraint. In section IV.6 though, we propose a real procedure for the design and installation of PVWPS and we therefore show the implementation of this constraint.

We use a bi-objective differential evolution algorithm [133], which is a stochastic algorithm, to solve the optimisation problem. We chose a stochastic algorithm because the optimisation problem is non-linear. We perform one optimisation for each motor-pump reference $MP$, and we therefore obtain one Pareto front for each motor-pump reference. We then draw the final Pareto front by going through the best points of the Pareto fronts of the motor-pump references.

## IV.2 Analysis of a reference result

In this section, we perform a first optimisation for the case study of Gogma.

We consider the four direct indicators in the $SEI$ and we take all the weighting coefficients equal to 1. The $SEI$ is therefore given by:

$$\begin{aligned} SEI = \; & \frac{7}{12}\left(\Delta\mathcal{I}_{wq}^{dry}(\boldsymbol{h}) + \Delta\mathcal{I}_{ee}^{dry}(\boldsymbol{h}) + \Delta\mathcal{I}_{wc}^{dry}(\boldsymbol{h}) + \Delta\mathcal{I}_{d}^{dry}(\boldsymbol{h})\right) + \\ & \frac{5}{12}\left(\Delta\mathcal{I}_{wq}^{wet}(\boldsymbol{h}) + \Delta\mathcal{I}_{ee}^{wet}(\boldsymbol{h}) + \Delta\mathcal{I}_{wc}^{wet}(\boldsymbol{h}) + \Delta\mathcal{I}_{d}^{wet}(\boldsymbol{h})\right) \end{aligned} \tag{37}$$

We consider the boundaries presented in Table IV-1 for the optimisation variables. The boundaries on $Lat$ and $Lon$ correspond to the dimensions of the village of Gogma. There are no areas to avoid in Gogma. If they were, we would have set the constraint that the position of the PVWPS ($Lat$, $Lon$) cannot be in these areas. In section IV.6, we show how to implement a constraint on the PVWPS position in the optimisation. Finally, we remind that the justification for the lower boundary of $V_t$ is given in section III.3.2.1.

*Table IV-1 – Boundary of the optimisation variables – Case of Gogma.*

| Variable | Discrete/ Continuous | Value for the current PVWPS of Gogma | Lower boundary | Upper boundary |
|---|---|---|---|---|
| **Sizing** | | | | |
| Peak power PV array $P_{pv,p}$ | Continuous | 620 $W_p$ | 0 $W_p$ | $10^4$ $W_p$ |
| Motor-pump reference $MP$ | Discrete | SQFlex 5A-7 | NA | NA |
| Tank volume $V_t$ | Continuous | 11.4 $m^3$ | 0.1 $m^3$ | 15 $m^3$ |
| **Position** | | | | |
| Latitude $Lat$ | Continuous | 11.7244 ° | 11.720 ° | 11.738 ° |
| Latitude $Lon$ | Continuous | -0.5722 ° | -0.585 ° | -0.567 ° |

NA: not applicable

In addition, we suppose that the values of the groundwater parameters are the same for all positions of the PVWPS in the village. They are taken equal to the values for the current PVWPS (see Table III-7).

### *IV.2.1 Mono-objective optimisations results*

Before performing the bi-objective optimisation, we perform two mono-objective optimisations: for the first one we aim at maximising the $SEI$ and for the second one we aim at minimising the $LCC$. This allows to verify that the two objective functions are contradictory and to better understand the influence of each objective function.

We also use the differential evolution algorithm of [133] and perform one mono-objective optimisation for each motor-pump reference $MP$. We keep the best result from all the motor-pump references as final result of the mono-objective optimisation. For each mono-objective optimisation (i.e. for each motor-pump reference), we consider 150 individuals and the optimisation stops when the value of the objective function has not changed for 20 generations. The starting population is generated randomly. The total computing time for the mono-objective optimisation, when the 8 motor-pump references are considered, is ~1 h with a HP EliteBook 840 G3 (processor: Intel(R) Core(TM) i7-6600U CPU @ 2.60GHz 2.70 GHz; RAM: 8 Go) [134].

#### *IV.2.1.1 Objective function: SEI*

We perform the mono-objective optimisation with the $SEI$ as objective function. The maximum value of the $SEI$ encountered is 0.105. The optimal values of the variables are given in Table IV-2. The optimal position of the PVWPS is represented by a green star in Figure IV-1. We then compute the $LCC$ for the optimal values of the variables. It is equal to \$3.50 $10^4$. The $SEI$ of 0.105 corresponds to the highest impact that can be encountered.

*Table IV-2 – Results of the mono-objective optimisation which aims at maximising the $SEI$.*

| | |
|---|---|
| $P_{pv,p}$ | 2.7 $10^3$ $W_p$ |
| $MP$ | SQFlex 2.5-2 |
| $V_t$ | 7.9 $m^3$ |
| $Lat$ | 11.7248 ° |
| $Lon$ | - 0.5709 ° |
| $LCC$ | \$3.50 $10^4$ |
| $SEI$ | 0.105 |

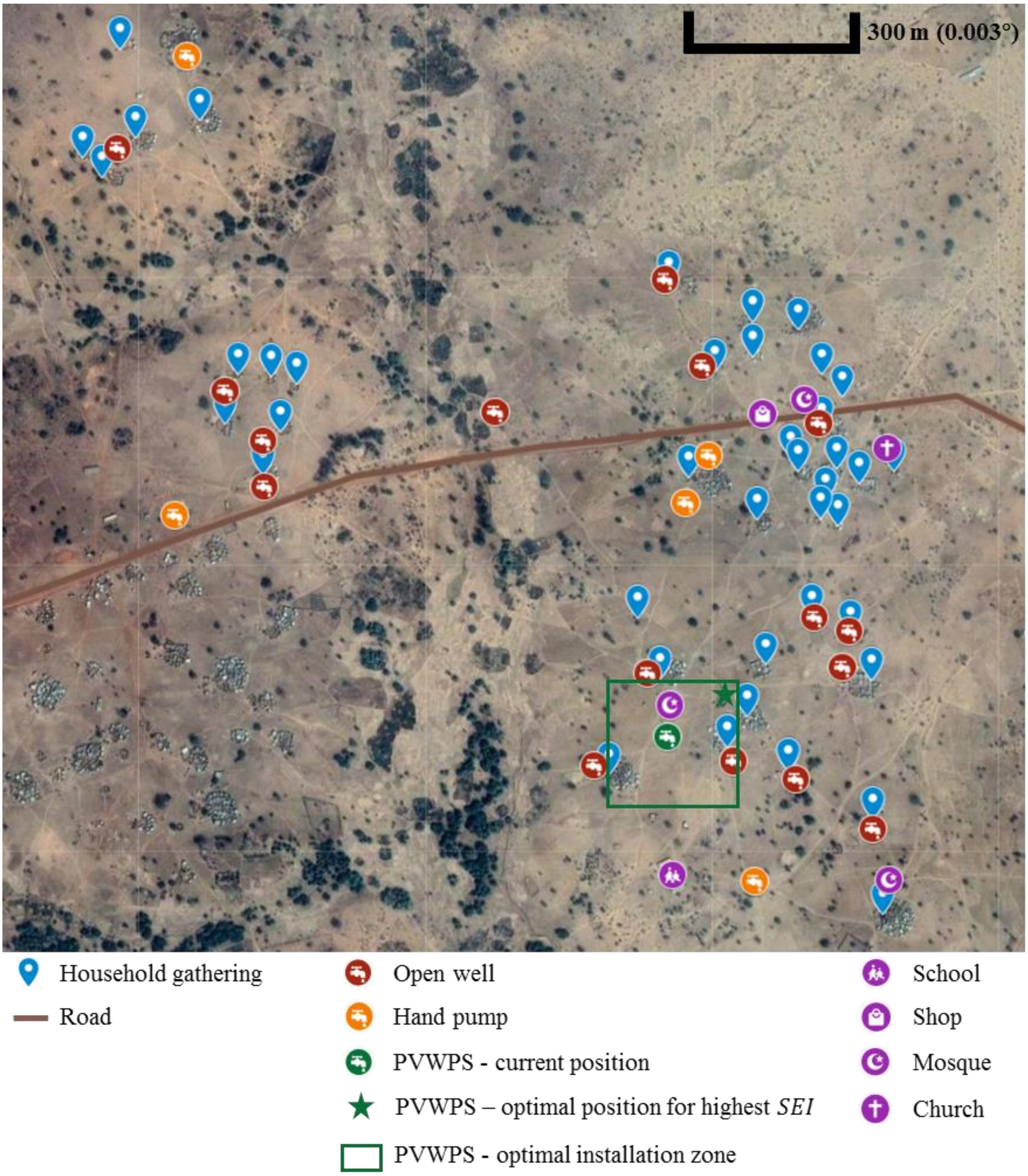


*Figure IV-1 – Optimal positions of the PVWPS.*

In Table IV-3, we provide more information about the quantities that are related to the value of the $SEI$.

*Table IV-3 – Demanders and consumers of the PVWPS and impact indicators.*

| | Dry | Wet |
|---|---|---|
| Number of households that wish to go to the PVWPS (number of demanders) $n_d$ | 39 | 39 |
| Number of households that effectively go to the PVWPS (number of consumers) $n_c$ | 36 | 38 |
| Number of consumers that used to go to an open well before the installation of the PVWPS $n_{c,ow}$ | 18 | 33 |
| Number of consumers that used to go to a hand pump before the installation of the PVWPS $n_{c,hp}$ | 18 | 5 |
| Variation of the water quality indicator $\Delta\mathcal{I}_{wq}(\boldsymbol{h})$ | 0.14 | 0.26 |
| Variation of the extraction easiness indicator $\Delta\mathcal{I}_{ee}(\boldsymbol{h})$ | 0.15 | 0.22 |
| Variation of the water cost indicator $\Delta\mathcal{I}_{wc}(\boldsymbol{h})$ | -0.28 | -0.30 |
| Variation of the distance indicator $\Delta\mathcal{I}_{d}(\boldsymbol{h})$ | 0.04 | -0.01 |
| Socio-economic impact $SEI$ | 0.06 | 0.17 |

It is interesting to observe that all the households that wish to go to the PVWPS are not able to go there ($n_c \neq n_d$). This is related to the fact that some of the indicators in the chosen $SEI$ function are contradictory (as explained in the next paragraph). The small difference between the number of PVWPS consumers during the dry season ($n_c$ = 36) and the wet season ($n_c$ = 38) is due to the difference in the water demand $Q_d$, irradiance $G_{pv}$ and ambient temperature $T_a$ between both seasons. Results also indicate that most consumers of the PVWPS used to go to open wells before the installation of the PVWPS. Indeed, as open wells are sources where the water quality is the worst and where extraction is the most difficult, the households that used to go to open wells are targeted in priority by the optimisation. This also explains the choice of the optimal position ($Lat$ = 11.7248°, $Lon$ = -0.5709°). Indeed, the household's density is relatively high around this position and the only neighbouring sources are open wells (see Figure IV-1).

Regarding the values of the impact indicators:

- We observe an improvement in the water quality indicator for both seasons ($\Delta\mathcal{I}_{wq}^{dry}(\boldsymbol{h})$ > 0 and $\Delta\mathcal{I}_{wq}^{wet}(\boldsymbol{h})$ > 0) which is explained by the fact that households which switch from an open well to the PVWPS see an improvement in water quality. 18 households ($n_{c,ow}^{dry}$) see an improvement in water quality during the dry season and 33 ($n_{c,ow}^{wet}$) during the wet season.
- The extraction easiness is also improved for both seasons ($\Delta\mathcal{I}_{ee}^{dry}(\boldsymbol{h})$ > 0 and $\Delta\mathcal{I}_{ee}^{wet}(\boldsymbol{h})$ > 0) as switching from an open well or a hand pump to the PVWPS is associated to an easier water extraction. 36 households ($n_c^{dry}$) see an improvement in extraction easiness during the dry season and 38 ($n_c^{wet}$) during the wet season. However, it is important to keep in mind that the improvement of the extraction easiness indicator is higher when an household switches from an open well to the PVWPS ($\Delta\mathcal{I}_{ee}(h)$~2) than when an household switches from a hand pump to the PVWPS ($\Delta\mathcal{I}_{ee}(h)$~1).
- The water cost has increased for both seasons ($\Delta\mathcal{I}_{wc}^{dry}(\boldsymbol{h})$ < 0 and $\Delta\mathcal{I}_{wc}^{wet}(\boldsymbol{h})$ < 0) because collecting water at the PVWPS is more expensive than at other water sources (section II.2.4). 36 households ($n_c^{dry}$) see an increase in water cost during the dry season and 38 ($n_c^{wet}$) during the wet season.
- The variation of the distance indicator is slightly positive during the dry season ($\Delta\mathcal{I}_{d}^{dry}(\boldsymbol{h})$ = 0.04) and slightly negative during the wet season ($\Delta\mathcal{I}_{d}^{wet}(\boldsymbol{h})$= -0.01). On average, for the dry season, PVWPS consumers see their distance to the water source reduced of 42 m with the installation of the PVWPS. For the wet season, they see their distance to the water source increased of 13 m.

Indeed, the share of PVWPS consumers that used to go to open wells is higher for the wet season than for the dry season and open wells are in general very close to the households (see Figure IV-1).

We see that the $SEI^{dry}$ (0.06) is lower than the $SEI^{wet}$ (0.17). As seen previously, this is due to the fact that more households used to go to open wells during the wet season than during the dry one ($n_{c,ow}^{wet}$ = 33 and $n_{c,ow}^{dry}$ = 18), triggering higher variation in the water quality and extraction easiness indicators (which are not compensated by the decrease in the variations of the water cost and distance indicators).

#### *IV.2.1.2 Objective function: LCC*

We perform the mono-objective optimisation with the $LCC$ as objective function. We add the constraint the the socio-economic impact $SEI$ has to be strictly higher than 0, to force the existence of a system. The minimum value of the $LCC$ encountered is \$2.72 $10^4$. This means that installing a PVWPS at least costs \$2.72 $10^4$. The associated values of the variables are given in Table IV-4. We then compute the $SEI$ for these values of the variables. It is equal to 0.001. For these values of the variables, one household consumes water at the PVWPS and only during the wet season. The encountered system does not have a real application because it has a very low $SEI$ and already a significant cost $LCC$, which is due to the high share of the $LCC$ that does not depend on the values of the sizing variables (see section III.5).

*Table IV-4 – Results of the mono-objective optimisation which aims at minimising the $LCC$, with the constraint $SEI > 0$.*

| | |
|---|---|
| $P_{pv,p}$ | 27 $W_p$ |
| $MP$ | SQFlex 2.5-2 |
| $V_t$ | 0.1 $m^3$ |
| $Lat$ | - 0.5735 ° |
| $Lon$ | 11.7263 ° |
| $LCC$ | \$2.72 $10^4$ |
| $SEI$ | 0.001 |

#### *IV.2.1.3 Comparing the results of the mono-objective optimisations*

We now compare the results of the mono-objective optimisations. The optimisation which aims at maximising the $SEI$ yields to a $SEI$ of 0.105 and to a $LCC$ of \$3.50 $10^4$. The optimisation which aims at minimising the $LCC$ yields to a $LCC$ of \$2.72 $10^4$ and a $SEI$ of 0.001. We observe that aiming to increase the socio-economic impact $SEI$ is associated to an increase in life-cycle cost $LCC$. Reciprocally, aiming to decrease the $LCC$ is associated to a decrease in $SEI$. Therefore, the minimisation of the $LCC$ and the maximisation of the $SEI$ are two contradictory objectives, which justifies the need for bi-objective optimisation. We also observe in Table IV-2 and Table IV-4 that the minimisation of the $LCC$ tends to lower the values of the PV array peak power $P_{pv,p}$ and of the tank volume $V_t$ and that the maximisation of the $SEI$ tends to increase the values of these variables.

### *IV.2.2 Bi-objective optimisation results*

As presented in section IV.1, we perform a bi-objective optimisation for each of the 8 motor-pump references $MP$. Before each bi-objective optimisation, we always perform the mono-objective optimisation with the $SEI$ as objective function. Then, we integrate the optimal values of the variables from the mono-

objective optimisation in the starting population of the bi-objective one. If we do not do this, we notice that the bi-objective optimisation may not find the maximum $SEI$ of the mono-objective optimisation. We also generate 60% of the starting population of the bi-objective optimisation from the optimal values of the variables obtained from the mono-objective optimisation: we consider smaller sizings and randomly chosen nearby positions (within a radius of ~100 m). The remaining 40% of the starting population are generated randomly. We do not perform the mono-objective optimisation with the $LCC$ as objective function because the points of the Pareto front with very low $SEI$ (<0.02) are not relevant (see section IV.2.1.2).

For each bi-objective optimisation (i.e. for each motor-pump reference), we consider 150 individuals and the optimisation stops after 150 generations. The total computing time for one bi-objective optimisation, when the 8 motor-pump references are considered, is ~2 h with a HP EliteBook 840 G3 [134]. When we add the time to run the mono-objective optimisation (~1 h), we obtain a total time of ~3 h. We chose these values of the optimisation parameters (e.g. number of individuals, number of generations) in order to keep the optimisation time below half a work day (~4 h) and facilitate the implementation of the optimisation methodology in the field (see section IV.6).

In Figure IV-2, we show the Pareto fronts of the 8 motor-pump references and the final Pareto front that is obtained by going through the best points of these 8 Pareto fronts.

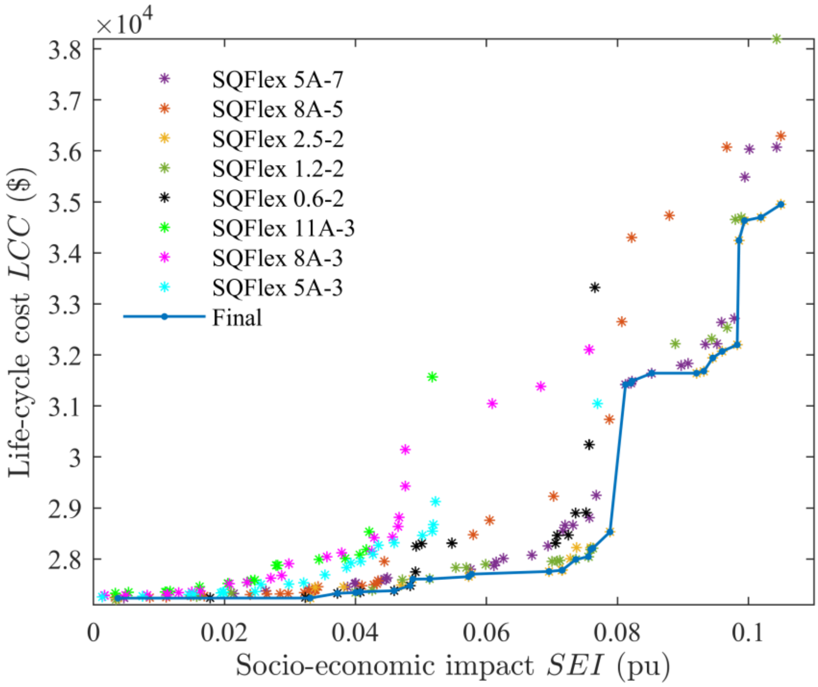


*Figure IV-2 – Points of the Pareto front for each of the motor-pump references and deduced final Pareto front.*

In Figure IV-3, we plot only the final Pareto front. We also add the results of the mono-objective optimisations (see section IV.2.1) and the values of the objective functions for the current PVWPS. For comparison, we also plot in pink the Pareto front obtained for 1000 individuals and 1800 generations, instead of 150 individuals and 150 generations. We observe a small difference between the fronts obtained with 150 individuals and 150 generations (in blue in Figure IV-3) and the one obtained with 1000 individuals and 1800 generations (in pink in Figure IV-3). In the rest of the thesis, we only consider results obtained with 150 individuals and 150 generations.

Figure IV-4, Figure IV-5 and Figure IV-6 show the values of the optimisation variables along the Pareto front. We also add the values of the variables for the current PVWPS on these figures.

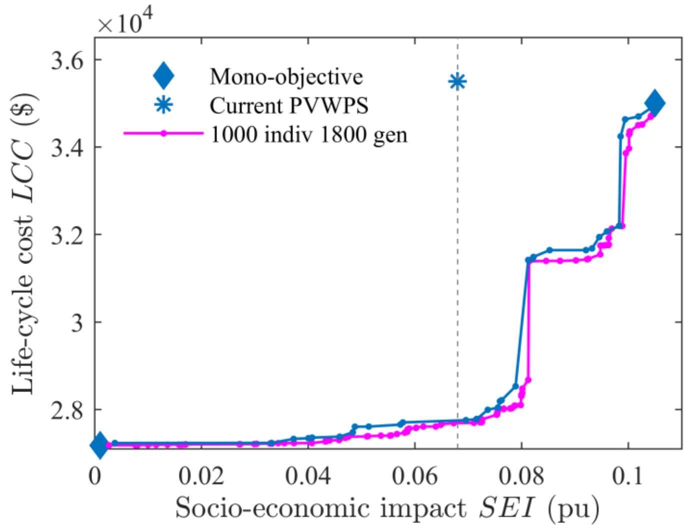


*Figure IV-3 – Pareto front.*

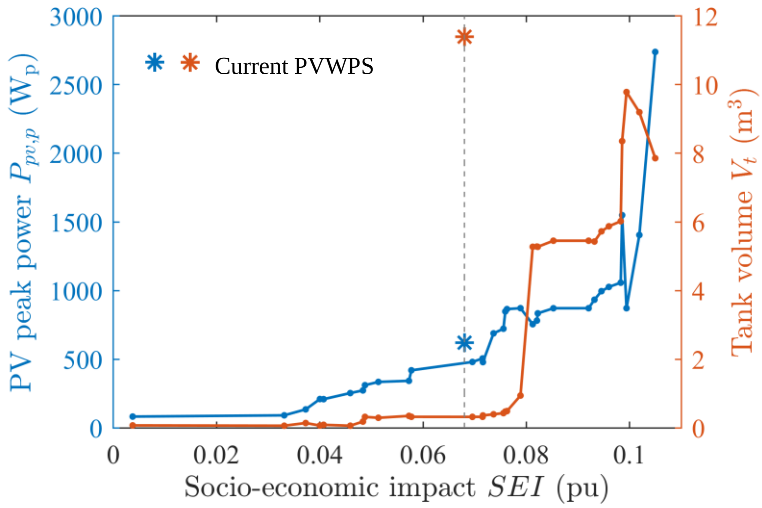


*Figure IV-4 – Variation of $P_{pv,p}$ and $V_t$ as a function of the SEI.*

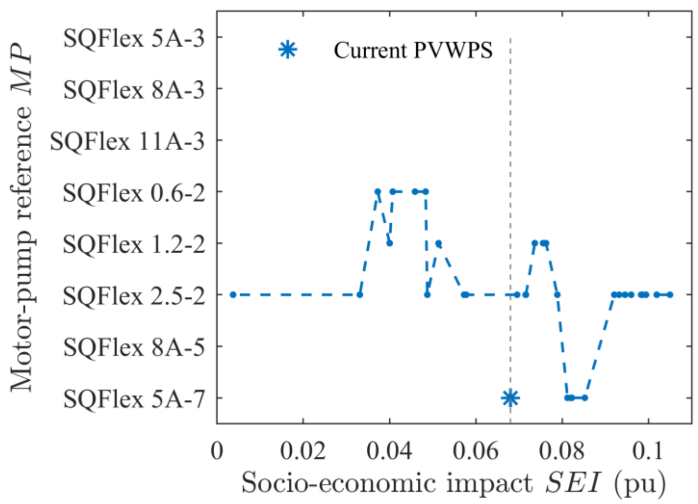


*Figure IV-5 – Variation of $MP$ as a function of the SEI.*

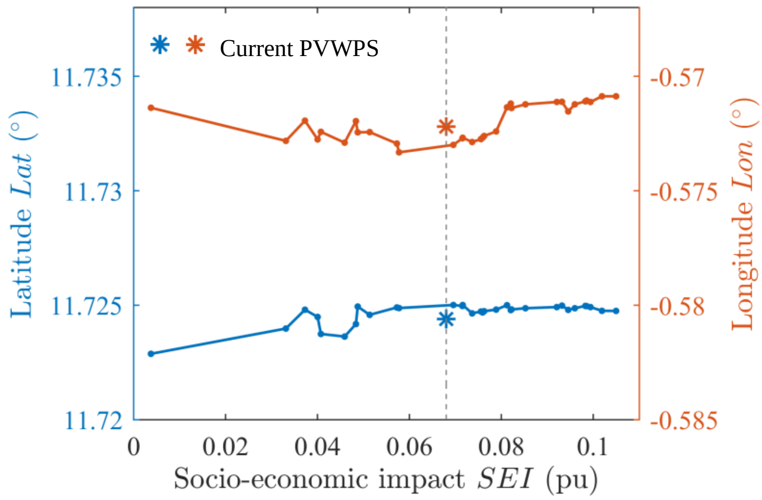


*Figure IV-6 – Variation of Lat and Lon as a function the SEI.*

Figure IV-3 is used to determine (1) the maximum socio-economic impact $SEI$ that can be expected from a PVWPS of cost $LCC$ and (2) the minimum cost $LCC$ to achieve a given socio-economic impact $SEI$. Logically, we observe that larger costs lead to more significant positive socio-economic impacts. Results also indicate that the difference in $LCC$ between the point of minimum $SEI$ and the point of maximum $SEI$ is \$7.9 $10^3$, which represents only 29% of the $LCC$ of the point of minimum $SEI$ (\$2.72 $10^4$). This suggests that significant economies of scale can be made and this goes in favour of selecting points with high values of $SEI$.

