A Flexible, Genuine Software for the Simulation and Sizing of Photovoltaic Pumping Systems

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Conception d'un logiciel libre et flexible pour la simulation et le dimensionnement des systèmes de pompage photovoltaïques

Tanguy LUNEL

RÉSUMÉ

Il existe peu de ressources aussi précieuses à la vie que l'eau. Cependant, aujourd'hui encore, de nombreuses populations à travers le monde manquent d'un accès décent à celle-ci. Une des raisons pour cela est l'éloignement de ces populations aux technologies modernes de captation et de distribution d'eau, souvent couplée à une situation socio-économique défavorable. La technologie de pompage photovoltaïque apporte une réponse à ce problème tout en respectant les critères du développement durable. Cette technologie permet de pomper de l'eau sans émettre de gaz à effet de serre même lorsque éloigné d'un réseau électrique. Cependant le coût associé et l'intermittence du système peuvent être des freins importants au développement de cette technologie. Plusieurs chercheurs ont déjà travaillé sur ces systèmes, proposant de nombreux modèles de modélisation permettant de mieux prévoir le volume d'eau pompé en fonction des données d'entrées. Cependant les liens entre les travaux académiques manquent, et il reste difficile de savoir quels modèles et stratégies sont les meilleurs pour améliorer les prévisions et diminuer les coûts.

Le travail réalisé ici met en place une approche logicielle afin de synthétiser les recherches existantes et de faciliter le dimensionnement des systèmes de pompage photovoltaïque destiné à la consommation domestique. Il consiste principalement en une agrégation des modèles trouvés dans la littérature au sein d'un logiciel libre, flexible et bien documenté. Ce logiciel est codé dans le langage de programmation Python et met à disposition de l'utilisateur des outils utiles à la modélisation et au dimensionnement de tels systèmes de pompage.

A l'aide de ce logiciel, plusieurs études comparatives sont menées pour évaluer la qualité des modèles de pompes, l'influence des fichiers météorologiques et la viabilité du couplage direct. Les résultats obtenus permettent de mettre en lumière les modèles de pompes à utiliser préférentiellement, ainsi que la variabilité provenant des fichiers météorologiques typiques tels que les standards TMY, CWEC et IWEC. Il est également montré que les systèmes présentant une pompe directement couplée à la matrice photovoltaïque, sans l'intermédiaire de convertisseur MPPT, représentent l'option la moins chère si les caractéristiques d'entrée de la pompe correspondent bien aux modules photovoltaïques. Dans le cas contraire l'option de couplage via un MPPT aboutit en moyenne à un système moins cher.

Le logiciel proposé laisse une grande place à des développements futurs. Néanmoins la suite de ce travail consiste prioritairement en la validation des prédictions du logiciel grâce à des résultats expérimentaux, après quoi, de nouveaux modèles pourraient être implantés pour améliorer la prise en charge de système de pompage destinés à l'agriculture par exemple.

Mots-clés : modélisation, dimensionnement, pompage, photovoltaïque, logiciel

A flexible, genuine software for the simulation and sizing of photovoltaic pumping systems

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ABSTRACT

There are few resources as precious to life as water. However, even today, many people around the world still lack decent access to it. One of the reasons for this is the remoteness of these populations from modern water collection and distribution technologies, often coupled with an unfavourable socio-economic situation. Photovoltaic pumping technology makes it possible to respond both to this problem and to the criteria of sustainable development. This technology makes it possible to pump water without emitting greenhouse gases even when located at a remote distance from an electrical grid. However, the associated initial investment and the intermittency of the system can be major obstacles to the development of this technology. Several researchers have already worked on these systems, proposing numerous forecasting models that allow better prediction of the volume of water pumped based on input data. However, links between the academic research are lacking, and it remains difficult to know which models and strategies are best suited to improving forecasts and reducing costs.

The work carried out here implements a software approach in order to synthesize existing research and facilitate photovoltaic pumping system sizing for domestic consumption. It mainly consists of an aggregation of models found in the literature within a free, flexible and well-documented software solution. This software is coded in the Python programming language and provides the user with useful tools for the modeling and sizing of such pumping systems.