We also observe in Figure IV-4 that the optimal values of the peak power of the PV array $P_{pv,p}$ and of the volume of the tank $V_t$ generally increase with the socio-economic impact $SEI$. Indeed, generally speaking, larger systems increase the number of beneficiaries and thus the socio-economic impact. Regarding the choice of motor-pump $MP$ (Figure IV-5), the optimisation favours references 5A-7, 2.5-2, 1.2-2 and 0.6-2. Finally, we observe a small variation in the position of the PVWPS along the Pareto front (Figure IV-6). We can therefore identify a zone of the village ($Lat$ ∈ [11.723°, 11.725°] × $Lon$ ∈ [-0.573°, -0.571°]) where the installation of the PVWPS would be optimal. We have represented this zone with a green rectangle in Figure IV-1. As for the optimal position for the highest $SEI$ (see section IV.2.1), this zone is selected because of the relatively high household density and the unavailability of hand pumps in the vicinity.

We can also compare the values of the objective functions and of the variables for the current PVWPS to the optimal results. In Figure IV-3, we observe that the cost $LCC$ of the current PVWPS (\$3.55 $10^4$) may have allowed to reach the highest possible $SEI$ of 0.105, instead of the $SEI$ of 0.068 of the current PVWPS. Results also indicate that the socio-economic impact of the current PVWPS (0.068) was obtained for a $LCC$ of \$3.55 $10^4$, whereas, according to the Pareto front, it could have been obtained for a $LCC$ of ~\$2.78 $10^4$. This suggests that the application of the methodology may have allowed to save ~\$7.7 $10^3$ in Gogma, for the expression of the $SEI$ function considered in this section. For the $SEI$ of the current PVWPS (0.068), Figure IV-4 indicates that the current PV array peak power $P_{pv,p}$ is close to the optimal one and that the current tank volume $V_t$ is much larger than the optimal one. Figure IV-5 suggests that the SQFlex 2.5-2 motor-pump may be more adapted than the current one (SQFlex 5A-7). Indeed, for the closest point of the

Pareto front ($SEI$ = 0.070), the optimal motor-pump is the SQFlex 2.5-2. Finally, Figure IV-6 shows that the current position of the PVWPS is close to the optimal position.

As shown by equation (37*)*, we consider all the direct indicators with all weights equal to one in the socio-economic impact $SEI$ for this example. We now study the results for the direct indicators along the Pareto front. For this purpose, we define the yearly variation of the indicator $i$, $\Delta\mathcal{I}_i^y(\boldsymbol{h})$, as:

$$\Delta\mathcal{I}_i^y(\boldsymbol{h}) = \frac{7}{12}\Delta\mathcal{I}_i^{dry}(\boldsymbol{h}) + \frac{5}{12}\Delta\mathcal{I}_i^{wet}(\boldsymbol{h}) \tag{38}$$

Figure IV-7 presents the values of the yearly variation of the 4 direct indicators along the Pareto front. In order to have a good understanding of Figure IV-7, we also compute, for each point of the Pareto front, the average number of consumers of the PVWPS over the year $n_c^y$, and the number of these consumers that used to go to open wells $n_{c,ow}^y$ and to hand pumps $n_{c,hp}^y$ before installation of the PVWPS. Results are given in Figure IV-8. The values of $n_c^y$, $n_{c,ow}^y$, $n_{c,hp}^y$, which correspond to the whole year, are obtained from seasonal values ($n_c^{dry}$, $n_{c,ow}^{dry}$, $n_{c,hp}^{dry}$ and $n_c^{wet}$, $n_{c,ow}^{wet}$, $n_{c,hp}^{wet}$) by using the $\frac{5}{12}$ and $\frac{7}{12}$ factors, similarly to what is done in equation (38).

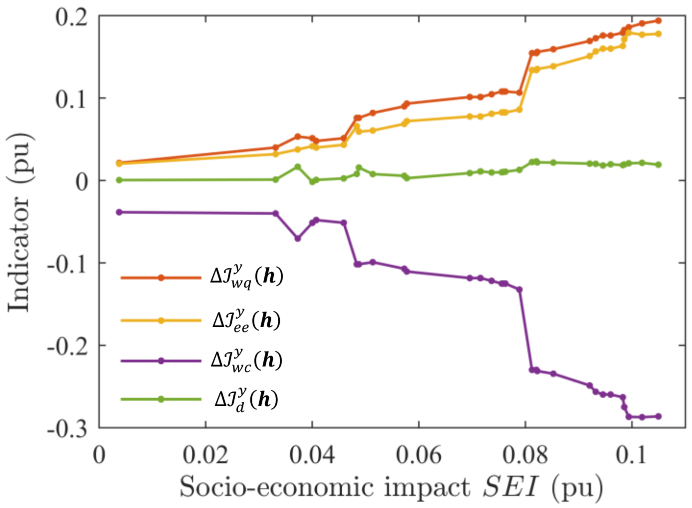


*Figure IV-7 – Values of the direct indicators variation along the Pareto front.*
*$\Delta\mathcal{I}_{wq}^y(\boldsymbol{h})$: variation of the water quality indicator, $\Delta\mathcal{I}_{ee}^y(\boldsymbol{h})$: variation of the extraction easiness indicator, $\Delta\mathcal{I}_{wc}^y(\boldsymbol{h})$: variation of the water cost indicator, $\Delta\mathcal{I}_{d}^y(\boldsymbol{h})$: variation of the distance indicator.*

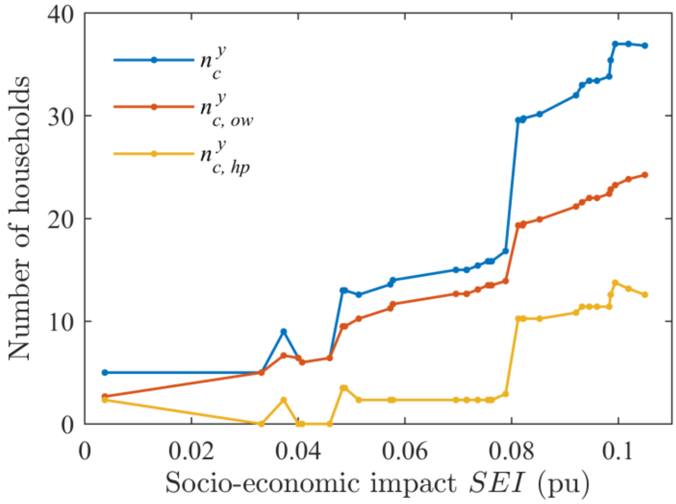


*Figure IV-8 – Number of PVWPS consumers along the Pareto front and sources where these consumers used to go before the installation of the PVWPS.*
*$n_c^y$: number of PVWPS consumers, $n_{c,ow}^y$: number of PVWPS consumers that used to go to an open well, $n_{c,hp}^y$: number of PVWPS consumers that used to go to a hand pump.*

We now analyse the variation of the impact indicators along the Pareto front (see Figure IV-7):

- The higher the $SEI$, the higher the yearly variation of the water quality indicator $\Delta\mathcal{I}_{wq}^y(\boldsymbol{h})$. Indeed, we observe in Figure IV-8 that the larger the PVWPS, the more households can switch from open wells, where water is not potable, to the PVWPS.
- The higher the $SEI$, the higher the yearly variation of the extraction easiness indicator $\Delta\mathcal{I}_{ee}^y(\boldsymbol{h})$. Indeed, we observe in Figure IV-8 that the larger the PVWPS, the more households can switch from hand pumps and open wells, where water extraction is arduous, to the PVWPS.
- The higher the $SEI$, the lower the yearly variation of the water cost indicator $\Delta\mathcal{I}_{\mathrm{wc}}^y(\boldsymbol{h})$. Indeed, as the PVWPS is more expensive than other water sources, the more households switch to the PVWPS, the higher the expenses for accessing water at the scale of the village.
- The yearly variation of the distance indicator $\Delta\mathcal{I}_d^y(\boldsymbol{h})$ remains close to 0 along the Pareto front. As explained in section IV.2.1, this is mainly due to the fact that open wells are close to the households (see Figure IV-1).

As presented in section III.5, the life-cycle cost $LCC$ is composed of the capital cost $CAPEX$ and the operational cost $OPEX$. Figure IV-9 presents the $CAPEX$ and the $OPEX$ along the Pareto front. We observe that the $OPEX$ remains nearly constant along the Pareto front, which is related to the fact that the $OPEX$ only slightly depends on the values of the optimisation variables (see section III.5).

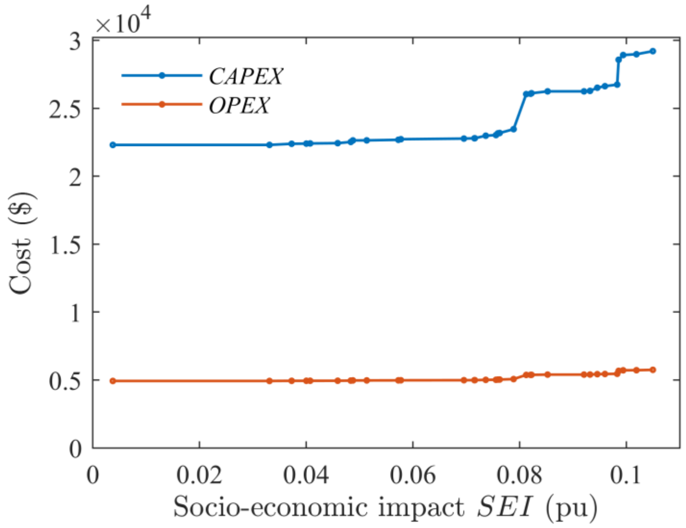


*Figure IV-9 – Capital and operational costs along the Pareto front.*

Finally, we observe in Figure IV-3 that the Pareto front is not smooth. Notably, at a couple of instances, there is a strong increase in the $LCC$ for a small increase of the $SEI$ between two points of the Pareto front, which we call a "vertical break". We here explain the most significant vertical break, for which the $LCC$ increases from \$2.85 $10^4$ to \$3.14 $10^4$ for an increase of the $SEI$ of only 0.079 to 0.081 (see Figure IV-10). In Figure IV-10, we also represent the number of PVWPS consumers $n_c^y$ and the ratio between the number of PVWPS consumers that used to go to an open well and the number of PVWPS consumers that used to go to a hand pump $\frac{n_{c,ow}^y}{n_{c,hp}^y}$.

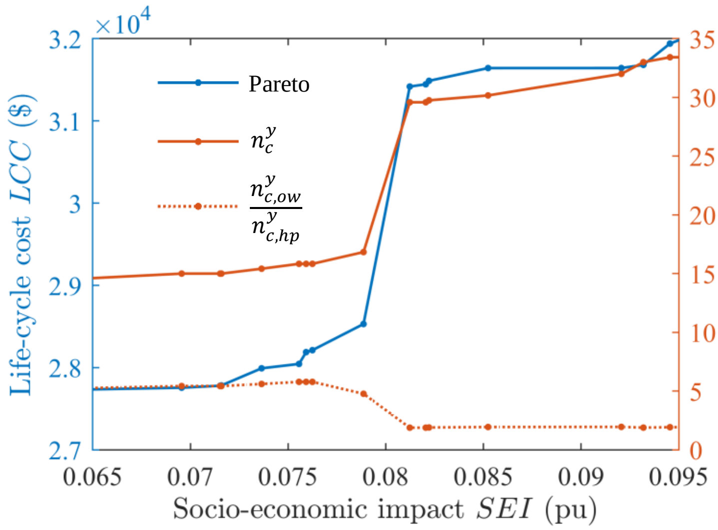


*Figure IV-10 – Vertical break at a SEI of ~0.08.*
*$n_c^y$: number of PVWPS consumers, $n_{c,ow}^y$: number of PVWPS consumers that used to go to an open well, $n_{c,hp}^y$: number of PVWPS consumers that used to go to a hand pump.*

At the moment of the vertical break, the total number of PVWPS consumers $n_c^y$ increases from 17 to 30, which is associated to an increase in the size of the system and more specifically of the tank volume (see Figure IV-4). This thus explains the high increase in the $LCC$. In addition, before the vertical break the ratio $\frac{n_{c,ow}^y}{n_{c,hp}^y}$ is higher than 4.5 and after the vertical break this ratio is lower than 2. Besides, the positive impact is

higher when an household switches from an open well to the PVWPS than when it switches from a hand pump to the PVWPS, thanks to higher improvements in water quality and extraction easiness (see section IV.2.1.1). Therefore, the drop of the ratio $\frac{n_{c,ow}^{y}}{n_{c,hp}^{y}}$ during the vertical break explains why the high increase in the $LCC$ does not go hand in hand with a high increase of the $SEI$. To summarize, to increase the $SEI$, we see that there is no other possibility than to increase the size and therefore the cost $LCC$ of the system but this cannot be done by maintaining a very high ratio $\frac{n_{c,ow}^{y}}{n_{c,hp}^{y}}$ (> 4.5), i.e. by attracting in the greatest majority households that used to go to open wells. We also observe a vertical break for a $SEI$ of ~0.08 for the Pareto front obtained for 1000 individuals and 1800 generations (in pink in Figure IV-3). The same explanations apply for this break as for the one observed on the Pareto front obtained with 150 individuals and 150 generations.

## IV.3 Influence of the error in the demand model output

In section III.2, we observed that, for the position of the current PVWPS, there is inaccuracy in the demand model output ($\boldsymbol{hs}^*_{\boldsymbol{aft}}, Q_d$). Indeed, there is ~10% error in the prediction of the households that wish to go to the PVWPS (see value of $\phi_{aft,PVWPS}$ in section III.2.1.2). In addition, there are important differences between the simulated and the measured demand curve at the PVWPS $Q_d$ (see Figure III-3 and Figure III-4). We remind that the simulated demand curve was obtained from the demand model with survey data as input and that the measured demand curve was obtained from the data acquired by the monitoring system of the current PVWPS (see section III.2.2).

In this section, we investigate the influence of the error in the demand model output on the optimisation results. To do so, we consider the block diagram presented in Figure IV-11. We perform a first optimisation with the measured $\boldsymbol{hs}^*_{\boldsymbol{aft}}$ and $Q_d$. We perform a second optimisation with the simulated $\boldsymbol{hs}^*_{\boldsymbol{aft}}$ and $Q_d$ for the position of the current PVWPS. As shown in Figure IV-11, the only variables for this optimisation are the sizing variables. Indeed, we remind that the measured output of the demand model is available only for the position of the current PVWPS, and thus the position cannot be integrated as an optimisation variable.

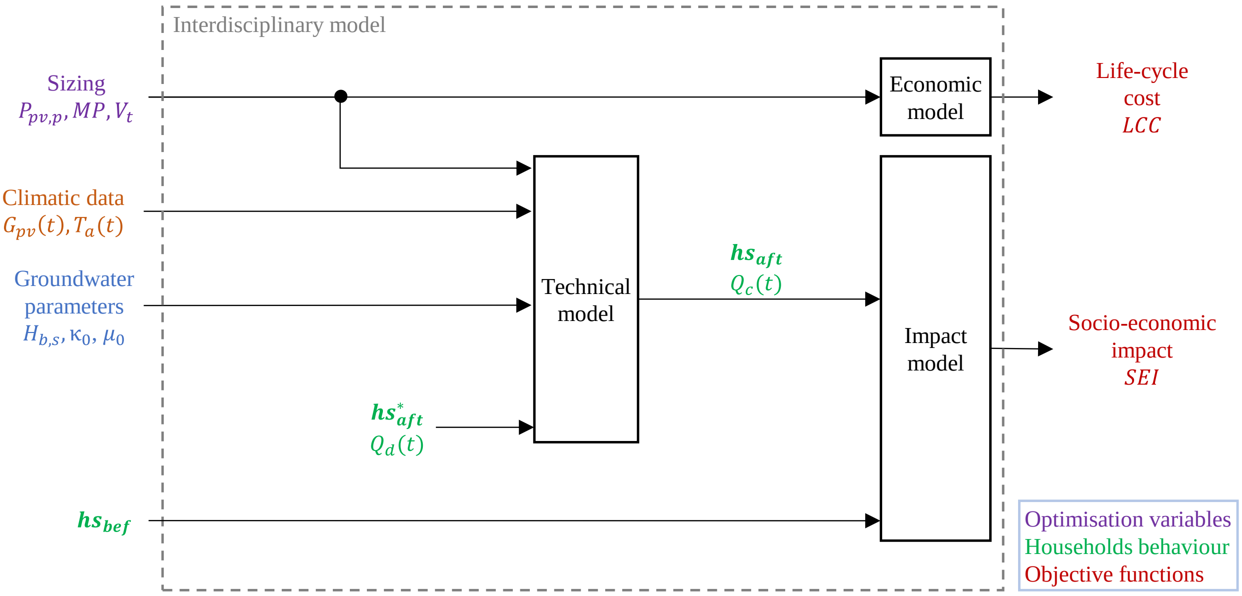


*Figure IV-11 – Block diagram considered for investigating the influence of the error in the demand model output.*

The results of the optimisations are presented in Figure IV-12. We observe that the maximum $SEI$ for the simulated demand model output (0.073) is different from the one for the measured demand model output (0.085). This is notably due to the error in the prediction of the households that wish to go to the PVWPS (~10%). Results also indicate that, for a given $SEI$, the $LCC$ associated to the simulated demand model output is always higher than the $LCC$ associated to the measured demand model output. This is due to the fact that the simulated daily water quantity demanded is up to 2.05 times larger than the measured one (see Table III-6).

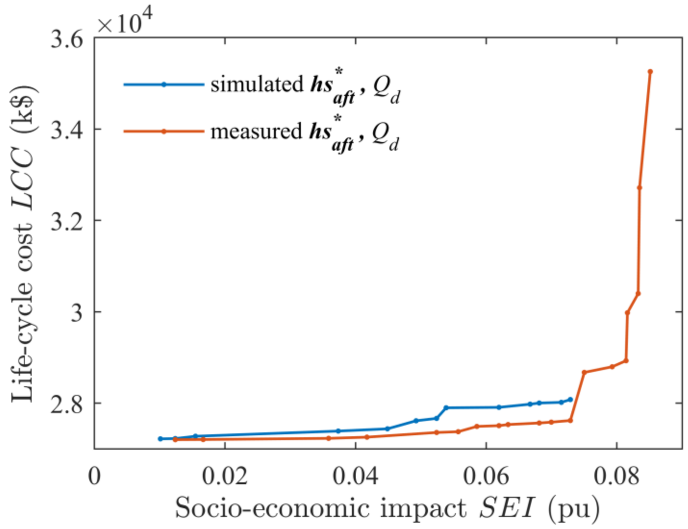


*Figure IV-12 – Influence of the error in the demand model output on the Pareto front.*

If an error in the demand estimation or an evolution of the demand with time is observed once the PVWPS has been installed, the PVWPS installer may adjust the peak power of the PV array $P_{pv,p}$ and choose another motor-pump reference $MP$. For this purpose, he can do another optimisation with $P_{pv,p}$ and $MP$ as only optimisation variables.

Finally, it is interesting to compare the Pareto front corresponding to the simulated demand output (in blue in Figure IV-12), which is obtained for the PVWPS fixed at the position of the current PVWPS, to the Pareto front of Figure IV-3, for which the position of the PVWPS is an optimisation variable which can vary in the whole village. We observe that the maximum socio-economic impact $SEI$ that can be reached when the position is fixed is 0.073, while, when the position is not fixed, the maximum $SEI$ is 0.105. This highlights that the conventional approach, which consists in setting the position before performing any optimisation (see Figure II-6), may reduce the maximum $SEI$ reachable.

## IV.4 Influence of the expression of the socio-economic impact function

As presented in section III.4.3, the weighting coefficients $w_i$ of the socio-economic impact $SEI$ function are chosen by the decision maker depending on the indicators that he wants to favour. In this section, we investigate the influence of that choice on the optimisation results. We consider the expressions of the $SEI$ function given in Table IV-5.

*Table IV-5 – Considered expressions of the SEI function.*

| | |
|---|---|
| $SEI_1$ | $\Delta\mathcal{I}_{wq}^{y}(\boldsymbol{h}) + \Delta\mathcal{I}_{ee}^{y}(\boldsymbol{h}) + \Delta\mathcal{I}_{wc}^{y}(\boldsymbol{h}) + \Delta\mathcal{I}_{d}^{y}(\boldsymbol{h})$ |
| $SEI_2$ | $\Delta\mathcal{I}_{wq}^{y}(\boldsymbol{h})$ |
| $SEI_3$ | $\Delta\mathcal{I}_{ee}^{y}(\boldsymbol{h})$ |
| $SEI_4$ | $\Delta\mathcal{I}_{wc}^{y}(\boldsymbol{h})$ |
| $SEI_5$ | $\Delta\mathcal{I}_{d}^{y}(\boldsymbol{h})$ |
| $SEI_6$ | $\Delta\mathcal{I}_{dia}^{y}(\boldsymbol{h})$ |

$\Delta\mathcal{I}_{wq}^{y}(\boldsymbol{h})$: variation of the water quality indicator, $\Delta\mathcal{I}_{ee}^{y}(\boldsymbol{h})$: variation of the extraction easiness indicator, $\Delta\mathcal{I}_{wc}^{y}(\boldsymbol{h})$: variation of the water cost indicator, $\Delta\mathcal{I}_{d}^{y}(\boldsymbol{h})$: variation of the distance indicator, $\Delta\mathcal{I}_{dia}^{y}(\boldsymbol{h})$: variation of the diarrhea indicator.

We perform an optimisation for each expression of the $SEI$ function and the resulting Pareto fronts are presented in Figure IV-13.

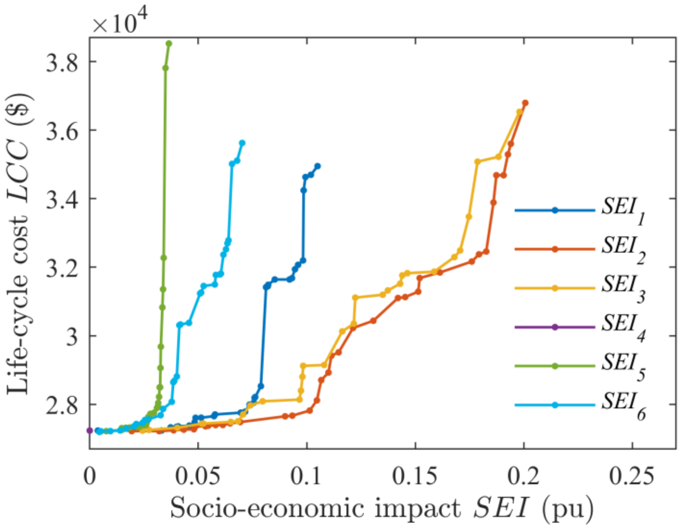


*Figure IV-13 – Pareto fronts obtained from the different expressions of the SEI function.*

We observe that the expression of the $SEI$ function has a large influence on the Pareto front. We now analyse the Pareto front obtained for each expression of the $SEI$ function:

- ➢ The Pareto front obtained for $SEI_1$, i.e. $\Delta\mathcal{I}_{wq}^{y}(\boldsymbol{h}) + \Delta\mathcal{I}_{ee}^{y}(\boldsymbol{h}) + \Delta\mathcal{I}_{wc}^{y}(\boldsymbol{h}) + \Delta\mathcal{I}_{d}^{y}(\boldsymbol{h})$, is the same as the one presented in section IV.2.2. Indeed, the expression of the $SEI$ function and the values of the parameters are the same.
- ➢ The Pareto front obtained for $SEI_2$, i.e. $\Delta\mathcal{I}_{wq}^{y}(\boldsymbol{h})$, reaches high values of the socio-economic impact $SEI$ (up to 0.20). For the different points of the front, we looked at the sources where consumers of the PVWPS used to go before installation of the PVWPS (not shown here). Logically, we observe that the optimisation targets in priority households that used to go open wells. Indeed, when an household switches from an open well to the PVWPS, there is an increment in water quality.

- The Pareto front obtained for $SEI_3$, i.e. $\Delta\mathcal{I}_{ee}^{y}(\boldsymbol{h})$, reaches high values of the $SEI$ (up to 0.20). When looking at the sources where consumers of the PVWPS used to go before installation of the PVWPS (not shown here), we see that the optimisation targets both households that used to go to open wells and that used to go to hand pumps. Indeed, when an household switches from an open well or a hand pump to the PVWPS, there is an increment in extraction easiness. In addition, for the point with the highest $SEI$ (0.20), all the households that wish to go to the PVWPS are able to go there ($n_c^y$ = $n_d^y$ = 41). Indeed, $SEI_3$ is maximum when as many households as possible switch from their previous source (open well or hand pump) to the PVWPS.
- There is no Pareto front for $SEI_4$, i.e. $\Delta\mathcal{I}_{wc}^{y}(\boldsymbol{h})$. Indeed, as presented in section II.2.4, collecting water at the PVWPS is more expensive than at any other water source of the village.
- The Pareto front obtained for $SEI_5$, i.e. $\Delta\mathcal{I}_{d}^{y}(\boldsymbol{h})$, does not reach high values of the $SEI$ (maximum reached of 0.04). Indeed, due to the high density of hand pumps and open wells in the village (see Figure IV-1), most of households were not travelling a long way to collect water before the installation of the PVWPS. This leaves small room for the improvements that can be provided by the optimisation.
- The Pareto front obtained for $SEI_6$, i.e. $\Delta\mathcal{I}_{dia}^{y}(\boldsymbol{h})$, does not reach very high values of the $SEI$ (maximum reached of 0.07). It is interesting to observe that the maximum reached by $SEI_6$ is equal to $\alpha_1$ (0.35) times the maximum reached by $SEI_2$ (0.20). This is consistent with the fact that the variation of the diarrhea indicator is obtained by multiplying the variation of the water quality indicator by the coefficient $\alpha_1$ (see equation (24)). In addition, as for $SEI_2$, the households that used to go open wells are targeted in priority by the optimisation.

## IV.5 Influence of the groundwater parameters

As presented in sections II.2.3 and III.3.1.1.5, it is not possible to determine the values of the groundwater parameters ($H_{b,s}$, $\kappa_0$ and $\mu_0$) for all positions ($Lat$, $Lon$) in a village. Indeed, as shown in section III.3.1.1.5, these parameters can be known only once a borehole has been drilled and pumping tests have been performed. At the scale of a village, we can only provide a range of variation (lower and upper boundary) of these parameters. In Appendix E, we show how to determine this range and deduce the range of variation of these parameters for the case of Gogma.

In order to quantify the effect of this uncertainty on groundwater parameters, we study here the influence of the values of the groundwater parameters on the optimisation results. For each parameter, we consider the lower boundary, the upper boundary and the value for the current PVWPS of Gogma (see Table IV-6).

*Table IV-6 – Value of the groundwater parameters for the sensitivity analysis – case of Gogma.*

| Groundwater parameter | Symbol | Lower boundary | Current PVWPS | Upper boundary |
|---|---|---|---|---|
| Height between the ground level and the static water level in the borehole | $H_{b,s}$ | 0 m | -4.9 m | -25 m |
| Aquifer losses coefficient | $\kappa_0$ | 0 $m^{-2}$ s | 2.0 $10^3$ $m^{-2}$ s | 6.9 $10^3$ $m^{-2}$ s |
| Borehole losses coefficient | $\mu_0$ | 0 $m^{-5}$ $s^2$ | 5.8 $10^5$ $m^{-5}$ $s^2$ | 1.9 $10^6$ $m^{-5}$ $s^2$ |

First of all, we perform an optimisation for each value of $H_{b,s}$ in Table IV-6, and keeping $\kappa_0$ and $\mu_0$ equal to their value for the current PVWPS of Gogma. The results are presented in Figure IV-14. We then proceed in the same way for $\kappa_0$ and $\mu_0$ as for $H_{b,s}$. The results for $\kappa_0$ and $\mu_0$ are given in Figure IV-15 and Figure IV-16 respectively.

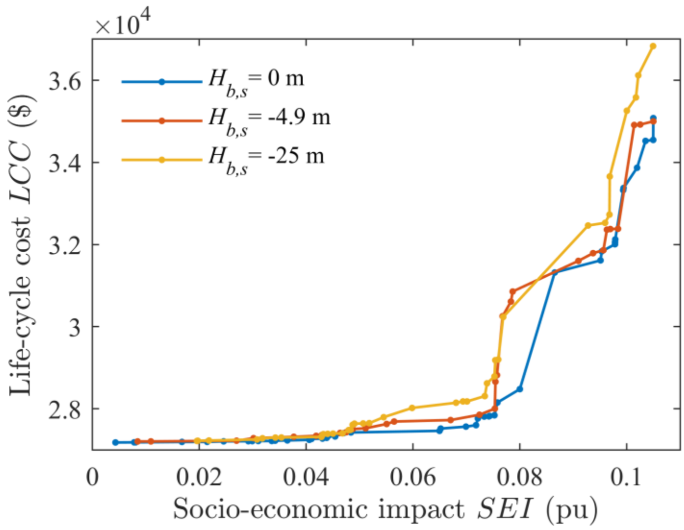


*Figure IV-14 – Pareto fronts obtained for different values of the static water level $H_{b,s}$.*

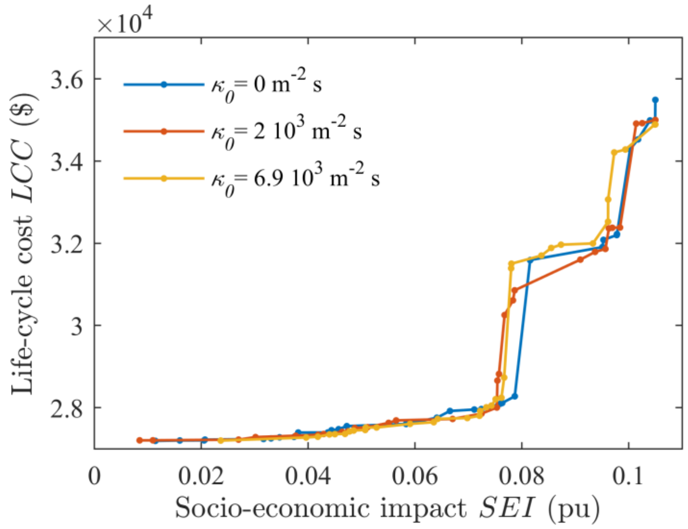


*Figure IV-15 – Pareto fronts obtained for different values of the aquifer losses coefficient $\kappa_0$.*

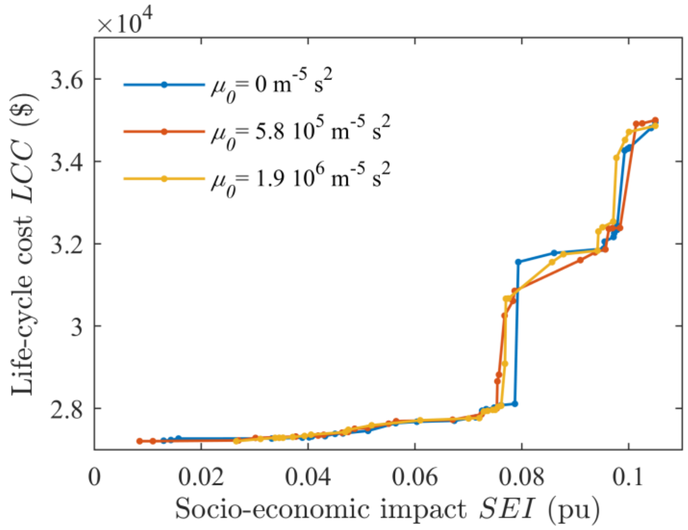


*Figure IV-16– Pareto fronts obtained for different values of the borehole losses coefficient $\mu_0$.*

Regarding the influence of static water level $H_{b,s}$ on the Pareto front (see Figure IV-14), we observe that the highest $SEI$ reached is the same for all three values of $H_{b,s}$ (0.105). However, in most cases, for a given $SEI$, the lower the value of $H_{b,s}$, the higher the $LCC$. For instance, for a given $SEI$, the $LCC$ for $H_{b,s}$ = -25 m is always higher than the $LCC$ for $H_{b,s}$ = 0 m (the difference between both $LCC$ reaches up to \$2.3 $10^3$). Regarding the aquifer loss coefficient $\kappa_0$ (Figure IV-15) and the borehole loss coefficient $\mu_0$ (Figure IV-16), we do not observe a specific influence of these parameters on the Pareto front.

We performed a similar analysis in [95]. In this article, we considered a mono-objective optimisation to determine the sizing of the PVWPS that allows to minimize the $LCC$ while fulfilling the water demand at the current PVWPS. We performed this optimisation for several values of the groundwater parameters and we also found that $H_{b,s}$ more strongly influences the optimisation results than $\kappa_0$ and $\mu_0$. All these results regarding the influence of groundwater parameters, are due to the fact that $H_{b,s}$ has a larger influence on the water level in the borehole $H_b$ than $\kappa_0$ and $\mu_0$ [95]. Even though $\kappa_0$ and $\mu_0$ have a low influence on the Pareto front, it remains essential to also measure these groundwater parameters through pumping tests, once the borehole has been drilled at a given position. Indeed, it permits to refine the optimal sizing of the PVWPS

and more importantly to make sure that the sizing chosen for the PVWPS does not threaten the sustainability of groundwater resources.

We also looked at the optimal latitude $Lat$ and longitude $Lon$ along the Pareto fronts of Figure IV-14, Figure IV-15 and Figure IV-16. In Table IV-7, we give, for each Pareto front, the minimum and maximum reached by the optimal latitude and longitude.

*Table IV-7 – Range of variation of the optimal position of the PVWPS for different values of the groundwater parameters.*

| Groundwater parameter | Value | Range of variation of the optimal latitude and of the optimal longitude: [range $Lat$ in °]×[range $Lon$ in °] |
|---|---|---|
| $H_{b,s}$ | 0 m | [11.723 to 11.726] × [-0.573 to -0.567] |
| | -4.9 m | [11.723 to 11.726] × [-0.573 to -0.571] |
| | -25 m | [11.723 to 11.725] × [-0.573 to -0.571] |
| $\kappa_0$ | 0 $m^{-2}$ s | [11.723 to 11.725] × [-0.573 to -0.570] |
| | 2.0 $10^3$ $m^{-2}$ s | [11.723 to 11.726] × [-0.573 to -0.571] |
| | 6.9 $10^3$ $m^{-2}$ s | [11.724 to 11.725] × [-0.573 to -0.571] |
| $\mu_0$ | 0 $m^{-5}$ $s^2$ | [11.722 to 11.725] × [-0.573 to -0.570] |
| | 5.8 $10^5$ $m^{-5}$ $s^2$ | [11.723 to 11.726] × [-0.573 to -0.571] |
| | 1.9 $10^6$ $m^{-5}$ $s^2$ | [11.724 to 11.725] × [-0.574 to -0.571] |

For each groundwater parameter, we observe that, for any value of the parameter, the optimal position of the PVWPS remains in the same area of the village ([11.722 to 11.726] × [-0.574 to -0.567]). Therefore, the values of the groundwater parameters do not have a significant influence on the optimal position of the PVWPS. This may lead us to think that the uncertainty on groundwater parameters is not so detrimental for the positioning of the PVWPS. However, it is important to keep in mind that the variation of the drilling cost with the position ($Lat$, $Lon$) of the PVWPS cannot be considered (see section III.5.1.2).

## IV.6 Proposition of an improved procedure for the design and installation of PVWPS

The proposed improved procedure for the design and installation of PVWPS is presented in Figure IV-17. It is based on the conventional procedure (see Figure II-6) and includes the optimisation methodology developed. In section IV.6.1, we discuss the main changes from the conventional procedure (in purple in Figure IV-17). In section IV.6.2, we show the application of the methodology for a case study and we go through all the steps.

### *IV.6.1 Procedure*

In order to evaluate the demand and impact models (see sections III.2 and III.4), data must be collected in the village. This is the purpose of step 1. The GPS coordinates of all the households and sources must be gathered as well as the water cost at all sources. In addition, the source choice $\boldsymbol{hs_{bef}}$ of at least 70% of the households of the village is recorded as well as their perception of water quality and extraction easiness at the sources they use. Regarding, the factual water quality of the water sources, it seems possible to assume that water from open wells is not potable and that water from hand pumps is potable, instead of performing water quality tests for all sources of the village. Indeed, this assumption is in accordance with the literature (see section I.1.1), has proven to be accurate for all sources in Gogma (see section II.2.7.2), and allows to save the cost of water quality tests (see Table II-2). According to section II.2, we estimate that the data collected at step 1 can be gathered in 5 days by one collector for a cost of \$800 in Gogma. When we compare this number to the potential savings from the application of the methodology in Gogma (~\$7.7 $10^3$, see section IV.2.2), the application of the improved procedure appears to be economically viable.

A first round of bi-objective optimisation is performed at steps 2 and 3, which allows to propose a first position ($Lat_1$, $Lon_1$), around which groundwater resources will be investigated. For this optimisation, the weights of the $SEI$ function are set by the decision maker depending on the indicators that he wants to favour. Besides, the constraint that the PVWPS cannot be located in the areas to avoid (e.g. burial sites, unsafe areas) is set. Finally, the groundwater parameters are set to their upper boundary (see Table IV-6) for all positions ($Lat, Lon$) in the village, which helps to avoid costs higher than expected when the borehole is effectively drilled. Thanks to this first round of optimisation, the decision maker can now count on a support tool which helps him to identify a potential position, around which to install the PVWPS ($Lat_1$, $Lon_1$). This position maximises the positive socio-economic impact $SEI$ on the village while minimising the cost of the system $LCC$. We remind that in the conventional situation the decision maker could only rely on his intuition for this positioning step (see section I.3.2).

During the steps 4 to 6, the borehole is drilled, the water quality is tested and the groundwater parameters ($H_{b,s}$, $\kappa_0$ and $\mu_0$) and the maximum flow rate that can be pumped $Q_{p,max}$ are determined through pumping tests (see sections II.2.6 and III.3.1.1.5).

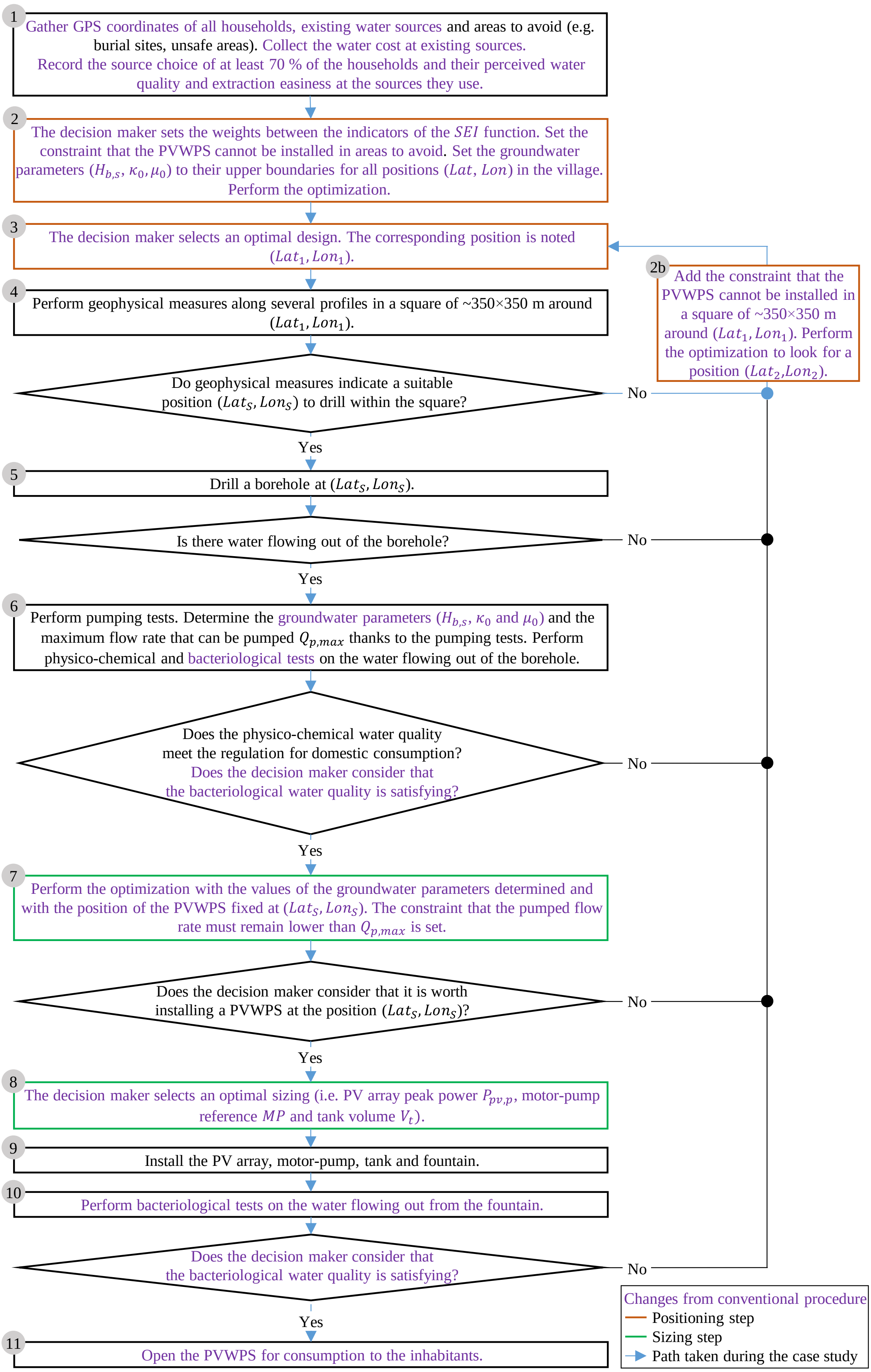


*Figure IV-17 – Procedure of application of the developed optimisation methodology.*

The second round of optimisation is then performed at steps 7 and 8, which allows to determine the values of the sizing variables. For this optimisation, the position is fixed at the position of the borehole and the constraint that the pump flow rate $Q_p$ must remain lower than $Q_{p,max}$ is set ($Q_p(t) < Q_{p,max}, \forall t$), in order to preserve the sustainability of groundwater resources. It is important to note that the determination of the groundwater parameters ($H_{b,s}$, $\kappa_0$ and $\mu_0$) is key to ensure that the above mentioned constraint is respected, as these parameters are involved in the computation of the pump flow rate $Q_p$ (see section III.3.1.1.5). Overall, this second round of optimisation helps the PVWPS installation company and the decision maker to determine the sizing of the PVWPS that maximize the positive socio-economic impact $SEI$ and minimize the life-cycle cost $LCC$, while preserving groundwater resources.

Finally, we also propose some modifications regarding bacteriological tests. Firstly, we propose to add bacteriological tests at the same time as physico-chemical tests, at step 6. Indeed, bacteriological tests cost only ~$20 (see section II.2.7.2) and they will provide information about the bacteriological quality of the groundwater. If the decision maker is not satisfied with the quality of the groundwater, he may then decide to change the position of the PVWPS before further investments. Secondly, we recommend that the second bacteriological tests are performed before the opening of the PVWPS for consumption to the inhabitants (see steps 10 and 11).

### *IV.6.2 Case study*

In this section, we apply the proposed procedure to the village of Gogma. However, the decision maker choices and the results of the geophysical studies, of the pumping tests and of the water quality analyses performed at the PVWPS are fictive. The path considered for this case study is represented in blue in Figure IV-17.

**Step 1**: The required data are collected (GPS coordinates, sources cost, source choice …). We also remind that there are no areas to avoid in Gogma (see section II.1.2.1).

**Step 2**: We suppose that the decision maker considers the expression of the socio-economic impact $SEI$, which features all the direct impact indicators with all weights equal to 1, as in section IV.2. The groundwater parameters ($H_{b,s}$, $\kappa_0$ and $\mu_0$) are set to their upper boundary (see Table IV-6) for all positions of the village. We perform the optimisation and we obtain the Pareto front in blue in Figure IV-18.

**Step 3**: We suppose that all the points of the Pareto front are within the budget of the decision maker and that he decides to consider the point of maximum $SEI$: $SEI$ = 0.105 and $LCC$ = \$3.68 $10^4$. The corresponding position of the PVWPS is $Lat_1$ = 11.72480° and $Lon_1$ = -0.57081°.

**Step 4**: The geophysical study is performed in a square of 350×350 m around the identified position. The coordinates of the scanned square are $Lat \in$ [11.72300°, 11.72650°] × $Lon \in$ [-0.57256°,-0.56906°]. We suppose that no suitable position to drill is encountered in the square.

**Step 2b**: We add the constraint that the position of the PVWPS cannot be in the scanned square and we run the optimisation again. The new Pareto front obtained is presented in red in Figure IV-18. Note that, if there would have been areas to avoid (e.g. burial sites, unsafe areas), they would have been considered with the same type of constraint on the PVWPS position.

**Step 3:** Due to the constraint on the position, the maximum $SEI$ that can be reached has dropped to 0.078. We suppose that the decision maker selects this point of maximum $SEI$. The corresponding position of the PVWPS is $Lat_2$ = 11.72480° and $Lon_2$ = -0.57263°.

**Step 4**: New geophysical studies are performed, and we suppose that this time a suitable position to drill is encountered at the position $Lat_S$ = 11.72500° and $Lon_S$ = -0.57290°.

**Step 5**: The borehole is drilled and water is flowing out from the borehole.

**Step 6**: Pumping tests are performed. According to the pumping tests, the maximum flow rate that can be pumped is $Q_{p,max}$ = 1.5 $10^{-3}$ $m^3/s$ and the values of the groundwater parameters are $H_{b,s}$= 17 m, $\kappa_0$ = 1.5 $10^3$ $m^{-2}$ s and $\mu_0$ = 5.0 $10^5$ $m^{-5}$ $s^2$. Physico-chemical and bacteriological tests are performed on the water from the borehole. We suppose that the water is found to be suitable for drinking in terms of physico-chemical and bacteriological quality.

**Step 7**: The optimisation is run to determine the sizing of the PVWPS. For this optimisation, the values of $Lat$ and $Lon$ are set to the position of the borehole that has been drilled ($Lat_S$, $Lon_S$), we use the values of the groundwater parameters that have been determined from the pumping tests and we set the constraint that the pump flow rate $Q_p$ must remain lower than $Q_{p,max}$. We obtain the Pareto front presented in yellow in Figure IV-18.

**Step 8**: We suppose that the decision maker chooses the point of highest $SEI$ (0.077) which corresponds to the following values of the sizing variables: $P_{pv,p}$= 1.0 $10^3$ $W_p$, $MP$ = SQFlex 2.5-2 and $V_t$ = 1.3 $m^3$.

**Step 9**: The PV array, motor-pump, tank and fountain are installed.

**Step 10**: Bacteriological tests are performed on the water from the fountain and we suppose that the water is found to be suitable for drinking in terms of bacteriological quality. According to the results of the physico-chemical tests of step 6 and of the bacteriological tests of step 10, the water is potable.

**Step 11**: The PVWPS is opened for consumption to the inhabitants.

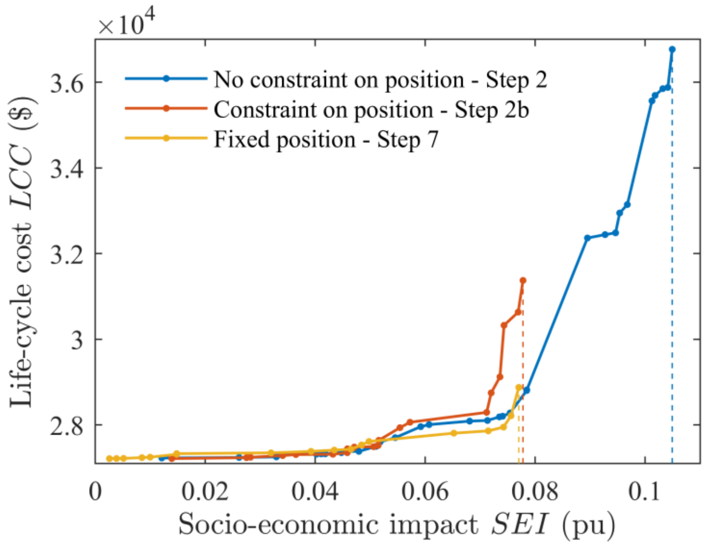


*Figure IV-18 – Pareto fronts obtained through the proposed procedure of design and installation of PVWPS.*

The procedure therefore appears as viable and should be tested in reality for the design of new PVWPS for domestic water access. The implementation of the procedure should be performed in collaboration with decision makers and local companies. With this in mind, the development of an interface for facilitating the use of the procedure by these stakeholders may be useful. The interface should notably permit to easily load data acquired by GIS mapping and by geophysical and hydrological measuring devices, as these data are required for the application of the procedure.