Using this software, several comparative studies are carried out to evaluate the quality of pump models, the influence of weather files and the viability of direct coupling. The results obtained highlight the pump models to be used preferentially, as well as the variability in pumped water output coming from the use of typical weather files such as TMY, CWEC and IWEC standards. It is also shown that systems with a pump directly coupled to the photovoltaic array, without the intermediary of MPPT converter, are the most cost-efficient option if the pump input characteristics match well with the photovoltaic modules. Otherwise the option of coupling via MPPT results in more cost-efficient systems on average.

The proposed software leaves room for further development. The continuation of this work consists primarily in validating the predictive power of the software through experimental results, after which new models could be implemented to improve the support of pumping systems for agriculture, for example.

Keywords: sizing, modeling, pumping, photovoltaic, software

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LIST OF ABREVIATIONS AND ACRONYMS

AC	Alternative Current
ASHRAE	American Society of Heating, Refrigerating and Air-conditioning Engineers
CI	Continuous Integration
CP	Centrifugal Pump
CWEC	Canadian Weather for Energy Calculation
DNI	Direct Normal Irradiance
DHI	Diffuse Horizontal Irradiance
DC	Direct Current
DP	Displacement Pump
e.m.f.	Electro-motive force
EPW	Energy Plus Weather
ETS	École de Technologie Supérieure
FH	Friction Head
GHI	Global Horizontal Irradiance
IWEC	International Weather for Energy Calculations
IAM	Incidence Angle Modifier
LLP	Load Losses Probability
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracker
NPV	Net Present Value
NREL	National Renewable Energy Laboratory

NRMSE	Normalized Root Mean
OPEX	Operational Expenditure
PEP	Python Enhancement Proposal
PVPS	Photovoltaic Water Pumping System
PV	Photovoltaic
PM	Permanent Magnet
RMSE	Root Mean Square Error
SAM	System Advisor Model, made by NREL
SAPM	Sandia PV Array Performance Model
SDM	Single-Diode Model
SOC	State Of Charge
STC	Standard Conditions
SH	Static Head
TDH	Total Dynamic Head
TMY	Typical Meteorological Year, standard file based on the Sandia method
TY	Typical Year
USD	United States Dollar
VFD	Variable Frequency Drives
WHO	World Health Organization
WY	Weather Year

LIST OF SYMBOLS AND UNITS OF MEASUREMENT

α_{SC}	Temperature dependence coefficient of I_{SC}	%/°C
β_{OC}	Temperature dependence coefficient of V_{OC}	%/°C
ω	Angular speed	$rad.s^{-1}$
η_{mp}	Efficiency of motor-pump	1
Φ	Magnetic flux	Wb or V.s
a	Ideality factor parameter	V
I_D	Current through a diode	A
I_L	Photocurrent	A
$I_{L,ref}$	Photocurrent at STC	A
I_0	Diode reverse saturation current	A
I_a	Currant through motor armature	A
I_{SC}	Short-circuit current	A
L_a	Armature inductance	H
$LLP_{accepted}$	Maximum Load Losses Probability tolerated	%
M_S	Number of modules in series	1
M_P	Number of modules in parallel	1
P	Power	W
P_e	Electric Power	W
Q	Water flow rate	L/min
K_E	Electromagnetic constant of a motor	$V.s.rad^{-1}$
K_m	Torque constant of a motor	$N.m.A^{-1}$
R_{load}	Resistance at the terminal of a PV cell or module	Ω
R_S	Resistance in series with R_{load}	Ω
R_{SH}	Resistance shunt, in parallel with R_{load}	Ω
R_a	Intrinsic armature resistance of a motor	Ω
T_m	Torque of a motor	N.m
T_p	Torque of a pump	N.m
V_{OC}	Open-circuit voltage	V
V_a	Voltage at terminals of motor armature	V
W_p	Unit for peak power of a photovoltaic module	W

INTRODUCTION

World Health Organization (WHO) stated in 2019 that 785 million people still lacked a basic drinking-water service, with 20% of them solely dependent on surface water, which is more prone to be polluted. As climate change winds its way to warmer temperatures, the WHO also warns that by 2025, 50% of global population could live in water-stressed areas (World Health Organization, 2019). These water issues are concentrated in developing countries where access to energy and global infrastructures are lacking as well. Moreover, even within a same country, there is a correlation between rural location, poor socio-economic condition and low water access. In rural Africa, when a basic water service is not available on site, it is found that 80% of drinking water supply is collected by woman, reinforcing gender inequalities in the society (United Nations, s.d.). Concerning the use of water in agriculture, IRENA states that only 5% of crops are irrigated in Africa, the rest of the cultivated land is rain-fed, and therefore more sensitive to meteorological hazards like droughts (IRENA, 2016). As a comparison, the proportion of irrigated crop is 20% for the rest of the world. These issues are even more problematic when they coincide with a rural location where the electricity grid is inexistent.