## IV.7 Partial conclusion

In this chapter, we first presented the optimisation problem. The objective functions are the life-cycle cost of the PVWPS, that we want to minimise, and its socio-economic impact, that we want to maximise. The optimisation variables are the PV array peak power, the motor-pump reference, the tank volume and the PVWPS latitude and longitude. The constraints are related to the operation of the motor-pump and to the preservation of groundwater resources. We then detailed and interpreted a reference optimisation result. In addition, we performed several analyses to understand the influence of the error in the demand model output, of the expression of the socio-economic impact function and of the groundwater parameters on the optimisation results. Finally, we proposed and described an improved procedure for the design and installation of PVWPS. It is based on the conventional procedure and includes the optimisation methodology developed.

# Conclusion

# Conclusion

## Overview

Improving water access remains one of the most significant challenges in rural sub-Saharan Africa. Photovoltaic water pumping systems (PVWPS) have proved to be an interesting solution to improve water access in off-grid rural areas. Our literature review highlighted that the conventional approach for the optimal design of PVWPS aims at determining the sizing of the PVWPS that minimizes its cost while maximising the share of the water needs of the inhabitants that is fulfilled. We identified two main drawbacks of this approach. Firstly, the positioning of the PVWPS is not considered in the optimal design and is performed in an arbitrary way by the decision maker, without any support tool. Secondly, the conventional approach does not aim at maximising the positive socio-economic impact of the PVWPS (e.g. use of water of a higher quality, reduced distance to collect water), although it is the main objective of institutions and governments which finance these systems. This also prevents from targeting the inhabitants of the village that have the worst access to water.

The aim of this PhD thesis was therefore to bridge these two gaps by developing a methodology that allows to determine the PVWPS sizings and positions in a village that both minimize the life-cycle cost of the PVWPS and maximize its positive socio-economic impact.

In order to determine the conventional procedure for the design and installation of PVWPS, to be able to apply the proposed methodology with actual data and to compare model results to experimental measurements, a PVWPS was designed and installed in the conventional way in the rural off-grid village of Gogma in Burkina Faso. We performed the GIS mapping of the village; we acquired cost and water quality data on the 22 water sources of the village; we performed 88 household surveys before the installation of the PVWPS and another 88 after the installation. Besides, hydrological measurements were performed for the installed PVWPS and a data logger was developed and installed to monitor the PVWPS continuously. To this date, 20 months of technical data have been collected by the monitoring system on the PVWPS (>2 $10^7$ data points), which forms a unique database for the study of such systems.

Then, we developed an interdisciplinary model which links the sizing and the position of the PVWPS to its socio-economic impact and its life-cycle cost. This interdisciplinary model is composed of four sub-models: demand, technical, impact and economic model. We presented these four sub-models and demonstrated their application with data from Gogma. The parameters of the demand and technical models were identified using local data and their results were compared to experimental measurements.

Finally, we defined an optimisation problem which aims at determining the sizings and the positions of the PVWPS which minimize the life-cycle cost of the PVWPS and maximize its socio-economic impact. We started by detailing a reference optimisation result. Then, we studied the influence of the error on the demand model output, of the definition of the socio-economic impact by the decision maker and of the groundwater resources on the optimisation results. Finally, we proposed an improved procedure for the design and installation of PVWPS, which is based on the conventional procedure and includes the optimisation methodology developed.

## Contributions

The contributions of this PhD thesis can be split into methodological contributions, that may apply to other types of systems than water systems, contributions to the field of water access, and technical contributions on PVWPS.

The two main methodological contributions are:

- The inclusion of the position of the system as an optimisation variable. This is notably done through the development of the demand model that simulates the demand for the service provided by the system depending on its position.
- The consideration of the socio-economic impact as an objective function of the optimisation. This is done through the development of the demand, technical and impact models that link the optimisation variables to the socio-economic impact.

The two main contributions for water access are:

- The development of a demand model that takes into account seasonality, considers the inclusion of a source of a new type, and predicts the load curve at the future water source. The load curve predicted by the demand model can then be used for the technical sizing of the future water system.
- The development of a theory of change regarding the repercussions of choosing a given water source, which goes along with the identification and organisation of relevant references of the literature on the subject. This helps to better understand the consequences of investing in improved water sources.

The six main technical contributions on PVWPS are:

- The development of a data logger and its use for the continuous monitoring of the PVWPS of Gogma. To our knowledge, it is the first time that a PVWPS for domestic water access has been monitored and that data on a PVWPS in rural sub-Saharan Africa have been collected. This permits a more precise forecast of the performance and sustainability of PVWPS for this water use and in this region, where they are particularly useful.
- The inclusion of the water demand at the PVWPS as an input of the energy conversion chain model. This allows to model the instantaneous operation of PVWPS which include a tank and a controller that stops and restarts the motor-pump depending on the water level in the tank.
- The development and the experimental validation of a data-driven borehole model. Contrarily to previous models, the developed model is not based on assumptions that are rarely met (e.g. homogenous and isotropic aquifer) and can be applied for all types of aquifers.
- The demonstration that irradiance data from a satellite database can be used instead of data from a local sensor for modelling and optimising PVWPS. This can favour the implementation of PVWPS in areas where no local irradiance measurements are available, which is often the case in sub-Saharan Africa.
- The demonstration that a time step of 1 hour can be used for modelling and optimising PVWPS, instead of smaller time steps (e.g. 1 minute). This notably allows to reduce computing time for the optimisation.

- The demonstration that is not indispensable to consider the thermal behaviour of PV modules and the evolution of the ambient temperature $T_a$ when modelling PVWPS for domestic water access.

## Perspectives

*The first perspective concerns the enhancement of the interdisciplinary model.* There is room for improving the four sub-models:

- For the demand model, the evolution of the demand along the lifetime of the system should be integrated. Indeed, the habits of the inhabitants may evolve over the lifetime of system (~20 years) and/or following technical modifications in the system. For instance, if a piping system that reaches each house individually is installed, the water quantity demanded and the time at which people use water may vary along time, as people get used to living with more accessible water.
- For the technical model, ageing of the PVWPS components and the evolution of groundwater resources with time, and notably with climate change, could be quantified for the site of Gogma. This objective is aligned with the aim of monitoring continuously the PVWPS of Gogma along its whole lifetime.
- For the impact model, the quantification of missing $\alpha$ coefficients, which are coefficients that relate two impact indicators, should be performed. Although the determination of all $\alpha$ coefficients of the theory of change for a given case study does not appear realistic, performing studies that specifically aim at determining one $\alpha$ coefficient is helpful as the obtained coefficient may be used in other case studies. Besides, in this thesis we only consider socio-economic impacts between before and after installation of the PVWPS. In the future, the evolution of the socio-economic impacts over the whole lifetime of the system should be integrated.
- For the economic model, the main scientific obstacle is the forecast of drilling costs depending on the position. Despite the key importance of forecasting drillings costs and more generally groundwater resources, it has remained a very challenging problem for decades in rural sub-Saharan Africa.

*The second perspective is the application of the methodology to other case studies involving PVWPS.* This will allow to see how the identified parameters of each sub-model and the results of the optimisation vary from one case study to another. This will go hand in hand with the development of an interface for facilitating the application of the proposed methodology.

*The third perspective is the use of the methodology for assessing the suitability of technically original solutions for water pumping (e.g. motor-pumps 'Saurea' and 'Futurepump').* It may therefore be used as a tool to guide governments in the financing of research and development efforts.

*The fourth perspective is the application of the methodology to other types of systems.* According to the specificities of the methodology, systems for which the demand for the service provided depends on the system's position and that have a significant socio-economic impact should be privileged. In the frame of rural areas of developing countries, community mills powered by photovoltaic energy where the inhabitants bring their grains to make flour may be a particularly interesting application. Indeed, depending on the mill's position different farmers may be targeted and there are significant socio-economic impacts associated with

being able to sell transformed agricultural products. In the frame of developed countries, an application may be the positioning of public charging stations for electrical vehicles (e.g. cars, bikes, scooters). Indeed, the demand at the charging station depends on its position and socio-economic impacts may include time loss to go to the charging station and facilitated access for people with reduced mobility.

# List of Publications

**Peer-reviewed journal articles – published/accepted**

1. **S. Meunier**, M. Heinrich, L. Queval, J.A. Cherni, L. Vido, A. Darga, Ph. 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, 2019, DOI: https://doi.org/10.1016/j.apenergy.2019.03.035

2. **S. Meunier**, D. T. Manning, L. Queval, J.A. Cherni, Ph. Dessante, D. Zimmerle "Determinants of the marginal willingness to pay for domestic water and irrigation in partially electrified villages: the case of Rwanda", International Journal of Sustainable Development & World Ecology, vol 26, no 6, pp. 547-559, 2019, DOI: https://doi.org/10.1080/13504509.2019.1626780

3. C.O. Peralta P., G.T.T. Vieira, **S. Meunier**, R.J. Vale, M.B.C. Salles, B.S. Carmo, "Evaluation of the $CO_2$ emissions reduction potential of Li-ion batteries in ship power systems", Energies, vol 12, no 3, art 375, 2019, DOI: https://doi.org/10.3390/en12030375

4. T. Vezin, **S. Meunier**, L. Queval, J.A. Cherni, L. Vido, A. Darga, Ph. Dessante, P.K. Kitanidis, C. Marchand, "Borehole water level model for photovoltaic water pumping systems", Applied Energy, 2019, DOI: https://doi.org/10.1016/j.apenergy.2019.114080

**Peer-reviewed journal articles – submitted**

5. M. Heinrich, **S. Meunier**, A. Samé, L. Quéval, A. Darga, L. Oukhellou, B. Multon, "Detection of cleaning interventions on photovoltaic modules with machine learning"
6. **S. Meunier**, L. Queval, A. Darga, Ph. 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"

**Peer-reviewed international conference papers – published/accepted**

7. **S. Meunier**, L. Queval, M. Heinrich, E.A. de la Fresnaye, J.A. Cherni, L. Vido, A. Darga, Ph. Dessante, B. Multon, P.K. Kitanidis, C. Marchand, "Effect of irradiance data on the optimal sizing of photovoltaic water pumping systems," 46th IEEE Photovoltaic Specialists Conference (PVSC), Chicago (IL), United States, June 2019 – *Nominated for the best student paper award*

8. **S. Meunier**, L. Queval, A. Darga, Ph. 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," 14th International Conference on Ecological Vehicles and Renewable Energies (EVER), Monaco, Monaco, May 2019, DOI: https://doi.org/10.1109/EVER.2019.8813580 – *Award of the best paper on renewable energies, Eligible for re-submission to the IEEE Transactions on Industry Applications*

9. **S. Meunier**, L. Queval, A. Darga, Ph. Dessante, C. Marchand, M. Heinrich, J.A. Cherni, L. Vido, B. Multon, "Influence of the temporal resolution of the water consumption profile on photovoltaic water

pumping systems modelling and sizing," 7th International Conference on Renewable Energy Research and Application (ICRERA), Paris, France, Oct. 2018, DOI: https://doi.org/10.1109/ICRERA.2018.8566828

**Peer-reviewed national conference papers – published**

10. **S. Meunier**, M. Heinrich, L. Queval, J.A. Cherni, L. Vido, A. Darga, Ph. Dessante, B. Multon, P.K. Kitanidis, C. Marchand, “Conception optimale des systèmes photovoltaïques de pompage d’eau en sites isolés avec prise en compte des aspects socio-économiques,” Conf. des Jeunes Chercheurs en Génie Électrique (JCGE), Ile d'Oleron, France, June 2019, URL : http://seeds.cnrs.fr/jcge-seeds-2019/264996.pdf
11. **S. Meunier**, M. Heinrich, L. Queval, A. Darga, J.A. Cherni, L. Vido, Ph. Dessante, B. Multon, C. Marchand, “Étude multidisciplinaire d’un système de pompage photovoltaïque dans une communauté rurale du Burkina Faso”, Journées Nationales du Photovoltaïque (JNPV), Dourdan, December 2018, URL: https://jnpv2018.geeps.centralesupelec.fr/archives/11-autres/JNPV_Meunier_Simon_Pompage_PV-Simon_Meunier_GeePs.pdf
12. A. N’Dour, **S. Meunier**, A. Kaboré , M. Heinrich, L. Queval, A. Darga, “Modules photovoltaïques contrefaits en vente sur le marché Africain : détection et caractérisation électrique d’échantillons issus du marché Burkinabé”, Journées Nationales du Photovoltaïque (JNPV), Dourdan, December 2018, URL: https://jnpv2018.geeps.centralesupelec.fr/archives/11-autres/JNPV_Arouna_28092018-Arouna_DARGA_GeePs-Centralesupelec.pdf
13. **S. Meunier**, M. Heinrich, J.A. Cherni, L. Queval, Ph. Dessante, L. Vido, A. Darga, B. Multon C. Marchand, “Modélisation et validation expérimentale d’un système de pompage photovoltaïque dans une communauté rurale isolée du Burkina Faso,” Symposium de Génie Electrique (SGE), Nancy, France, July 2018, URL: http://actes.sge-conf.fr/2018/articles/article_182692.pdf
14. **S. Meunier**, "Optimisation d’un système de pompage photovoltaïque pour les communautés rurales des pays en voie de développement", Conf. des Jeunes Chercheurs en Génie Électrique (JCGE), Arras, France, June 2017, URL: https://hal.archives-ouvertes.fr/hal-01629662

# Appendix

# Appendix

## Appendix A. Household survey

**Preliminary remark**: The layout of the original survey has been adapted here to save space. The survey has been translated from French.

*Text explaining the survey, to read completely to the surveyee*

Hello,

I am here on behalf of French and English laboratories to research water use in rural Burkina Faso. You have been selected to answer our survey.

Your participation is completely optional, however your responses will help us understand living condition in Burkina Faso.

We will be asking you personal information about your family and household. Do not worry, survey results are strictly confidential. Your answers will be anonymized. When the information is summarized for your village, you may see the results if you are interested. We will follow up with you in 1 year to see how the answers to the survey change over time.

Please feel free to speak with all other members of your household to answer to the questions of the survey. If questions are unclear, let me know and I can explain further.

Do you agree to participate to this survey?

- ☐ Yes
- ☐ No

Thank you for your time,

University of Paris-Saclay / Imperial College London

Thank you for participating in this research!

If you have any questions about this project, you can contact the project coordinator at any time at: simon.meunier@centralesupelec.fr.

Would you like a written version of these contacts?

### a. Household Characteristics

*Surveyor.* Date and time of the survey: ________________________

*Surveyor*. GPS coordinates of the household: Lat = _________; Lon = ___________

S1. Are there specific problems in the village that worry people in your household?

- ☐ Yes, detail:________________________
- ☐ No

Give the following description for each members of the household:

| S2. N° member | S3. Name | S4. Present during survey? | S5. Does he/she live here usually or he/she is just passing? | S6. Position in the household | S7. Observation of children. Do they have the following characteristics? | S8. Gender | S9. Age | S10. Occupation | S11. Highest level of education validated | S12. Does he know how to read? | S13. Does he know how to write? |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | Yes<br>No | 1. Usually<br>2. Just passing | 1. Head of the household<br>2. 1st wife of the head<br>3. 2nd wife of the head<br>4. 3rd wife of the head<br>5. 4th wife the head<br>6. Son/daughter of the head<br>7. Father/mother of the head<br>8. Brother/Sister of the head<br>9. Other: | 1. Distended belly<br>2. Fair hair<br>3. Oedema on face or limbs | Male/ Female | | 1. Agriculture<br>2. Livestock<br>3. Building<br>4. Manufacture<br>5. Transformation<br>6. Trade<br>7. Service<br>8. Student<br>9. Housewife<br>10. Other: | | Yes<br>No | Yes<br>No |
| Same question for the other members of the household | | | | | | | | | | | |
| Comments: | | | | | | | | | | | |

S14. How many houses do you own? ________________________________

Observation. Characteristics of the houses owned by the household:

| House n° | S15. Material of the walls | S16. Material of the roof | S17. Material of the floor |
|---|---|---|---|
| 1 | 1. Clay<br>2. Concrete<br>3. Other:_________ | 1. Straw<br>2. Sheet metal<br>3. Other:_______ | 1. Clay<br>2. Concrete<br>3. Straw Carpet<br>4. Woven Carpet<br>5. Other |
| Same questions for other houses | | | |
| Comments: | | | |

S18. Is there anything that your household need? ___________________________________________

Does the household have access to the following services?

| Service | Answer |
|---|---|
| S19. Lighting | ☐ Yes, with kerosene<br>☐ Yes, with electricity<br>☐ Yes, other: _____<br>☐ No |
| S20. Food and water heating | ☐ Yes, with wood<br>☐ Yes, with gas<br>☐ Yes, other: _____<br>☐ No |
| S21. Do people of your household sleep under a mosquito netting? | ☐ Yes, everybody<br>☐ Yes, but only _____<br>☐ No |
| S22. How many phones does your household own? | ☐ Yes<br>☐ No |
| S23. Is the phone network fine in your houses? | ☐ Yes<br>☐ No |
| S24. Do people of your household have access to the internet? | ☐ Yes, on the phone<br>☐ Yes, at a shop with a computer<br>☐ Yes, other:______<br>☐ No |
| S25. How many bikes does your household own? | ☐ Yes<br>☐ No |
| S26. How many motorbikes does your household own? | ☐ Yes<br>☐ No |
| Comments: | |

## b. Agriculture and livestock

S27. In how many fields do people of your household work in? _________________________

For each of the fields in which people of the household work in:

| Field n° | S28. Is it the field of the household, does the household rent it, or do people of the household work in it as contractual? | S29. What is the size of the field? | S30. How much of each product is produced from each field yearly? (considering only non-lost products and including products gathered before harvest) | S31. How much of this product has the household sold in the village, outside of the village and consumed last month? |
|---|---|---|---|---|
| 1 | 1. Own<br>2. Rent<br>3. Contractual | ____ha/$m^2$/paces /Football fields | ______ kg/tons/bags of ______ | ___% sold in village<br>___% sold outside village<br>___% self-consumption |
| | | | ______ kg/tons/bags of ______ | ___% sold in village<br>___% sold outside village<br>___% self-consumption |
| Same questions for other fields | | | | |
| Comments | | | | |

*Surveyor*: If bags used, how much does a bag weigh? _________ kg per bag

S32. Do members of your household borrow fertilizer?

- ☐ Yes, every year
- ☐ Yes, it happened some times
- ☐ No

For each type of animal owned by the household:

| Type of animal | S33. Number of this animal | S34. How many of this animal has the household sold in the village, outside the village and consumed last month? |
|---|---|---|
| 1. Chicken<br>2. Turkey<br>3. Hens with eggs<br>4. Hens without eggs<br>5. Rabbit<br>6. Goat<br>7. Sheep<br>8. Pig<br>9. Beef<br>10. Cows with milk<br>11. Cows without milk<br>12. Donkey<br>13. Dog<br>14. Other | | ___ sold in village<br>___ sold outside village<br>___ self-consumption |
| Same questions for other types of animals | | ___ sold in village<br>___ sold outside village<br>___ self-consumption |
| Comments: | | |

## c. Diseases and access to health

For every member of the household that was sick during the last 30 days:

| N° member | S35. Which disease? | S36. Which symptoms? | S37. Is he still sick? | S38. For how long was he sick/has he been sick? | S39. What did you do to heal him? | S40. Where is the person who you visited to heal him? | S41. How much did the consultation to heal him cost? | S42. How much did the drugs to heal him cost? |
|---|---|---|---|---|---|---|---|---|
| 1 | 1. Diarrhea<br>2. Malaria<br>3. Typhoid fever<br>4. Yellow fever<br>5. Amibiase<br>6. Bilharziose<br>7. Polio<br>8. Meningitis<br>9. Hepatitis A<br>10. Hepatitis E<br>11. Dengue<br>12. Cholera<br>13. Onchocerciasis<br>14. Other: | 1. Stomatchache<br>2. Liquid stool<br>3. Blood in the stool<br>4. Vomiting<br>5. Sweating<br>6. Headache<br>7. Fever<br>8. Rapid loss of weight<br>9. Dehydration<br>10. Convulsion<br>11. Blindness<br>12. itching<br>13. Other: | | | 1. Go to doctor<br>2. Go to pharmacist<br>3. Go to marabout<br>4. Self-medicine and advice from family<br>5. Nothing<br>6. Other: | 1. Sanogho<br>2. Garango<br>3. Tenkodogo<br>4. Komina<br>5. Other | | |
| Same questions for the other members of the household | | | | | | | | |
| Comments: | | | | | | | | |

## d. Time use

How much time did women of your household, who are not at school anymore, have spent doing the following activities yesterday?
*Surveyor*: Get an average answer from all the women together.

| Activity | S43. Time spent |
|---|---|
| Work in the field | |
| Productive activity: transformation | |
| Cook for the household | |
| Collect water for drinking and cooking | |
| Wash clothes | |
| Collect water for washing yourself + wash yourself | |
| Take care of children | |
| Take care of sick people and sick children | |
| Sleep (night + nap) | |
| Free time | |
| Other: ____________ | |
| Other: ____________ | |
| Comment: | |

## e. Safety

S44. Do members of your household feel safe in the village?
- ☐ Yes
- ☐ No, afraid of robbers
- ☐ No, afraid of snakes
- ☐ No, detail ____________________________________________

## f. Household water use

S45. What is the main problem that members of your household encounter regarding water?
________________________________________________________

| Use | S46. From which source does the water come from? | S47. During which months of the year do you go to this source? | S48. What is the water quantity used? | S49. What is the name of the members who collect water for this use? | S50. At what time of the day do you collect water for this use? | S51. Is the water for this use collected at the same time as water for another use? (specify the use) | S52. How long does it take to each person who collects water for this use? | S53. Do members who collect water use water at the source or bring it back home? | S54. Do you treat water? | S55. Are you satisfied with the water quality? | S56. Are you satisfied with the water quantity ? |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Drinking | Surveyor: Show on map if necessary | | __ Barrique/ Buckets/ L | | 1. 6-10h<br>2. 10-14h<br>3. 14-18h<br>4. 18-22h<br>5. 22-6h | | | 1. At the source<br>2. Bring home | 1. Filter with plastic<br>2. Make it boil<br>3. Add chlorine<br>4. No<br>5. Other: ___ | 1. Yes<br>2. No, detail _____ | 1. Yes<br>2. No, detail _____ |
| Drinking (if another source is used) | | | | | | | | | | | |
| Same questions for other uses: cooking, personal hygiene, laundry, animal drinking | | | | | | | | | | | |

*Surveyor*: If barrique used, how many liters does a barrique contain? _________ Liters per barrique
*Surveyor*: If bucket used, how many liters does a bucket contain _________ Liters per Bucket

Answer the questions for each of the following sources:

| Water source (fill only for sources used by the members of the household) | S57. How long did it take you to queue at the source and extract water from the source yesterday? | S58. Do you find it arduous to take out water from the source? | S59. Does your back hurt when you extract water from the source? | S60. Does the source dry up during certain moments of the year ? |
|---|---|---|---|---|
| Open well 1 | _______________ min | 1. Not arduous<br>2. Arduous<br>3. Very arduous<br>Detail: _________ | 1. Does not hurt<br>2. Hurts<br>3. Hurts a lot<br>Details: ___________ | Yes/No<br><br>If yes, during which months? ______<br><br>If yes, why does it dry up?______ |
| Open well 2 | | | | |
| same questions for other water sources for domestic use: hand pump, PVWPS | | | | |
| Comments | | | | |

How much did you spend for the following things the last month:

| | S61. Money spent (XOF) |
|---|---|
| Buying water to water vendors that come to your home | |
| Buying water at the store | |
| Buying water at the open well 1<br><br>Same question for open well 2, hand pump 1, hand pump 2, PVWPS | |
| Paying for the maintenance of open well 1<br><br>Same question for open well 2, hand pump 1, hand pump 2, PVWPS | |
| Comments: | |

## g. Income and sparings

*Surveyor*: The following questions are only for the head of the household. At this point, separate him from the rest of the household members and remind him that the data collected are strictly anonymous.

*Head only*: How much did your household cashed in during the previous month from the following sources:

| Category | S62. Money earned (XOF) |
|---|---|
| Crop sales | |
| Milk/eggs sales | |
| Animal/meat sales | |
| Trade, sell at shop | |
| Wages earned | |
| Government payments/pensions | |
| Money received from family | |
| Other | |
| Comments: | |

S63. *Head only*: What is the amount of current household's savings? Consider money from household and money invested in other places but not the value of real estate. ________________________XOF

S64. *Head only*: Is some money of the household saved at a cooperative and/or at a bank?

- ☐ Bank
- ☐ Cooperative
- ☐ Bank and cooperative
- ☐ No

S65. *Head only*: Have you ever borrowed money from a cooperative or a bank?

- ☐ Bank
- ☐ Cooperative
- ☐ Bank and cooperative
- ☐ No

S66. *Head only*: Do you participate to a tontine[8]?

- ☐ Yes
- ☐ No

*Surveyor:* The following question is only for the women of the household who are not at school anymore. At this point, separate them from the rest of the household members and remind them that the data collected are strictly anonymous.

S67. *Women of the household who are not at school anymore*: How many of you participate to a tontine? ____, details: ______________

## h. Closing the survey

S68. Date and time of the end of the survey: ________________________________________

Thank you for your participation!

[8] voluntary system of group savings

# Appendix B. Motor-pump model polynomial coefficients – case of the SQFlex 5A-7

| Polynomial | $Q_p = P_a^{4,4}(P_{pv}, TDH)$ | | | $TDH = P_b^{4,4}(P_{pv}, Q_p)$ | | |
|---|---|---|---|---|---|---|
| Formula | $Q_p = \sum_{m+n=0}^{m+n=4} k_{m,n} {P_{pv}}^m \, TDH^n$ | | | $TDH = \sum_{m+n=0}^{m+n=4} l_{m,n} {P_{pv}}^m \, {Q_p}^n$ | | |
| Coefficients | **Index** | **Value** | **Unit** | **Index** | **Value** | **Unit** |
| | $k_{0,0}$ | 2.3 $10^{-4}$ | $m^3\ s^{-1}$ | $l_{0,0}$ | 4.2 | m |
| | $k_{1,0}$ | 6.5 $10^{-6}$ | $m^3\ s^{-1}$ | $l_{1,0}$ | 1.5 $10^{-1}$ | $m\ W^{-1}$ |
| | $k_{0,1}$ | -5.2 $10^{-5}$ | $m^2\ s^{-1}$ | $l_{0,1}$ | -3.4 $10^{4}$ | $m^{-2}\ s$ |
| | $k_{2,0}$ | -7.3 $10^{-9}$ | $m^3\ s^{-1}\ W^{-2}$ | $l_{2,0}$ | -6.1 $10^{-5}$ | $m\ W^{-2}$ |
| | $k_{1,1}$ | - 2.9 $10^{-8}$ | $m^2\ s^{-1}\ W^{-1}$ | $l_{1,1}$ | -1.4 $10^{2}$ | $m^{-2}\ s\ W^{-1}$ |
| | $k_{0,2}$ | 8.3 $10^{-8}$ | $m\ s^{-1}$ | $l_{0,2}$ | 5.4 $10^{7}$ | $m^{-5}\ s^2$ |
| | $k_{3,0}$ | 3.6 $10^{-12}$ | $m^3\ s^{-1}\ W^{-3}$ | $l_{3,0}$ | 5.2 $10^{-8}$ | $m\ W^{-3}$ |
| | $k_{2,1}$ | 1.1 $10^{-10}$ | $m^2\ s^{-1}\ W^{-2}$ | $l_{2,1}$ | -1.5 $10^{-2}$ | $m^{-2}\ s\ W^{-2}$ |
| | $k_{1,2}$ | -2.0 $10^{-9}$ | $m\ s^{-1}\ W^{-1}$ | $l_{1,2}$ | 9.4 $10^{4}$ | $m^{-5}\ s^2\ W^{-1}$ |
| | $k_{0,3}$ | 2.8 $10^{-8}$ | $s^{-1}$ | $l_{0,3}$ | -4.1 $10^{10}$ | $m^{-8}\ s^3$ |
| | $k_{4,0}$ | -6.7 $10^{-16}$ | $m^3\ s^{-1}\ W^{-4}$ | $l_{4,0}$ | -2.1 $10^{-11}$ | $m\ W^{-4}$ |
| | $k_{3,1}$ | -3.9 $10^{-14}$ | $m^2\ s^{-1}\ W^{-3}$ | $l_{3,1}$ | 1.8 $10^{-5}$ | $m^{-2}\ s\ W^{-3}$ |
| | $k_{2,2}$ | 1.5 $10^{-13}$ | $m\ s^{-1}\ W^{-2}$ | $l_{2,2}$ | -15 | $m^{-5}\ s^2\ W^{-2}$ |
| | $k_{1,3}$ | 1.0 $10^{-11}$ | $s^{-1}\ W^{-1}$ | $l_{1,3}$ | -1.3 $10^{7}$ | $m^{-8}\ s^3\ W^{-1}$ |
| | $k_{0,4}$ | -2.6 $10^{-10}$ | $m^{-1}\ s^{-1}$ | $l_{0,4}$ | 7.8 $10^{12}$ | $m^{-11}\ s^4$ |

## Appendix C. Satellite climatic data

Regarding satellite ambient temperature data, the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2), provides the ambient temperature with a temporal resolution of 1 minute [135]. The data are available, for every location of the world, since 1980 and are regularly updated with one month of delay.

Regarding satellite irradiance data, the Copernicus Atmosphere Monitoring Service provides the direct normal irradiance $G_{dn}$, the global horizontal one $G_{gh}$ and the diffuse horizontal one $G_{dh}$ for the actual weather conditions with a temporal resolution of 1 minute [106]. The data are available, for locations between -66° and 66° in both latitude and longitude, since 2004 and are regularly updated with two days of delay. The irradiance on the plane of the PV array $G_{pv}$, can then be deduced from satellite data by [136]:

$$G_{pv}(t) = G_{dn}(t)\,cos\big(AOI(t,\theta,\lambda)\big) + G_{gh}(t)\,\zeta\,\frac{1-cos(\theta)}{2} + G_{dh}(t)\,\frac{1+cos(\theta)}{2} \qquad (39)$$

where $\zeta$ is the albedo of the surrounding environment, $\theta$ and $\lambda$ are the tilt and azimuth of the PV array respectively, $AOI$ is the angle of incidence between the sun's rays and the PV array. The $AOI$ is computed by using the MATLAB library PVLIB developed by the Sandia National Laboratories [137]. For the PVWPS of Gogma, according to the observation of the local environment a value of 0.25 is considered for the albedo $\zeta$ [91].

In Figure C.1 and Figure C.2, we compare the ambient temperature $T_a$ and the irradiance $G_{pv}$ obtained from satellite data and from local measurements, for the period between 19 February to 21 February 2018, The correlation between local measurements and satellite data is fair for ambient temperature ($R^2 = 0.83$) and good for irradiance ($R^2 = 0.96$).

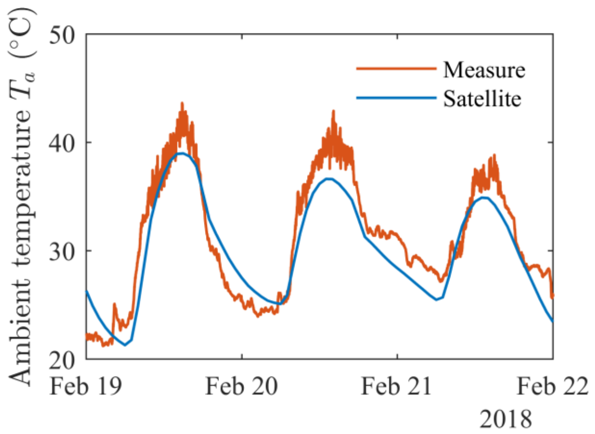


*Figure C-1 – Comparison of the ambient temperature from local measurements and from satellite data.*

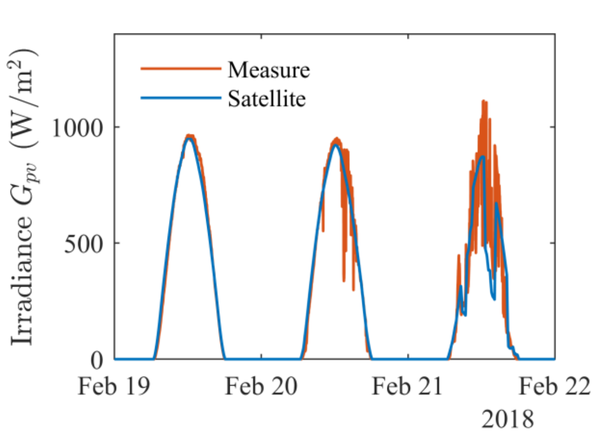


*Figure C-2 – Comparison of the irradiance on the plane of the PV array from local measurements and from satellite data.*

# Appendix D. Economic survey for local companies

**Preliminary remark:** The survey contained questions on solar pumps (i.e. PVWPS) and hand pumps. Here, we write down only the questions on solar pumps as it is the focus of this thesis.

**Preliminary remark:** The layout of the original survey has been adapted here to save space. The survey has been translated from French.

*Text explaining the survey, to read completely to the surveyee*

Date:

Name:

Company/Institution:

Email:

I am a student at Imperial College London and I am currently carrying a research project on the economic analysis and life cycle cost of solar pumps and hand pumps in Burkina Faso. You have been chosen to participate to this interview because of your knowledge on solar pumps and/or hand pumps. This survey includes oral and written questions. Questions refer to solar pumps and hand pumps and, depending on your expertise, you may be asked only about a part of the survey.

Are you selling:

- ☐ Hand pumps
- ☐ Solar pumps

Do you do maintenance for:

- ☐ Hand pumps
- ☐ Solar pumps

Preventive maintenance for a pumping system consists in verifying regularly that the pumping system is working correctly and possibly performing some minor maintenance operations such as greasing some parts. This intervention is not the consequence of a specific request of the village due to a dysfunction of the pumping system.

Do you do preventive maintenance for:

- ☐ Hand pumps
- ☐ Solar pumps

Do you do repairs for:

- ☐ Hand pumps
- ☐ Solar pumps

Remarks:

- If you do not have a precise idea of the costs, please do not answer
- If one of the question is not clear enough, please do not hesitate to ask for clarifications.
- Your answers to the questionnaire will be anonymized and only used for the research project.

## a. Written survey

1. How much do you charge for the following components of a solar pump?

| Components | Price |
|---|---|
| Solar panels<br>- Give power<br>- Give brand and reference if possible | |
| Connection cables<br>- Give length<br>- Give cross section<br>- Give materials | |
| Motor-pump<br>- Give power, flow rate and maximum pumping height if possible<br>- Give brand and reference if possible | |
| Reservoir<br>- Give materials<br>- Give volume | |
| Borehole<br>- Give depth<br>- Give diameter | |
| Support structure for solar panels | |
| Pipes<br>- Give materials<br>- Give diameter<br>- Give length | |
| Standpipes | |

2. What lifetime do you consider for the following components of a solar pump?

| Components | Lifespan |
|---|---|
| Solar panels<br>- If you draw a distinction according to the brand, please mention it. | |
| Connection cables<br>- If you draw a distinction according to the material, please mention it. | |
| Pump<br>- If you draw a distinction according to the brand, please mention it. | |
| Reservoir<br>- If you draw a distinction according to the material, please mention it. | |
| Borehole<br>- If you draw a distinction according to the depth or diameter, please mention it. | |
| Support structure for solar panels | |
| Pipes<br>- If you draw a distinction according to the material, please mention it. | |
| Standpipes | |

## b. Oral survey

1. On average, how many years will a solar pump last?

2. What reasons can lead to the closing or abandonment of a solar pump?

3. Do you offer a guarantee for the solar pumps installed?
    a. If yes, for how long is it effective?
    b. If yes, what does it cover?

4. According to you, are the prices of solar systems components:
    - ☐ Very low
    - ☐ Low
    - ☐ Normal
    - ☐ High
    - ☐ Very high

Comments:

5. How much do you charge for the installation of a solar pump with a reservoir (transport and workforce included, not considering the cost of the components)?

| Distance between the solar pump and the office of your company | Cost |
|---|---|
| 50 km | |
| 200 km | |
| 400 km | |

### *b.1. Preventive maintenance*

1. In general, who is responsible for the preventive maintenance of solar pumps?

2. In general, who pays for the preventive maintenance of solar pumps?

3. Which preventive maintenance scheme do you usually use for solar pumps?
    - ☐ A package
    - ☐ A single payment

**If package :**

- o Is it:
- ☐ A monthly fee
- ☐ An annual fee
- ☐ A multiyear fee. Specify the number of years:

- o How much do you charge for it?

| Distance between the solar pump and the office of your company | Cost |
|---|---|
| 50 km | |
| 200 km | |
| 400 km | |

**If single payment for each intervention:**

- o How much do you charge for it?

| Distance between the solar pump and the office of your company | Cost |
|---|---|
| 50 km | |
| 200 km | |
| 400 km | |

4. What is, on average, the frequency of intervention for preventive maintenance on a solar pump?

5. According to you, are the costs of preventive maintenance interventions (transport included, without the cost of the components) for solar pumps:
    - Very low
    - Low
    - Normal
    - High
    - Very high

Comments:

### *b.2. Repairs*

1. In general, who is responsible for the repairs of solar pumps?

2. In general, who pays for the repairs of solar pumps?

3. Which repairs scheme do you usually use for solar pumps?
    - A package
    - A single payment

**If package:**

- Is it:
    - A monthly fee
    - An annual fee
    - A multiyear fee. Specify the number of years:

- How much do you charge for it?

| Distance between the solar pump and the office of your company | Cost |
|---|---|
| 50 km | |
| 200 km | |
| 400 km | |

**If single payment for each intervention:**

- How much do you charge for it?

| Distance between the solar pump and the office of your company | Cost |
|---|---|
| 50 km | |
| 200 km | |
| 400 km | |

4. What is, on average, the frequency of intervention for repairs on a solar pump?

5. According to you, are the costs of repairs (transport included, without the cost of the components) for solar pumps:
    - Very low
    - Low
    - Normal
    - High
    - Very high

Comments:

Thank you for your participation!

## Appendix E. Range of variation of groundwater parameters

There are 3 groundwater parameters: the height between the ground level and the static water level in the borehole $H_{b,s}$, the aquifer losses coefficient $\kappa_0$ and the borehole losses coefficient $\mu_0$. In this section, we present how to determine the range of variation of these parameters for a given location in Africa, without drilling a borehole and performing pumping tests.

Regarding $H_{b,s}$, MacDonald et al. [9] provided a map with the range of variation of $H_{b,s}$ for all locations of Africa (see Figure E.1). We added the location of Gogma on this map. Gogma is at the limit between the category "0 to -7 m" and the category "-7 m to -25 m". Thus, we consider that $H_{b,s}$ is comprised between 0 and -25 m in Gogma.

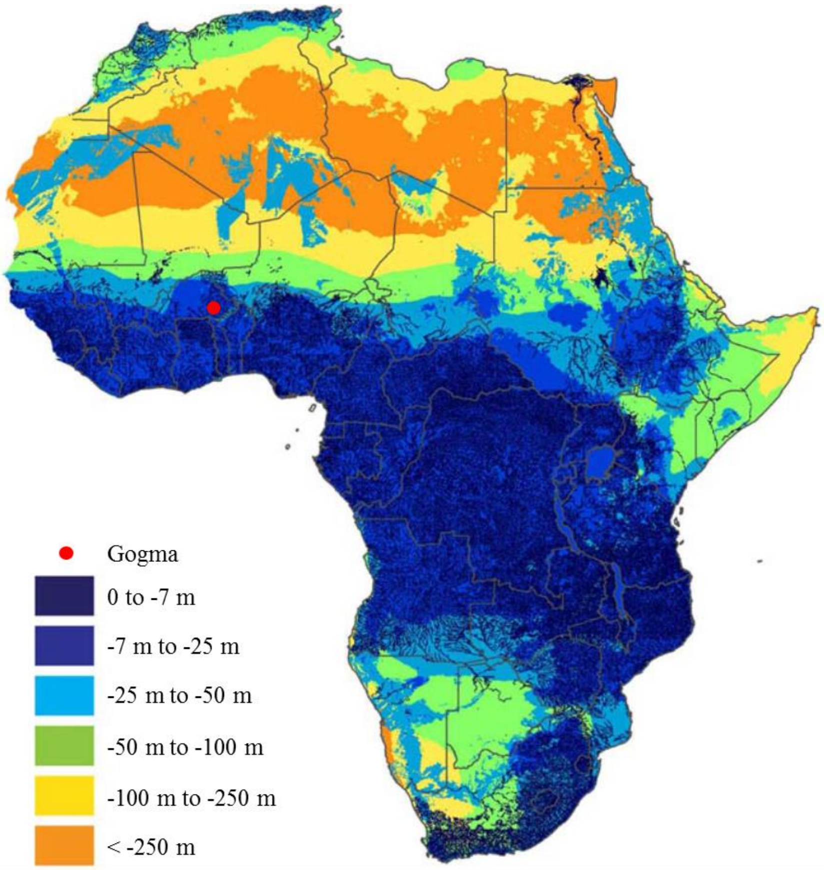


*Figure E-1 – Range of variation of $H_{b,s}$ in Africa [9].*

Regarding $\kappa_0$ and $\mu_0$, no map is available. However, we encountered values of these parameters in studies performed worldwide [78, 93, 138, 139]: 72 values were found for $\kappa_0$ and $\mu_0$. For $\kappa_0$, the minimum and maximum values encountered are 0.5 $m^{-2}$ s and 2.3 $10^3$ $m^{-2}$ s, respectively. For $\mu_0$, the minimum and maximum values encountered are 13 $m^{-5}$ $s^2$ and 6.2 $10^5$ $m^{-5}$ $s^2$, respectively. From this and after discussions with hydrologist Prof. Peter K. Kitanidis, we set the following ranges of variation for $\kappa_0$ and $\mu_0$:

- $\kappa_0 \in [0, 6.9\ 10^3]$ $m^{-2}$ s
- $\mu_0 \in [0, 1.9\ 10^6]$ $m^{-5}$ $s^2$

# Extended summary in French

# Extended summary in French

## Chapitre I : Revue de littérature

En Afrique subsaharienne, les alternatives les plus communes pour l'accès à l'eau pour l'usage domestique dans les zones pauvres et non connectées au réseau électrique sont les puits ouverts, desquels l'eau est extraite avec un seau et une corde, et les pompes à main. L'eau des puits ouverts n'est pas potable car ils sont exposés à la contamination extérieure. En revanche, l'eau des pompes à main est potable. Cependant, pour les pompes à main, tout comme pour les puits ouverts, l'extraction d'eau est difficile, le débit d'extraction est limité par la force humaine et ces pompes ne permettent pas d'atteindre les ressources en eau profondes (> 50 m). Les technologies de pompage d'eau électrifiées permettent de remédier à ces difficultés. Les deux principales sources d'énergie pour l'électrification des pompes sont l'énergie photovoltaïque et le diesel. Les systèmes de pompage photovoltaïques (PVWPS) sont compétitifs économiquement avec les pompes diesel et ont une durée de vie plus longue, des besoins en maintenance plus réduits et n'émettent pas de fumées toxiques. Nous avons de plus mis en évidence que les émissions de gaz à effet de serre des PVWPS pour l'accès à l'eau domestique sont faibles, notamment car un PVWPS de faible puissance (~1 kW) fournit un service à haute valeur ajoutée (i.e. fournir de l'eau à des dizaines de ménages). Cela explique pourquoi nous ne nous intéresserons pas aux émissions de gaz à effet de serre des PVWPS dans cette thèse.

La conception d'un PVWPS pour un village rural consiste à déterminer son architecture, sa position dans le village et son dimensionnement. Conventionnellement, ces éléments sont déterminés de la manière suivante :

- Architecture : le stockage grâce à un réservoir d'eau est privilégié par rapport aux batteries, pour des raisons de fiabilité qui sont cruciales dans ces zones rurales.
- Position : le décideur propose une position dans le village en suivant quelques lignes directrices.
- Dimensionnement : les articles scientifiques actuels visent à déterminer le dimensionnement du système qui minimise le coût sur cycle de vie et qui maximise la satisfaction de la demande en eau des habitants.

Conformément à la littérature, l'architecture avec le réservoir d'eau nous paraît aussi la plus adaptée et nous considérons donc cette architecture dans cette thèse. Cependant, concernant la position et le dimensionnement, nous avons identifié les manquements suivants de l'approche conventionnelle :

- Le positionnement est un sujet très peu abordé dans la littérature et aucun outil de support n'est fourni au décideur pour le positionnement du PVWPS.
- La position et le dimensionnement ne sont pas couplés, c'est-à-dire que les travaux sur le dimensionnement des PVWPS ne prennent pas en compte le fait que la demande en eau au PVWPS dépend de sa position dans le village. En effet, un grande partie des villages d'Afrique subsaharienne sont très étendus (plusieurs km$^2$) et les conditions d'accès à l'eau ne sont pas les mêmes dans toutes les zones du village. Ainsi, l'affluence à un nouveau point d'eau (ici le PVWPS) dépendra de sa position dans le village.

- L’approche conventionnelle pour la conception des PVWPS ne considère pas l’impact sur le développement socio-économique (e.g. utilisation d’une eau de meilleure qualité, diminution de la distance à parcourir pour la collecte d’eau), alors que la maximisation de cet impact positif est l’objectif principal des institutions qui financent les PVWPS. Cela empêche de plus de cibler les habitants du village qui ont l’accès à l’eau le plus défavorable.

*L’objectif de cette thèse est donc de développer une méthodologie de conception optimale des PVWPS qui permette de déterminer les dimensionnements du PVWPS et ses positions dans le village qui maximisent l’impact positif sur le développement socio-économique et minimisent le coût sur cycle de vie du PVWPS.* Cet objectif est atteint en trois étapes principales:

- **Chapitre II**. Un PVWPS est conçu et installé de manière conventionnelle dans un village rural d’Afrique subsaharienne. D’une part, cela permet de comprendre en détail la situation actuelle concernant les PVWPS et de mettre en place une méthodologie qui se base sur cette situation. D’autre part, cela permet de collecter des données pour appliquer la méthodologie développée et pour valider les modèles proposés.
- **Chapitre III**. Nous construisons un modèle interdisciplinaire liant le dimensionnement et la position du PVWPS à son impact socio-économique et à son coût du cycle de vie. Le modèle interdisciplinaire est composé de 4 sous-modèles : demande, technique, impact et économique.
- **Chapitre IV**. Nous définissons un problème d'optimisation pour déterminer les dimensionnements et les positions du PVWPS qui maximisent l'impact positif sur le développement socio-économique et minimisent le coût du cycle de vie du PVWPS puis nous présentons les résultats.

Pour résumer, dans le chapitre II, nous apprenons de la conception et de l’installation d’un PVWPS de manière conventionnelle. Ensuite, dans les chapitres III et IV, nous utilisons les connaissances acquises pour proposer une méthodologie améliorée de conception et d’installation des PVWPS (i.e. nous déterminons comment nous aurions pu concevoir et installer le PVWPS mis en place conventionnellement de manière plus optimale).

Ce travail a été effectué au sein d’une équipe interdisciplinaire composée de chercheurs en génie électrique (laboratoires GeePs et SATIE), politique environnementale (Imperial College London), économétrie (Colorado State University) et hydrologie (Stanford University) en collaboration avec l’entreprise Burkinabé DargaTech, spécialisée dans les systèmes d’énergie solaire.

## Chapitre II : Dispositif expérimental

### Village d’étude

Le village de Gogma (latitude 11.73°, longitude -0.58°) compte 1100 habitants répartis dans 125 ménages. Les ménages sont eux-mêmes regroupés en 41 concessions. La grande majorité des habitants travaillent dans le domaine de l’agriculture et vivent avec un revenu inférieur à 1 $/jour. Les ménages n’ont pas accès à l’électricité. Nous avons identifié 4 types d’usages domestiques de l’eau : boire, cuisiner, se laver et laver les vêtements. L’eau pour ces usages est collectée auprès de 22 points d’eau répartis en 3 catégories : 16 puits ouverts desquels l’eau est extraite avec un seau et une corde, 5 pompes à main et 1 PVWPS.

**Conception, installation et description du PVWPS**

Nous avons suivi les différentes étapes de la conception et de l’installation du PVWPS qui a été coordonnée par l’entreprise Burkinabé DargaTech. L’analyse de ces étapes et les discussions avec les membres de DargaTech nous ont permis de mettre en évidence la procédure conventionnelle d’installation des PVWPS au Burkina Faso. Elle est détaillée sur la figure 1. Cette procédure a duré 5 mois à Gogma entre fin 2017 et début 2018 et le PVWPS a été ouvert à la consommation en janvier 2018.

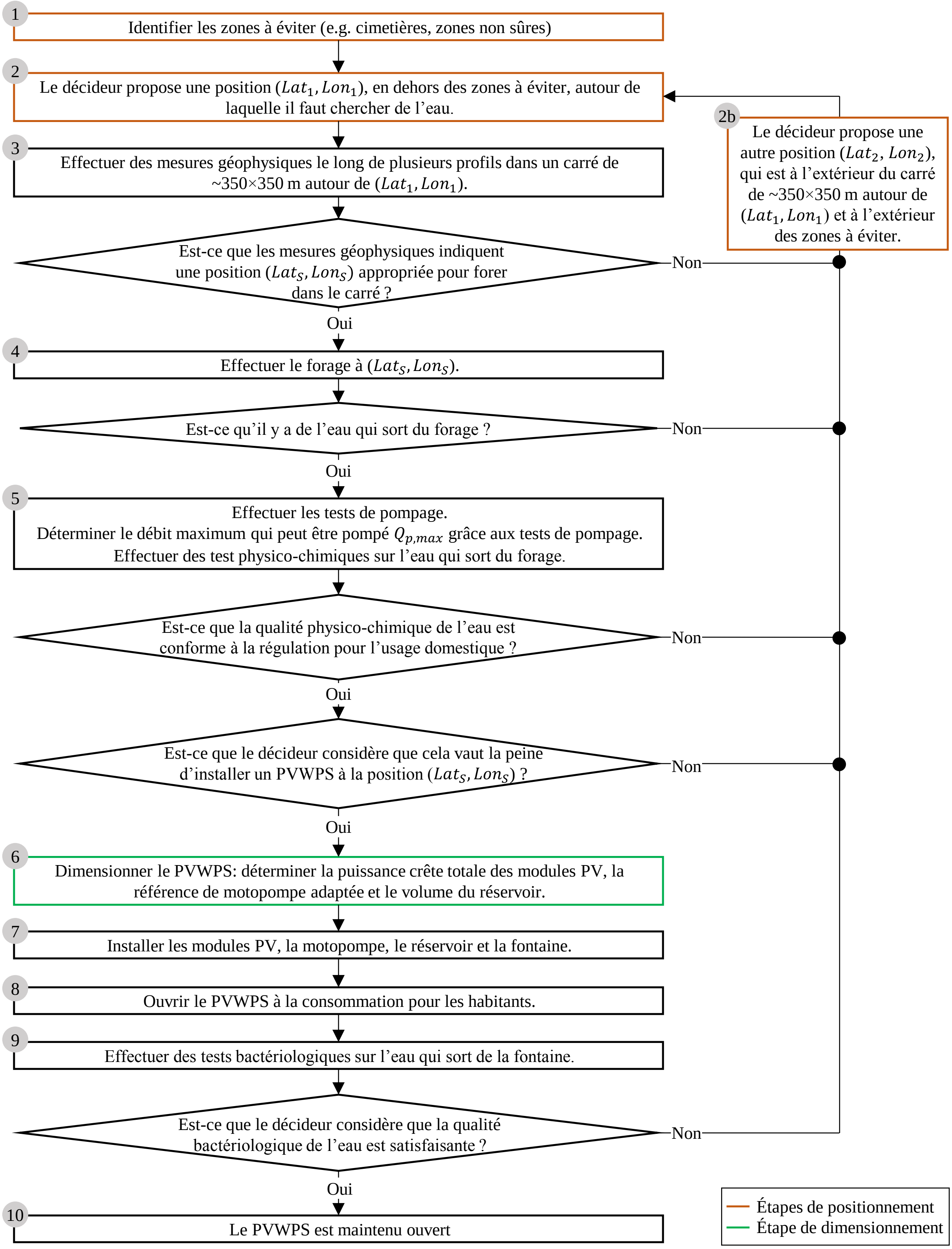


*figure 1 – Procédure conventionnelle pour la conception et l'installation de PVWPS.*

La figure 2 présente l'architecture du PVWPS installé et la figure 3 montre le système. Une vidéo du village et du PVWPS est aussi disponible au lien suivant : [https://youtu.be/VrjM0edKVsI](https://youtu.be/VrjM0edKVsI). Ce système comprend

des modules PV polycristallins pour une puissance crête totale de 620 $W_c$, une motopompe Grundfos SQFlex 5A-7 et un réservoir d'eau cylindrique en acier de 11.4 $m^3$. Le contrôleur régule l'énergie fournie par les modules PV à la motopompe, selon le niveau d'eau dans le réservoir, obtenu par un interrupteur à flotteur. L'eau est collectée à la fontaine par les habitants.

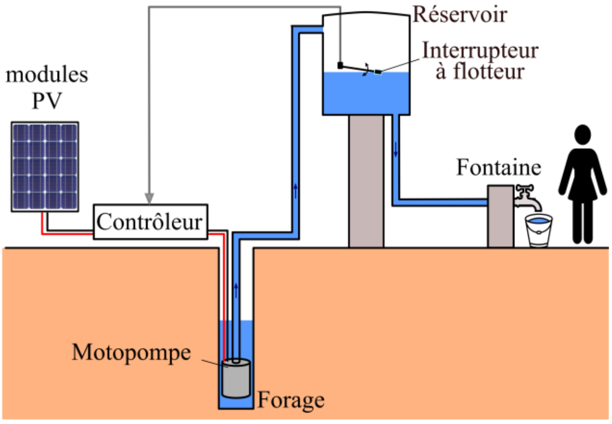


*figure 2 – Architecture du PVWPS.*

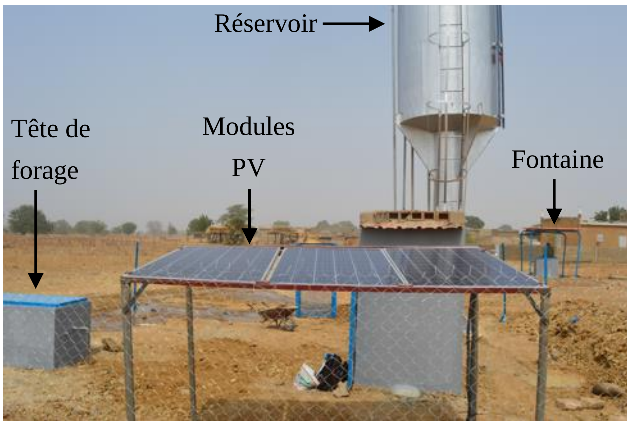


*figure 3 – Photo du PVWPS.*

**Collecte de données**

Voici les données principales qui ont été collectées à Gogma :

- Les coordonnées GPS des ménages, des sources d'eau et des points importants du village ont été relevées et sont représentées sur la photo satellite de la figure 4.
- Des mesures géophysiques ont été effectuées, avant la mise en place du PVWPS actuel, visant à détecter l'éventuelle présence d'eau (voir figure 4).
- Nous avons déterminé le coût pour collecter de l'eau à chaque source grâce aux carnets de comptes des sources.
- Des enquêtes ménage socio-économiques ont été effectuées, avant et après l'ouverture à la consommation du PVWPS, auprès de 88 ménages tirés au sort parmi les 125 ménages du village. Ces enquêtes ont notamment permis de connaître le choix de source de chaque ménage avant et après l'installation du PVWPS, ainsi que de savoir comment les ménages perçoivent la qualité de l'eau et la facilité d'extraction aux sources qu'ils utilisent. Les données recueillies pour les 88 ménages intérrogés sont extrapolées aux 37 ménages du village qui n'ont pas été interrogés, notamment grâce à la connaissance de la position GPS de ces 37 ménages.
- Des tests de pompage ont été réalisés pour le PVWPS actuel. Ils ont permis de déterminer le débit maximum $Q_{p,max}$ qui peut être extrait du forage sans mettre en péril les ressources en eau.
- Des analyses bactériologiques ont été effectuées pour toutes les sources d'eau afin de quantifier leur qualité.
- Le PVWPS est monitoré en continu depuis janvier 2018 grâce à un système de collection de données autonome que nous avons nous-mêmes conçu et installé. Les grandeurs collectées sont l'irradiance, la température ambiante, la tension et le courant des modules PV, le débit pompé, le débit collecté à la fontaine et le niveau d'eau dans le forage. Les données sont collectées avec un pas de temps de

2 s. À notre connaissance, c’est la première fois qu’un PVWPS pour l’accès à l’eau domestique est monitoré et que des données ont été collectées sur un PVWPS en Afrique subsaharienne rurale.

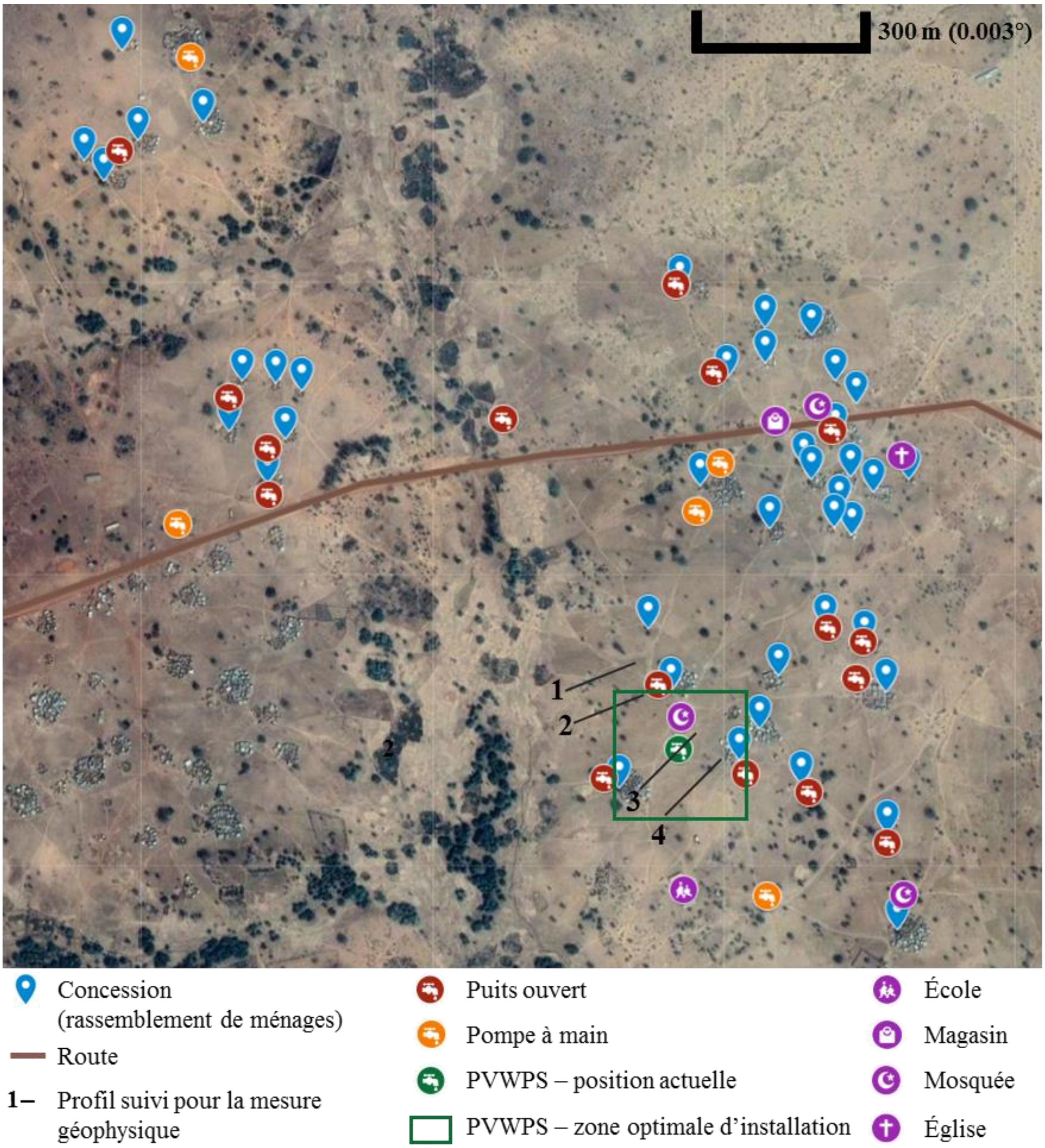


*figure 4 – Cartographie GPS du village de Gogma.*

## Chapitre III : Modèle interdisciplinaire

Le modèle interdisciplinaire lie le dimensionnement et la position du PVWPS à son impact socio-économique et à son coût du cycle de vie. Le synoptique du modèle est représenté sur la figure 5.

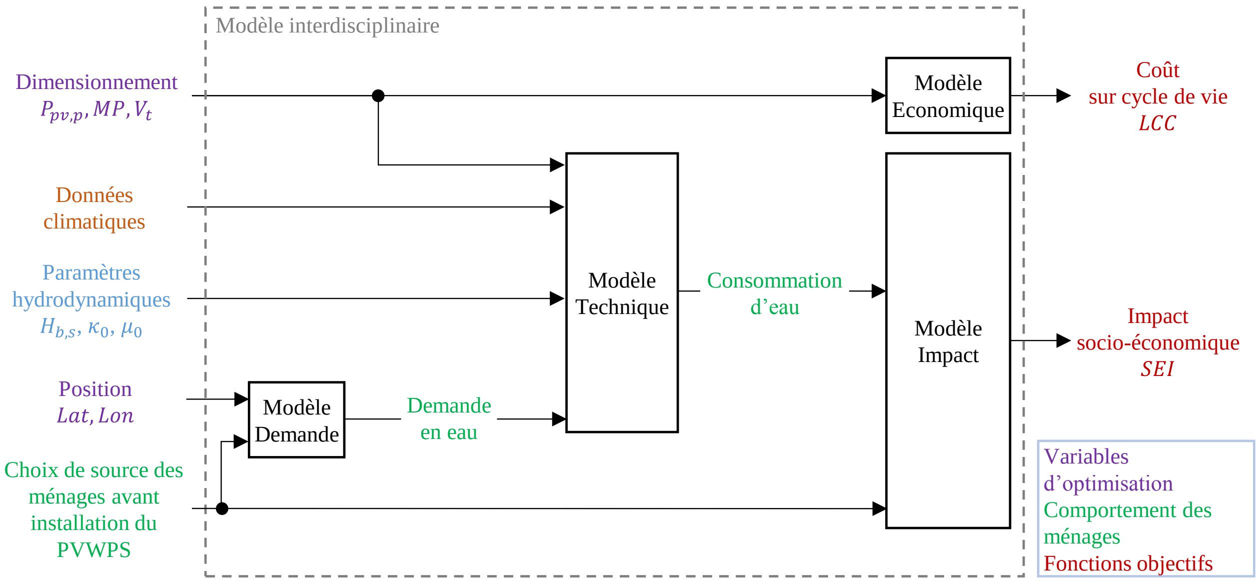


*figure 5 – Synoptique du modèle interdisciplinaire.*

### Entrées

Les entrées du modèle interdisciplinaire peuvent être regroupées en 4 catégories :

1. *Variables d'optimisation.* Nous distinguons deux types de variables d'optimisation: (1) les variables de dimensionnement du PVWPS et (2) la position du PVWPS dans le village, qui est donnée par sa longitude $Lon$ et sa latitude $Lat$. Les variables de dimensionnement incluent la puissance crête totale des modules PV dans les conditions de test standard (STC) $P_{pv,p}$, la référence de la motopompe $MP$ et le volume du réservoir d'eau $V_t$. Nous avons numérisé les courbes caractéristiques de 8 références de motopompes.
2. *Données climatiques.* Ce sont les données d'irradiance et de température ambiante.
3. *Paramètres hydrodynamiques*: le niveau d'eau statique dans le forage $H_{b,s}$ (i.e. le niveau d'eau lorsqu'il n'y a pas de pompage), le coefficient de pertes dues à l'aquifère $\kappa_0$ et le coefficient de pertes dues au forage $\mu_0$. Ces paramètres hydrodynamiques dépendent des ressources en eau. Ils sont déterminés après avoir fait un forage puis des tests de pompage. Par exemple, ils ont été déterminés pour le PVWPS actuel de Gogma grâce aux tests de pompage effectués (voir Chapitre II). Sans faire de forage et de tests de pompage, il est seulement possible de donner une plage de variation de ces paramètres (voir Appendix E).
4. *Le choix de source des ménages avant installation du PVWPS.*

### Sorties

Les sorties du modèle interdisciplinaire sont le coût du PVWPS sur cycle de vie $LCC$ et son impact socio-économique $SEI$.

### Sous-modèles

Le *modèle de demande* est un modèle d'économétrie qui permet de prévoir le choix de source d'eau effectué par chaque ménage à partir:

- des distances entre le ménage et les différentes sources d'eau ;
- de la perception du ménage de la qualité de l'eau des différentes sources.

Nous pouvons donc, pour chaque position du PVWPS, prévoir quels ménages quitteraient leur ancienne source d'eau au profit du PVWPS. Cela permet d'obtenir la demande en eau au PVWPS. Les paramètres de ce modèle sont identifiés grâce au choix de source des ménages et à leur perception et distance aux sources avant installation du PVWPS (données collectées grâce aux enquêtes ménage).

Le *modèle technique* permet de déterminer le pourcentage de la demande en eau au PVWPS qui est satisfait, c'est-à-dire la consommation d'eau, et d'identifier les ménages qui bénéficient effectivement du PVWPS. Les entrées du modèle sont les données climatiques, les paramètres hydrodynamiques et le dimensionnement du PVWPS. Ce modèle prend en compte les différentes étapes de la conversion d'énergie au sein du PVWPS et la réponse de la nappe phréatique au pompage d'eau. Nous avons validé ce modèle pour le système actuel de Gogma grâce aux données acquises par le système de collection de données. Nous évaluons ce modèle pour une année avec un pas de temps de 1h. Grâce aux modèles de demande et technique, nous pouvons donc prédire quels ménages vont effectivement quitter leur ancienne source d'eau pour le PVWPS.

Le *modèle d'impact* permet alors d'évaluer l'impact socio-économique $SEI$ associé à ces changements de sources d'eau. L'impact socio-économique est évalué grâce à des indicateurs. Nous avons séparé ces indicateurs en deux catégories :

- *Indicateurs directs*. Ils résultent directement du changement de source d'eau. Ils sont au nombre de 4 : la qualité de l'eau utilisée, la facilité pour extraire l'eau, le prix à payer pour utiliser l'eau et la distance à parcourir pour collecter l'eau.
- *Indicateurs indirects*. Ils résultent des indicateurs directs. Ces indicateurs considèrent notamment la prévalence des maladies hydriques (diarrhée, trachome), les gains de temps, les dépenses de santé et l'accès à l'éducation.

Nous quantifions tout d'abord l'effet des changements de sources d'eau sur les indicateurs directs, puis l'effet de la variation des indicateurs directs sur la valeur des indicateurs indirects. L'impact socio-économique est égal à la somme pondérée des valeurs des indicateurs directs et indirects, normalisées au préalable. Les coefficients de pondération dépendent du choix du décideur politique, selon les indicateurs qu'il veut favoriser.

Le *modèle économique* permet de déterminer le coût du PVWPS sur cycle de vie $LCC$ à partir de son dimensionnement (valeurs de $P_{pv,p}$, $MP$ et $V_t$). Le modèle prend en compte les coûts d'investissement et de fonctionnement et l'actualisation de la monnaie. Les données utilisées pour ce modèle ont été collectées auprès d'entreprises Burkinabès.

# Chapitre IV : Conception optimale

**Problème d'optimisation**

Les 2 fonctions objectifs de l'optimisation sont le coût sur cycle de vie $LCC$ du PVWPS, que nous voulons minimiser, et l'impact socio-économique $SEI$, que nous voulons maximiser. Les variables de l'optimisation

sont la puissance de crête totale des modules PV $P_{pv,p}$, la référence de motopompe $MP$, le volume du réservoir d'eau $V_t$, la latitude $Lat$ et la longitude $Lon$ du PVWPS. La référence de motopompe $MP$ est la seule variable discrète. Nous effectuons une optimisation pour chaque référence de motopompe $MP$ et nous obtenons donc un front de Pareto pour chaque référence de motopompe. Nous déterminons alors le front de Pareto final en passant par les meilleurs points des fronts de Pareto associés aux références de motopompes.

Nous ne mettons pas de contrainte sur la satisfaction de la demande en eau et nous considérons donc aussi les systèmes sous-dimensionnés, pour lesquels la consommation d'eau est inférieure à la demande en eau.

Nous utilisons un algorithme d'évolution différentielle bi-objectif, qui est un algorithme stochastique pour l'optimisation. Nous avons choisi un algorithme stochastique car le problème d'optimisation est non-linéaire.

**Analyse d'un résultat de référence**

Nous présentons ici un exemple de résultat d'optimisation pour lequel l'impact socio-économique considère les 4 indicateurs directs avec des poids tous identiques. Nous supposons de plus que, pour toutes les positions de Gogma, les valeurs des paramètres hydrodynamiques sont les mêmes que les valeurs déterminées pour le PVWPS actuel. La figure 6 montre le front Pareto obtenu.

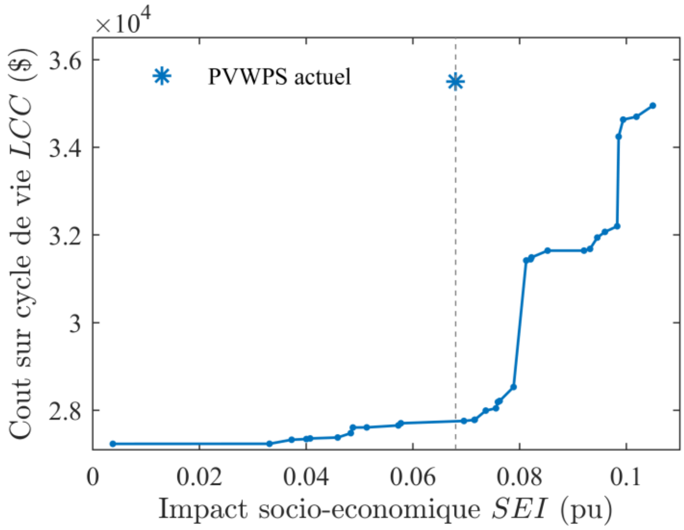


*figure 6 – Front de Pareto.*

La figure 7, la figure 8 et la figure 9 illustrent l'évolution des variables d'optimisation le long du front de Pareto. Nous présentons aussi sur ces figures les valeurs des fonctions objectifs et des variables pour le système actuel de Gogma.

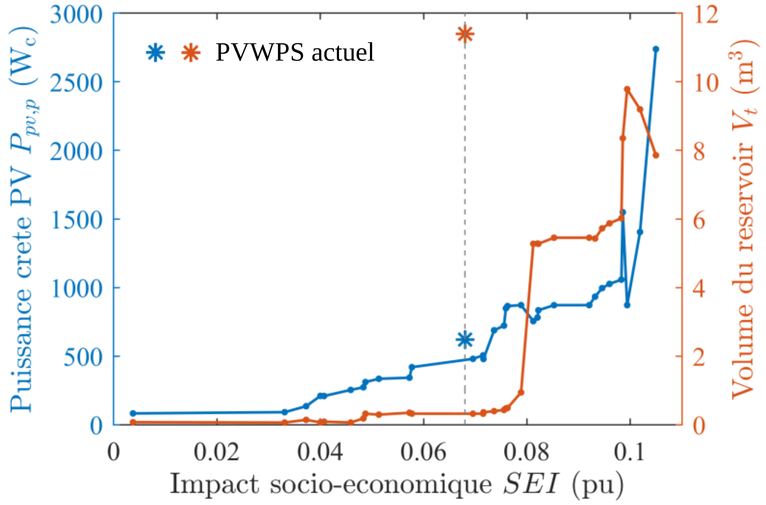


*figure 7 – Variation de $P_{pv,p}$ et $V_t$ en fonction de $SEI$.*

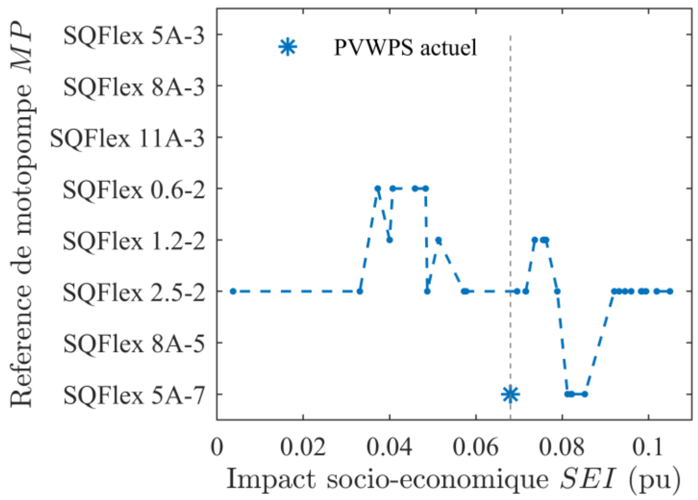


*figure 8 – Variation de $MP$ en fonction de $SEI$.*

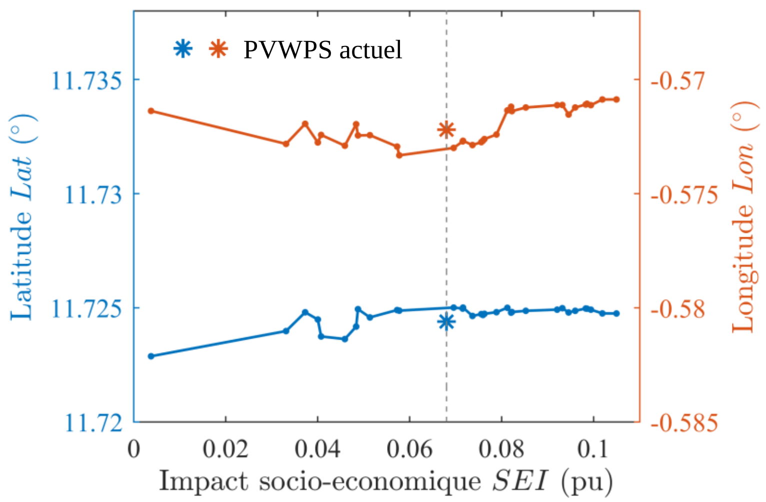


*figure 9 – Variation de $Lat$ et $Lon$ en fonction de $SEI$.*

La figure 6 permet de déterminer (1) l'impact socio-économique $SEI$ maximum envisageable pour un PVWPS de coût $LCC$ et (2) la coût minimal $LCC$ pour atteindre un impact socio-économique $SEI$ donné. Il apparaît logiquement que des dépenses plus importantes conduisent à des impacts socio-économiques positifs plus significatifs. Les résultats indiquent aussi que la différence de $LCC$ entre le point de minimum $SEI$ et le point de maximum $SEI$ est 7.9 $10^3$ \$, ce qui représente 29% du coût $LCC$ du point de minimum $SEI$ (2.72 $10^4$ \$). Cela suggère que, dans la mesure du possible, il est préférable de choisir des points du front avec des valeurs de $SEI$ élevées.

Nous observons de plus sur la figure 7 que les valeurs optimales de la puissance crête totale des modules PV $P_{pv,p}$ et du volume du réservoir $V_t$ augmentent avec l'impact socio-économique $SEI$. En effet, de manière générale, des systèmes de plus grande taille permettent d'accroître le nombre de bénéficiaires et donc l'impact socio-économique. Concernant le choix de motopompe (figure 8), l'optimisation privilégie les références 5A-7, 2.5-2, 1.2-2 et 0.6-2. Enfin, nous observons une faible variation de la position du PVWPS le long du front de Pareto (figure 9). Cela permet d'identifier une zone du village ($Lat \in$ [11.723°, 11.725°] × $Lon \in$ [-0.573°, -0.571°]) où l'installation du PVWPS serait optimale. Nous avons représenté cette zone par un rectangle vert sur la figure 4. Nous observons sur la figure 4, que la densité de ménages est relativement élevée dans cette zone et que les seules sources d'eau disponibles sont des puits ouverts, qui sont des sources de mauvaise qualité (eau non potable) et pour lesquelles l'extraction d'eau est très fastidieuse. Ainsi, dans le cas où un PVWPS est installé dans cette zone, les ménages proches du PVWPS peuvent alors quitter leur puits ouvert pour le PVWPS. Cela conduit à un fort impact socio-économique et explique notamment le choix de cette zone par l'optimisation.

Nous pouvons aussi comparer les valeurs des fonctions objectifs et des variables pour le système actuel aux résultats optimaux. Sur la figure 6, nous observons que le coût du PVWPS actuel (3.55 $10^4$ \$) aurait pu permettre d'atteindre l'impact socio-économique $SEI$ le plus élevé (0.105), à la place du $SEI$ du PVWPS actuel (0.068). En outre, il apparaît que l'impact socio-économique du système actuel (0.11) a été obtenu pour un coût $LCC$ de 3.55 $10^4$ \$ alors que, d'après le front de Pareto, il aurait pu être obtenu pour un coût de seulement ~2.78 $10^4$ \$. Cela suggère que l'application de la méthodologie aurait pu permettre d'économiser ~7.7 $10^3$ \$ à Gogma, pour l'expression du $SEI$ considérée ici. Pour le $SEI$ du PVWPS actuel (0.068), la figure 7 indique que la puissance crête totale des modules PV $P_{pv,p}$ actuelle est proche de la puissance optimale mais que le volume du réservoir $V_t$ actuel est bien plus large que le volume optimal. La figure 8 suggère que la motopompe SQFlex 2.5-2 serait plus adaptée que la motopompe actuelle (SQFlex 5A-7). En effet, pour le point du front de Pareto le plus proche ($SEI$ = 0.070), la motopompe optimale est la SQFlex 2.5-2. Enfin, la figure 9 montre que la position actuelle du PVWPS est proche de la position optimale.

Nous avons en outre évalué l'influence de l'erreur en sortie du modèle de demande, de la définition de l'impact socio-économique par le décideur politique et des ressources en eau sur les résultats d'optimisation.

**Proposition de procédure améliorée pour la conception et l'installation des PVWPS**

La procédure améliorée proposée est présentée sur la figure 10. Elle est basée sur la procédure conventionnelle (voir figure 1) et inclut la méthodologie d'optimisation développée.

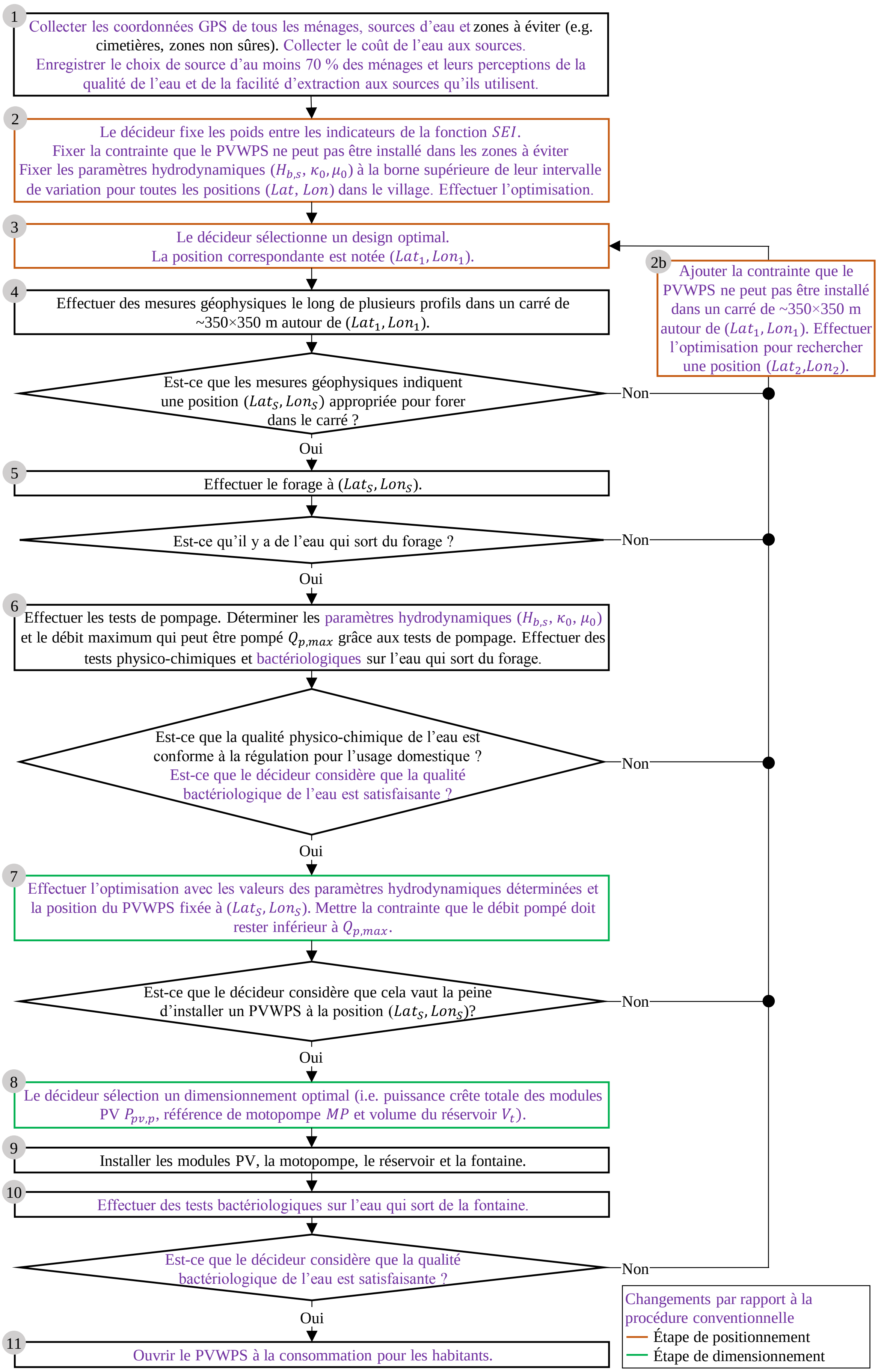


*figure 10 – Procédure améliorée pour la conception et l'installation des PVWPS.*

Nous présentons ici les différences entre la procédure conventionnelle (voir figure 1) et la procédure améliorée proposée (voir figure 10).

Pour évaluer les modèles de demande et d'impact, il est nécessaire de collecter des données dans le village. C'est l'objet de l'étape 1. Les coordonnées GPS de tous les ménages et sources doivent être recueillies ainsi que le coût de l'eau à toutes les sources. Il faut aussi recueillir le choix de source d'au moins 70% des ménages du village ainsi que leur perception de la qualité de l'eau et de la facilité d'extraction aux sources qu'ils utilisent. Nous estimons que cette collecte de données coûte environ ~800 $ pour un village comme Gogma. Lorsque nous comparons ce coût avec les économies potentielles liées à l'application de la méthodologie développée à Gogma (~7.7 $10^3$ $), cela suggère que l'application de la procédure améliorée est économiquement viable.

Une première optimisation bi-objectif est effectuée aux étapes 2 et 3, ce qui permet de proposer une première position ($Lat_1$, $Lon_1$), autour de laquelle les ressources en eau seront examinées. Pour cette optimisation, les poids de la fonction $SEI$ sont définis par le décideur en fonction des indicateurs qu'il souhaite privilégier. Enfin, les paramètres hydrodynamiques sont pris égaux à la limite supérieure de leur intervalle de variation pour toutes les positions ($Lat$, $Lon$) du village, ce qui aide à éviter des coûts plus élevés que prévu lors du forage et du dimensionnement du PVWPS. Grâce à cette première phase d'optimisation, le décideur peut désormais compter sur un outil lui permettant d'identifier une position potentielle ($Lat_1$, $Lon_1$) autour de laquelle installer le PVWPS. Cette position maximise l'impact socio-économique positif $SEI$ sur le village tout en minimisant le coût sur cycle de vie du système $LCC$. Nous rappelons que dans la situation classique, le décideur ne pouvait compter que sur son intuition pour cette étape de positionnement.

Au cours des étapes 4 à 6, le forage est effectué, la qualité de l'eau est testée et les paramètres hydrodynamiques ($H_{b,s}$, $\kappa_0$ et $\mu_0$) et le débit maximal pouvant être pompé $Q_{p,max}$ sont déterminés grâce aux essais de pompage.

Une seconde optimisation bi-objectif est ensuite effectuée aux étapes 7 et 8, ce qui permet de déterminer les valeurs des variables de dimensionnement. Pour cette optimisation, la position est fixée à la position du forage et la contrainte que le débit de la pompe doit rester inférieur à $Q_{p,max}$ est définie, afin de préserver les ressources en eau. Il est important de noter que la détermination des paramètres hydrodynamiques ($H_{b,s}$, $\kappa_0$ et $\mu_0$) est essentielle pour garantir le respect de la contrainte mentionnée précédemment car ces paramètres sont nécessaires pour calculer le débit pompé. Dans l'ensemble, cette deuxième phase d'optimisation aide la société qui installe le PVWPS et le décideur à déterminer le dimensionnement du PVWPS qui maximise l'impact socio-économique positif $SEI$ et minimise le coût du cycle de vie $LCC$, tout en préservant les ressources en eau.

Enfin, nous proposons également quelques modifications concernant les tests bactériologiques. Premièrement, nous proposons d'ajouter des tests bactériologiques en même temps que les tests physico-chimiques, à l'étape 6. En effet, les tests bactériologiques ne coûtent que ~20 $ (voir section II.2.7.2) et fournissent des informations sur la qualité bactériologique de l'eau du forage. Si le décideur n'est pas satisfait par la qualité de l'eau du forage, il peut alors décider de modifier la position du PVWPS avant d'effectuer

de nouveaux investissements. Deuxièmement, nous recommandons que les seconds tests bactériologiques soient toujours effectués avant l'ouverture du PVWPS à la consommation (voir étapes 10 et 11).

# References

# References


[1] F. Carlevaro, C. Gonzalez, *Costing improved water supply systems for low-income communities: A practical manual*, 1st ed, IWA Publishing, 2015.

[2] WaterAid, "Handpumps Technical Brief," 2013. [Online]. Available: https://washmatters.wateraid.org/sites/g/files/jkxoof256/files/technical-brief-handpumps_1.pdf [accessed 10 Oct 2018].

[3] G. F. White, D. J. Bradley, A. U. White, "Drawers of water: Domestic water use in East Africa," *Bulletin World Health Organization*, vol. 80, no. 1, pp. 63-73, 1972.

[4] J. Ntouda, F. Sikodf, M. Ibrahim, I. Abba, "Access to drinking water and health of populations in Sub-Saharan Africa," *Comptes Rendus Biologies*, vol. 336, no. 5–6, pp. 305–309, 2013.

[5] H. Ritchie, M. Roser, "Water Use and Sanitation," 2015. [Online]. Available: https://ourworldindata.org/water-use-sanitation [accessed 20 Oct 2018].

[6] Agence Française de Développement (AFD) and Programme Solidarité Eau, "Réalisation et gestion des forages équipés d'une pompe à motricité humaine en Afrique subsaharienne",
2011. [Online]. Available:
https://www.pseau.org/outils/ouvrages/afd_realisation_et_gestion_des_forages_equipes_d_une_pompe_a_motricite_humaine_en_afrique_subsaharienne_2011.pdf [accessed 10 Oct 2018].

[7] J. Bartram, S. Cairncross, "Hygiene, sanitation, and water: forgotten foundations of Health", *PLoS Med*, vol. 7, no. 11, 2010.

[8] World health organization (WHO) and United Nations Children's Fund (UNICEF), "Progress on Sanitation and Drinking Water - Joint Monitoring Programme on Water Supply and Sanitation," 2010, [Online]. Available:
http://www.who.int/water_sanitation_health/monitoring/9789241563956/en/ [accessed 10 Oct 2018].

[9] A. M. MacDonald, H. C. Bonsor, B. É. Ó. Dochartaigh, R. G. Taylor, "Quantitative maps of groundwater resources in Africa", *Environmental Research Letters*, vol. 7, no. 2, 2012

[10] S. Cairncross, V. Valdmanis, *Disease Control Priorities in Developing Countries – Chap. 41 Water supply, sanitation and hygiene promotion*, 2nd ed, New York: Oxford University Press, 2006.

[11] J. Smet, C. van Wijk, "Small Community Water Supplies," *Technical Paper Series 40 - IRC International Water and Sanitation Centre*, 2002.

[12] J. M. Puerta, "Study on the Performance and Sustainability of Water and Sanitation Initiatives in Rural Areas," Inter-American development bank, 2016. [Online]. Available: https://publications.iadb.org/en/study-performance-and-sustainability-water-and-sanitation-initiatives-rural-areas-drinking-water [accessed 10 Oct 2018].

[13] N. H. Ravindranath, H. I. Somashekar, S. Dasappa, C. J. Reddy, "Sustainable biomass power for rural India: Case study of biomass gasifier for village electrification," *Current Science*, vol. 87, no. 7, pp. 932–941, 2004.

[14] J. P. Murenzi, T. S. Ustun, "The case for microgrids in electrifying Sub-Saharan Africa," in *6th International Renewable Energy Congress (IREC)*, Sousse, Tunisia, 2015.

[15] H. Ahlborg, L. Hammar, "Drivers and barriers to rural electrification in Tanzania and Mozambique–Grid-extension, off-grid, and renewable energy technologies," *Renewable Energy*, vol. 61, pp. 117–124, 2014.

[16] A. K. Akella, R. P. Saini, M. P. Sharma, “Social, economical and environmental impacts of renewable energy systems,” *Renewable Energy*, vol. 34, no. 2, pp. 390–396, 2009.

[17] World Bank, “Access to electricity, rural (% of rural population),” 2016. [Online]. Available: https://data.worldbank.org/indicator/EG.ELC.ACCS.RU.ZS [accessed 17 Dec 2018].

[18] 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”, MSc thesis, Imperial College London, UK, 2018.

[19] W. Ratterman, J. Cohen, A. Garwood, “Green Empowerment Solar Pumping Systems (SPS) Introductory and Feasibility Guide,” 2003. [Online]. Available: https://sswm.info/sites/default/files/reference_attachments/RATTERMAN%20et%20al%202003%20Solar%20Pumping%20Systems.pdf [accessed 17 Dec 2018].

[20] I. Odeh, Y. G. Yohanis, B. Norton. “Economic viability of photovoltaic water pumping systems”, *Solar Energy*, vol. 80, no. 7, 850–860, 2006.

[21] M. Abu-Aligah, “Design of Photovoltaic Water Pumping System and Compare it with Diesel Powered Pump.,” *Jordan Journal of Mechanical and Industrial Engineering*, vol. 5, no. 3, 2011.

[22] B. Singh, A. K. Mishra, R. Kumar, “Solar Powered Water Pumping System Employing Switched Reluctance Motor Drive”, *IEEE Transactions on Industry Applications*, vol. 52, no. 5, pp. 3949-3957, 2016.

[23] M. I. Chergui, M. O. Benaissa, “Strategy photovoltaic pumping system in scattered area,” in *4$^{th}$ International Conference on Renewable Energy Research and Applications (ICRERA)*, pp. 283–286, Palermo, Italy, 2015.

[24] S. Ould-Amrouche, D. Rekioua, A. Hamidat, “Modelling photovoltaic water pumping systems and evaluation of their CO2 emissions mitigation potential,” *Applied Energy*, vol. 87, no. 11, pp. 3451–3459, 2010.

[25] J. Yang, A. Olsson, J. Yan, B. Chen, “A hybrid life-cycle assessment of CO2 emissions of a PV water pumping system in China,” *Energy Procedia*, vol. 61, pp. 2871–2875, 2014.

[26] J. V. Mapurunga Caracas, G. De Carvalho Farias, L. F. Moreira Teixeira, L. A. De Souza Ribeiro, “Implementation of a High-Efficiency, High-Lifetime, and Low-Cost Converter for an Autonomous Photovoltaic Water Pumping System,” *IEEE Transactions on Industry Applications*, vol. 50, no. 1, pp. 631–641, 2014.

[27] S. K. Jha, “Application of solar photovoltaic system in Oman–Overview of technology, opportunities and challenges,” *International Journal of Renewable Energy Research*, vol. 3, no. 2, pp. 331–340, 2013.

[28] A. M. Armanuos, A. Negm, A. H. M. H. El Tahan, “Life Cycle Assessment of Diesel Fuel and Solar Pumps in Operation Stage for Rice Cultivation in Tanta, Nile Delta, Egypt,” *Procedia Technology*, vol. 22, pp. 478–485, 2016.

[29] P. R. Mishra, R. Panguloori, N. Udupa, D. Mitra, “Economic evaluation of solar hybrid DC grid for petrol pump stations,” in *Annual IEEE India Conference (INDICON)*, 2013.

[30] R. J. Chilundo, U. S. Mahanjane, D. Neves, “Design and Performance of Photovoltaic Water Pumping Systems: Comprehensive Review towards a Renewable Strategy for Mozambique,” *Journal of Power and Energy Engineering*, vol. 6, no. 7, p. 32, 2018.

[31] S. S. Chandel, M. Nagaraju Naik, R. Chandel, “Review of solar photovoltaic water pumping system technology for irrigation and community drinking water supplies,” Renewable and Sustainable Energy Reviews, vol. 49, pp. 1084–1099, 2015.

[32] R. Foster, A. Cota, “Solar Water Pumping Advances and Comparative Economics,” *Energy Procedia*, vol. 57, pp. 1431–1436, 2014.

[33] R. Parajuli, G. R. Pokharel, P. A. Ostergaard, "A comparison of diesel, biodiesel and solar PV-based water pumping systems in the context of rural Nepal," *International Journal of Sustainable Energy*, 2013.

[34] Z. Girma, "Techno-economic analysis of photovoltaic pumping system for rural water supply in Ethiopia," *International Journal of Sustainable Energy*, vol. 36, no. 3, pp. 277–295, 2017.

[35] A. Allouhi, M. S. Buker, H. El-houari, A. Boharb, M. Benzakour Amine, T. Kousksou, A. Jamil, "PV water pumping systems for domestic uses in remote areas: Sizing process, simulation and economic evaluation," *Renewable Energy*, vol. 132, pp. 798–812, 2019.

[36] A. Kumar, T. C. Kandpal, "Potential and cost of CO2 emissions mitigation by using solar photovoltaic pumps in India," *International Journal of Sustainable Energy*, vol. 26, no. 3, pp. 159–166, 2007.

[37] M. N. I. Sarkar, H. R. Ghosh, "Techno-economic analysis and challenges of solar powered pumps dissemination in Bangladesh", *Sustainable Energy Technologies and Assessments*, vol. 20, pp. 33-46, 2017.

[38] S. Rehman, A. Z. Sahin, "Performance comparison of diesel and solar photovoltaic power systems for water pumping in Saudi Arabia," *International Journal of Green Energy*, vol. 12, no. 7, pp. 702–713, 2015.

[39] Organisation for Economic Co-operation and Development (OECD), "Greenhouse gas emissions," 2017. [Online]. Available: https://stats.oecd.org/Index.aspx?DataSetCode=AIR_GHG [accessed 20 Aug 2019].

[40] R. Sen, S. C. Bhattacharyya, "Off-grid electricity generation with renewable energy technologies in India: An application of HOMER," *Renewable Energy*, vol. 62, pp. 388–398, 2014.

[41] K. Meah, S. Fletcher, S. Ula, "Solar photovoltaic water pumping for remote locations," *Renewable and Sustainable Energy Reviews*, vol. 12, no. 2, pp. 472–487, 2008.

[42] A. S. Mundada, K. K. Shah, J. M. Pearce, "Levelized cost of electricity for solar photovoltaic, battery and cogen hybrid systems," *Renewable and Sustainable Energy Reviews*, vol. 57, pp. 692–703, 2016.

[43] V. C. Sontake, V. R. Kalamkar, "Solar photovoltaic water pumping system - A comprehensive review," *Renewable and Sustainable Energy Reviews*, vol. 59, pp. 1038–1067, 2016.

[44] B. D. Vick, B. A. Neal, "Analysis of off-grid hybrid wind turbine/solar PV water pumping systems," *Solar Energy*, vol. 86, no. 5, pp. 1197–1207, 2012.

[45] E. G. Wagner, J. N. Lanoix, "Water supply for rural areas and small communities," World Health Organization (WHO), 1959. [Online]. Available: https://www.who.int/water_sanitation_health/dwq/monograph42.pdf [accessed 19 Dec 2018].

[46] A single drop for safe water, Oxfam, Kadtundaya foundation inc., MTB, "Hand pump and sanitation facilities design manual," 2011. [Online]. Available: https://www.singledrop.org/wp-content/uploads/2010/12/Handpump_and_Sanitation_Facilities_Design_Manual.pdf [accessed 20 Aug 2018].

[47] A. C. Telmo, "A Water Supply and Sanitation Study of the Village of Gouansolo in Mali, West Africa," MSc Thesis, Michigan Technological University, MI: USA, 2002.

[48] The United Nations Refugee Agency (UNHCR), "The geophysical exploration for groundwater at the Kakuma refugee camp and the proposed Kaloeyei refugee camp in Turkana county, Kenya," 2016. [Online]. Available: https://seg.org/Portals/0/SEG/About%20SEG/GWB/Projects/Geophysical%20Exploration%20GW%20Kakuma_Kalobeyei%20Turkana%20County-Rev%200%20Final%20Report%20No%20financials.pdf [accessed 15 May 2018].

[49] A. R. Freeze, J. A. Cherry, *Groundwater*, Pearson Publishing, 1979.

[50] Y. Bakelli, A. Hadj Arab, B. Azoui, "Optimal sizing of photovoltaic pumping system with water tank storage using LPSP concept", *Solar Energy*, vol. 85, no. 2, pp. 288-294, 2011.

[51] D. H. Muhsen, A. B. Ghazali, T. Khatib, "Multiobjective differential evolution algorithm-based sizing of a standalone photovoltaic water pumping system," *Energy Conversion and Management*, vol. 118, pp. 32–43, 2016.

[52] D. H. Muhsen, A. B. Ghazali, T. Khatib, I. A. Abed, E. M. Natsheh, "Sizing of a standalone photovoltaic water pumping system using a multi-objective evolutionary algorithm," *Energy*, vol. 109, pp. 961–973, 2016.

[53] A. Hamidat, B. Benyoucef, "Systematic procedures for sizing photovoltaic pumping system, using water tank storage," *Energy Policy*, vol. 37, no. 4, pp. 1489–1501, 2009.

[54] C. Nauges, D. Whittington, "Estimation of water demand in developing countries: An overview," *World Bank Research Observer*, vol. 25, no. 2, pp. 263–294, 2009.

[55] X. Mu, D. Whittington, J. Briscoe, "Modeling village water demand behavior: A discrete choice approach," *Water Resources Research*, vol. 26, no. 4, pp. 521-529, 1990.

[56] C. Nauges, C. Van Den Berg, "Perception of health risk and averting behavior: An analysis of household water consumption in Southwest Sri Lanka," *Toulouse School of Economics (TSE) Working Papers 09-139*, 2009.

[57] C. Nauges, J. Strand, "Estimation of non-tap water demand in Central American cities," *Resource and Energy Economics*, vol. 29, no. 3, pp. 165–182, 2007.

[58] T. H. Persson, "Household choice of drinking–water source in the Philippines," *Asian Economic Journal*, vol. 16, no. 4, pp. 303–316, 2002.

[59] Deutsche gesellschaft für internationale zusammenarbeit (GIZ), "Access to Water and Sanitation in Sub-Saharan Africa." 2016. [Online]. Available: http://www.oecd.org/water/GIZ_2018_Access_Study_Part%20I_Synthesis_Report.pdf [accessed 11 Aug 2019].

[60] African Development Bank (AfDB), "Improve the quality of life for the people of Africa - Annual Development Effectiveness Review 2016," 2016. [Online]. Available: https://www.afdb.org/fileadmin/uploads/afdb/Documents/Development_Effectiveness_Review_2016/ADER_2016_-_07_Chapter_5__En_.pdf [accessed 20 July 2018].

[61] J. A. Cherni, I. Dyner, F. Henao, P. Jaramillo, R. Smith, R. O. Font, "Energy supply for sustainable rural livelihoods. A multi-criteria decision-support system," *Energy Policy*, vol. 35, no. 3, pp. 1493–1504, 2007.

[62] M. Beccali, M. Cellura, D. Ardente, "Decision making in energy planning: the ELECTRE multicriteria analysis approach compared to a FUZZY-SETS methodology," *Energy Conversion and Management*, vol. 39, no. 16-18, pp. 1869-1881, 1998.

[63] United Nations Development Programme (UNDP), "Human Development Report 2016: Human Development for Everyone," 2016. [Online]. Available: https://www.un-ilibrary.org/economic-and-social-development/human-development-report-2016_b6186701-en [accessed 20 Aug 2018].

[64] Respublica, "Respublica – ONG Burkina Faso," 2019. [Online]. Available: http://www.respublica.asso.fr/ong-humanitaire-au-burkina-faso [accessed 12 Aug 2019].

[65] Eau Fil du Soleil, “Gogma - Crowdfunding,” 2017. [Online]. Available: https://www.kisskissbankbank.com/fr/projects/turning-sun-into-water/tabs/description [accessed 15 Aug 2019].

[66] Eau Fil du Soleil, “Eau fil du soleil - website,” 2019. [Online]. Available: https://eaufildusoleil.blogspot.com/ [accessed 15 Aug 2019].

[67] DargaTech SARL, “DargaTech,” 2019. [Online]. Available: https://www.facebook.com/dargatech/ [accessed 15 Aug 2019].

[68] Grundfos, “Grundfos - main page,” 2019. [Online]. Available: https://www.grundfos.com/ [accessed 10 Aug 2019].

[69] Grundfos, “Performance curve of SQFlex 5A-7 motor-pump,” 2019, [Online]. Available: https://product-selection.grundfos.com/product-detail.product-detail.html?custid=GMA&productnumber=95027342&qcid=421916400 [accessed 10 Aug 2019].

[70] Grundfos, “CU 200 controller,” 2019, [Online]. Available: https://product-selection.grundfos.com/product-detail.product-detail.html?custid=GMA&productnumber=96625360 [accessed 10 Aug 2019].

[71] Institut Supérieur d’Application des Géosciences - ISAG, “ISAG - Website,” 2019. [Online]. Available: https://www.facebook.com/ISAG.Geosciences/ [accessed 05 March 2019].

[72] Laboratoire Aina, “Water quality tests in Gogma performed for the NGO Eau Fil du Soleil,” 2018.

[73] Windows, “GPS Satellite.” 2017, [Online]. Available: https://www.microsoft.com/fr-fr/p/gps-satellite/9wzdncrfj0dg?activetab=pivot%3Aoverviewtab [accessed 07 Oct 2018].

[74] United States Environmental Protection Agency (EPA), “Frequency Domain Electromagnetic Methods,” 2016. [Online]. Available: https://archive.epa.gov/esd/archive-geophysics/web/html/frequency_domain_electromagnetic_methods.html [accessed 22 Nov 2018].

[75] Solinst, “Water Level Meter 101 Datasheet”, 2016. [Online]. Available: https://www.solinst.com/products/level-measurement-devices/101-water-level-meter/datasheet/ [accessed 12 May 2019].

[76] Massachusetts Institute of Technology, “Safe water for one billion people,” 2008. [Online]. Available: http://web.mit.edu/watsan/methods_waterqualitystandards.html [accessed 01 Oct 2018].

[77] The Pennsylvania State University, “Groundwater Surveillance In the Vicinity of Mahoning County Landfills, 2006-2008,” 2008. [Online]. Available: https://www.mahoninghealth.org/wp-content/uploads/file/Documents/Documents/SpecialReports/Groundwater%20Surveillance%20around%20Mahoning%20County%20Landfills%202006-2008.pdf [accessed 05 Dec 2018].

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

[79] M. Heinrich, S. Meunier, A. Samé, L. Quéval, A. Darga, L. Oukhellou, B. Multon, “Detection of cleaning interventions on photovoltaic modules with machine learning” – *submitted*

[80] Axo Energy, “Website – Axo Energy,” 2019. [Online]. Available: https://axoenergy.blogspot.com/?fbclid=IwAR0yZtbFxO40k-kkS6n8Wf4MCFZLl6Iwiy79rbZku7CVHQkXlX4PAjopR5M [accessed 12 July 2019].

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

[82] V. Caplain, “Water demand and organization and payment schemes for solar pumping systems in emerging countries: a case study in Burkina Faso,” MSc Thesis, Imperial College London, UK, 2018.

[83] C. Boone, P. Glick, D. E. Sahn, “Household Water Supply Choice and Time Allocated to Water Collection: Evidence from Madagascar,” vol. 47, no. 12, pp. 1826-1850, 2011.

[84] The World Bank Water Demand Research Team, “The demand for water in rural areas: determinants and policy implications,” *The World Bank Research Observer*, vol.8, no. 1, pp. 47–70, 1993.

[85] J.-A. L. Geere, P. R. Hunter, P. Jagals, “Domestic water carrying and its implications for health: a review and mixed methods pilot study in Limpopo Province, South Africa,” *Environmental Health*, vol. 9, no. 1, pp. 52, 2010.

[86] J. C. Ho, K. C. Russel, J. Davis, “The challenge of global water access monitoring: Evaluating straight-line distance versus self-reported travel time among rural households in Mozambique,”, *Journal of Water and Health*, vol. 12, no. 1, pp. 173–183, 2014.

[87] The Pennsylvania State University, “Detecting Multicollinearity Using Variance Inflation Factors,” 2018. [Online]. Available: https://newonlinecourses.science.psu.edu/stat462/node/180/ [accessed 05 Dec 2018].

[88] R. M. Craparo, *Significance level*, N. J. Salkind (Ed.), Encyclopedia of Measurement and Statistics 3, Thousand Oaks, CA: SAGE Publications, 2007.

[89] M. Koehl, M. Heck, S. Wiesmeier, J. Wirth, “Modeling of the nominal operating cell temperature based on outdoor weathering,” *Solar Energy Materials and Solar Cells*, vol. 95, no. 7, pp. 1638–1646, 2011.

[90] S. Ponce-Alcántara, J. P. Connolly, G. Sánchez, J. M. Míguez, V. Hoffmann, R. Ordás, “A Statistical Analysis of the Temperature Coefficients of Industrial Silicon Solar Cells,” *Energy Procedia*, vol. 55, pp. 578–588, 2014.

[91] A. McEvoy, T. Markvart, L. Castañer, *Practical Handbook of Photovoltaics - Fundamental and Applications*, 2nd ed, Academic Press, 2011.

[92] P. E. Campana, H. Li, J. Yan, “Dynamic modelling of a PV pumping system with special consideration on water demand,” *Applied Energy*, vol. 112, pp. 635–645, Dec. 2013.

[93] W. H. Bierschenk, “Determining well efficiency by multiple step-drawdown tests,” International Association of Scientific Hydrology, 1963. [Online]. Available: http://hydrologie.org/redbooks/a064/064043.pdf [accessed 05 Oct 2018].

[94] T. E. Reilly, L. Franke, G. D. Bennett, “The principle of superposition and its application in ground-water hydraulics,” US Geological Survey, Open-File Report 84-459, 1987. [Online]. Available: https://pubs.usgs.gov/of/1984/0459/report.pdf [accessed 05 Oct 2018].

[95] T. Vezin, S. Meunier, L. Queval, J. A. Cherni, L. Vido, A. Darga, Ph. Dessante, P. K. Kitanidis, C. Marchand, "Borehole water level model for photovoltaic water pumping systems”, *Applied Energy*, 2019.

[96] B. R. Munson, D. F. Young, T. H. Okiishi, *Fundamentals of Fluid Mechanics*, 5th ed., Wiley, 2006.

[97] Grundfos, “Performance curve of the SQFlex 8A-5 motor-pump,” 2019. [Online]. Available: https://product-selection.grundfos.com/product-detail.product-detail.html?custid=GMA&productnumber=95027346&qcid=638323312 [accessed 10 Aug 2019].

[98] Grundfos, “Performance curve of the SQFlex 2.5-2 motor-pump,” 2019. [Online]. Available: https://product-selection.grundfos.com/product-detail.product-detail.html?custid=GMA&productnumber=95027330&qcid=465405409 [accessed 11 Aug 2019].

[99] Grundfos, “Performance curve of the SQFlex 1.2-2 motor-pump,” 2019. [Online]. Available: https://product-selection.grundfos.com/product-detail.product-detail.html?custid=GMA&productnumber=95027328&qcid=638333508 [accessed 10 Aug 2019].

[100] Grundfos, “Performance curve of the SQFlex 0.6-2 motor-pump,” 2019. [Online]. Available: https://product-selection.grundfos.com/product-detail.product-detail.html?from_suid=1568265188468049659394174057898&hits=3&productnumber=95027324&searchstring=95027324&qcid=638338263 [accessed 4 Aug 2019].

[101] Grundfos, “Performance curve of the SQFlex 11A-3 motor-pump,” 2019. [Online]. Available: https://product-selection.grundfos.com/product-detail.product-detail.html?custid=GMA&productnumber=95027441&qcid=638354821 [accessed 10 Aug 2019].

[102] Grundfos, “Perfromance curve of the SQFlex 8A-3 motor-pump,” 2019. [Online]. Available: https://product-selection.grundfos.com/product-detail.product-detail.html?custid=GMA&productnumber=95027344&qcid=638356657 [accessed 10 Aug 2019].

[103] Grundfos, “Performance curve of the SQFlex 5A-3 motor-pump,” 2019. [Online]. Available: https://product-selection.grundfos.com/product-detail.product-detail.html?from_suid=15682666844790044808622003218224&hits=1&productnumber=95027338&searchstring=95027338&qcid=638358897 [accessed 13 Aug 2019].

[104] S. Meunier, L. Queval, A. Darga, Ph. 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," *7th International Conference on Renewable Energy Research and Application (ICRERA)*, pp. 494-499, Paris, France, 2018.

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

[106] European Commission, “Copernicus Atmosphere Monitoring Service (CAMS),” 2017, [Online]. Available: http://www.soda-pro.com/web-services/radiation/cams-radiation-service [accessed 01 Oct 2018].

[107] J. Mayne, “Useful theory of change models,” *Canadian Journal of Program Evaluation*, vol. 30, no. 2, 2015.

[108] A. A. Anderson, “The community builder’s approach to Theory of Change,” The Aspen Institute, 2009, [Online]. Available: http://www.theoryofchange.org/pdf/TOC_fac_guide.pdf [accessed 15 Jan 2018].

[109] S. Meunier, D. T. Manning, L. Queval, J.A. Cherni, Ph. Dessante, and D. Zimmerle "Determinants of the marginal willingness to pay for domestic water and irrigation in partially electrified villages: the case of Rwanda", *International Journal of Sustainable Development & World Ecology*, vol 26, no. 6, pp. 547-559, 2019.

[110] L. Fewtrell, R. B. Kaufmann, D. Kay, W. Enanoria, L. Haller, J. M. Jr. Colford, “Water, Sanitation, and Hygiene Interventions to Reduce Diarrhoea in Less Developed Countries: A Systematic Review and Meta-Analysis,” *Lancet Infectious Diseases*, vol. 5, no. 1, pp. 42-52, 2005.

[111] D. Whittington, X. Mu, R. Roche, “Calculating the value of time spent collecting water: Some estimates for Ukunda, Kenya,” *World Development*, vol. 18, no. 2, pp. 269–280, 1990.

[112] H. Waddington, B. Sinlstveit, H. White, L. Fewtrell, “Water, Sanitation and Hygiene Interventions to Combat Childhood Diarrhea in Developing Countries,” International Initiative for Impact Evaluation, 2009. [Online]. Available: https://www.3ieimpact.org/sites/default/files/2019-01/sr1-WASH.pdf [accessed 15 Dec 2018].

[113] World Health Organization (WHO), “Water, sanitation and hygiene links to health,” 2004. [Online]. Available: http://www.who.int/water_sanitation_health/publications/facts2004/en/ [accessed 15 Dec 2017].

[114] S. Cairncross, J. L. Cuff, “Water use and health in Mueda, Mozambique,” *Transactions of The Royal Society of Tropical Medicine and Hygiene*, vol. 81, no. 1, pp. 51-54, 1987.

[115] E. Gross, I. Günther, Y. Schipper, “Women: Walking and Waiting for Water The Time Value of Public Water Supply,” *Courant Research Centre: Poverty, Equity and Growth-Discussion Papers*, no. 134, 2013.

[116] H. Batteson, K. Davey, R. Shaw, “Guidance manual on water supply and sanitation programmes”, Technical report, WEDC Loudhborough University, 1998. [Online]. Available: http://www.rural-water-supply.net/_ressources/documents/default/1-491-2-1366101476.pdf [accessed 15 Dec 2017].

[117] The water project, “A good education begins with access to safe water and proper sanitation,” 2017. [Online]. Available: https://thewaterproject.org/why-water/education.

[118] A. A. Churchill, D. de Ferranti, R. Roche, C. Tager, A. A. Walter, and A. Yazer, “Rural water supply and sanitation: time for a change.,” *World Bank Discussion Paper*, no. 18, 1987.

[119] United Nations Development Programme (UNDP), “Human Development Report,” 2006. [Online]. Available: http://hdr.undp.org/en/reports/global/hdr2006/ [accessed 29 Dec 2018].

[120] Policy and Operations Evaluation Department, Ministry of Foreign Affairs, the Netherlands, “Rural water and sanitation - Assessing impacts,” 2012. [Online]. Available: https://www.oecd.org/dac/evaluation/Evaluation%20insights%20WASH%20final%20draft.pdf [accessed 17 May 2018].

[121] United Nations (UN), “The Millennium Development Goals Report.” 2015. [Online]. Available: https://www.un.org/millenniumgoals/2015_MDG_Report/pdf/MDG%202015%20rev%20(July%201).pdf [accessed 17 May 2018].

[122] J. M. Rohrer, "Thinking clearly about correlations and causation: Graphical causal models for observational data," *Advances in Methods and Practices in Psychological Science*, vol. 1, no. 1, pp. 27–42, 2018.

[123] J. A. List, S. Sadoff, M. Wagner, "So you want to run an experiment, now what? Some simple rules of thumb for optimal experimental design," *Experimental Economics*, vol. 14, no. 4, p. 439, 2011.

[124] Marie Tapiwa Bossyns, "Appropriate Renewable Energy for Water Pumping in Rural Mozambique," MSc Thesis, Universiteit Gent, 2013.

[125] C. Zhang, P. E. Campana, J. Yang, C. Yu, J. Yan, "Economic assessment of photovoltaic water pumping integration with dairy milk production," *Energy Conversion and Management*, vol. 177, pp. 750–764, 2018.

[126] E. Phiri, P. Rowley, R. E. Blanchard, "The feasibility of solar water-pumping in a rural village of Malawi," *in 1st International Conference on Solar Energy Solutions for Electricity and Water Supply in Rural Area*, Cairo, Egypt, 2015.

[127] M. Montorfano, D. Sbarbaro, L. Moran, "Economic and Technical Evaluation of Solar-Assisted Water Pump Stations for Mining Applications: A Case of Study," *IEEE Transactions on Industry Applications*, vol. 52, no. 5, pp. 4454–4459, 2016.

[128] B. Bouzidi, "New sizing method of PV water pumping systems", *Sustainable Energy Technologies and Assessments*, vol. 4, pp. 1‑10, 2013.

[129] I. Yahyaoui, A. Atieh, A. Serna, F. Tadeo, "Sensitivity analysis for photovoltaic water pumping systems: Energetic and economic studies," *Energy Conversion and Management*, vol. 135, pp. 402–415, 2017.

[130] Off-grid Europe, "Off-grid Europe - Grundfos SQ Flex," 2017. [Online]. Available: https://www.off-grid-europe.com/accessories/pumps/grundfos/sq-flex [accessed 23 May 2018].

[131] B. Bora, K. Yadav, M. Bangar, A. Kumar, O. S. Sastry, "Analysis of temperature effect on optimum sizing of solar photovoltaic water pumping system," in *42nd IEEE Photovoltaic Specialist Conference (PVSC)*, New Orleans, USA (LA), 2015.

[132] A. A. Ghoneim, "Design optimization of photovoltaic powered water pumping systems," *Energy Conversion and Management*, vol. 47, no. 11–12, pp. 1449–1463, 2006.

[133] K. Price, R. M. Storn, J. A. Lampinen, *Differential evolution: a practical approach to global optimization (natural computing series)*, Secaucus, NJ, USA: Springer-Verlag New York, Inc., 2005.

[134] Hewlett-Packard (HP), "HP EliteBook 840 G3 - datasheet," 2018. [Online]. Available: http://www8.hp.com/h20195/V2/GetPDF.aspx/4aa6-3222eee [accessed 2 Sept 2019].

[135] National Aeronautics and Space Administration (NASA), "Modern-Era Retrospective analysis for Research and Applications, Version 2," 2017, [Online]. Available: https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/ [accessed 01 Oct 2018].

[136] L. Fraas, L. Partain, *Solar cells and their applications*, 2nd ed., Wiley, 2010.

[137] Sandia National Laboratories,"PV_LIB Toolbox", 2018, [Online]. Available: https://pvpmc.sandia.gov/applications/pv_lib-toolbox/ [accessed 02 Dec 2018].

[138] I. Nazrul, A. Zahangir, M. Minhaz, "Determination of Well Loss and Aquifer Loss of New Construction Deep Water Well at Artesian Aquifer in Khulna City, Bangladesh", *Recent Trends in Civil Engineering & Technology*, vol. 3, no. 1, pp. 8-13, 2013.

[139] D. P. Dufresne, "Developing Better Regional Groundwater Flow Models with Effective Use of Step-Drawdown Test Results", *Florida Water Resources Journal*, vol. 63, no. 2, pp. 36-40., 2011.

université PARIS-SACLAY

ÉCOLE DOCTORALE
Physique et ingénierie : électrons, photons, sciences du vivant (EOBE)

**Titre :** Conception optimale des systèmes photovoltaïques de pompage d'eau pour les communautés rurales – une approche technique, économique et sociale

**Mots clés :** Modélisation interdisciplinaire, Analyse multi-critères, Conception optimale, Planification des infrastructures, Système photovoltaïque de pompage d'eau

**Résumé :** Les systèmes photovoltaïques de pompage d'eau (PVWPS) sont une solution intéressante pour améliorer l'accès à l'eau dans les communautés rurales des pays en voie de développement. Cette thèse développe une méthodologie de conception optimale des PVWPS pour l'accès à l'eau domestique basée sur une approche interdisciplinaire. L'objectif est de déterminer les dimensionnements du PVWPS et ses positions géographiques dans le village qui maximisent l'impact positif du système sur le développement socio-économique et minimisent son coût sur cycle de vie. Cette méthodologie est appliquée au cas d'un village rural du Burkina Faso, où nous avons collecté des données techniques et sociaux-économiques depuis 2 ans. La première originalité principale de ce travail est la modélisation du lien entre la conception du PVWPS et son impact socio-économique, ce qui permet d'inclure l'impact socio-économique comme fonction objectif de l'optimisation. La seconde originalité principale est l'intégration de la position géographique du PVWPS dans le village comme variable d'optimisation, en plus du dimensionnement du système. Cette méthodologie pourrait également être appliquée à la mise en place d'autres types de systèmes, tels que les moulins communaux alimentés par l'énergie photovoltaïque dans les zones isolées ou les bornes de recharges publiques pour les véhicules électriques dans les villes.

**Title :** Optimal design of photovoltaic water pumping systems for rural communities – a technical, economic and social approach

**Keywords :** Interdisciplinary modelling, Multi-criteria analysis, Optimal design, Infrastructure planning, Photovoltaic water pumping system

**Abstract :** Photovoltaic water pumping systems (PVWPS) are an interesting solution to improve access to water in rural communities of developing countries. This thesis develops a methodology for the optimal design of PVWPS for domestic consumption based on an interdisciplinary approach. The objective is to determine the sizings of the PVWPS and its geographical positions in the village that maximise the positive impact of the system on socio-economic development and minimise its life-cycle cost. This methodology is applied to the case of a rural village in Burkina Faso, where we have been collecting technical and socio-economic data for 2 years. The first main originality of this work is the modelling of the link between the design of a PVWPS and its socio-economic impact, which allows to include the socio-economic impact as an objective function of the optimisation. The second main originality is the inclusion of the geographical position of the PVWPS in the village as an optimisation variable, in addition to the sizing of the system. There is potential for applying the proposed methodology for the set-up of other types of systems such as community mills powered by photovoltaic energy in isolated areas and public charging points for electrical vehicles in cities.

**Université Paris-Saclay**
Espace Technologique / Immeuble Discovery
Route de l'Orme aux Merisiers RD 128 / 91190 Saint-Aubin, France