Off-grid pumping stations are often considered a promising solution to mitigate these water supply issues (IRENA, 2016). In the past many pumping stations running on fossil fuels were installed throughout the world for improving the access to water. These pumping stations have the advantage of being flexible and convenient, but also brings a high dependence on the fuel cost and have a high carbon footprint. It is estimated that in Bangladesh alone up to 6.73 million tons of CO_2 were emitted by the diesel water pumps in 2015 (Wong, 2019).

In this context, photovoltaic water pumping systems (PVPS) seems to have a very high potential. Indeed, they provide a low carbon energy, have an output flow rate correlated with the sunny weather that brings higher water needs, and is found to be more cost efficient than the diesel pumps by 20% to 40% (IRENA, 2016 ; Muhsen, Khatib, & Nagi, 2017 ; Wong, 2019). Since the price of photovoltaic modules decreases, it is expected that the price of PVPS will decrease as well, in contrast with the high volatility of diesel fuel prices. Some other positive outcomes were reviewed in the literature, like the reduction in gender inequality for women, the increase in crop diversity and therefore in nutrition quality for local populations (Wong, 2019), and the storage of carbon in the irrigated land (Olsson, Campana, Lind, & Yan, 2015).

However, PVPS are not the perfect solution. First, they are intermittent by nature, requiring energy storage in the form of a battery or a reservoir to ensure a sufficient water supply at any time of the day. From an environmental perspective, a PVPS can also be linked to a higher risk of water resource depletion if it is not properly sized by taking into account the water recharge of the phreatic table. Moreover, it is reported that even if such systems are less expensive in the long term, PVPS represent an initial investment up to seven times higher than its diesel counterpart (Wong, 2019). This cost difference can result in increased inequalities between very-poor farmers and those who can afford such investments. Wong highlights the fact that all the supposedly positive outcomes have to be balanced and put into perspective as it always depends on the complex socio-economic context of the community where the PVPS is installed.

In any case, research on PVPS must continue to make it a more reliable, inclusive and affordable technology.

In this perspective, this work focuses on the affordability issue. In order to reduce the overall cost of a pumping system, accurate sizing is particularly helpful as it avoids the unneeded costs of oversize PVPS. Therefore, this thesis investigates paths to improve simulation and sizing of PVPS. The specific objectives of this work are to:

1. Provide a functional tool to help PVPS installers with sizing.
2. Assess which model to use against others in order to reduce simulation and sizing error.

In order to reach these objectives, the considered strategy is to create a free and open-source software providing tools for modeling and sizing of PVPS. This software is aimed at being a solid and documented basis facilitating its use and development by other researchers and engineers around the world.

This thesis first presents a review of the existing literature on the modeling and sizing of PVPS. The second chapter introduces the reader to the philosophy, structure and possibilities offered by the software tool developed in the scope of this research. The third chapter uses the software tool to investigate some PVPS modeling concerns not addressed until now in the literature. These results are then critically discussed and put into perspective with previous studies in the fourth chapter.

CHAPTER 1

LITERATURE REVIEW

The literature review is constructed around three main areas of interest. It first introduces the reader to a general and practical understanding of photovoltaic water pumping systems (PVPS). Secondly, it focuses on the way to model the elements and the system functioning, allowing to link the sun conditions to the flow of water. Subsequently, the review describes the main sizing procedures used for optimizing the PVPS.

1.1 Functioning and components of a PVPS

A PVPS is a system minimally composed of a photovoltaic (PV) array and a pump, converting the solar energy in mechanical energy in order to move water from one place to another. In a more advanced set up, the system can be completed by power electronics, or power conditioning unit, maximizing the quantity of energy used by the pump. These electronics are typically: Maximum Power Point Tracker (MPPT), a DC/DC or DC/AC converter. Moreover, the system often includes a way to store energy in the form of a battery or a water reservoir (i.e. chemically or mechanically). This energy storage allows to access water even when the solar resource is missing.

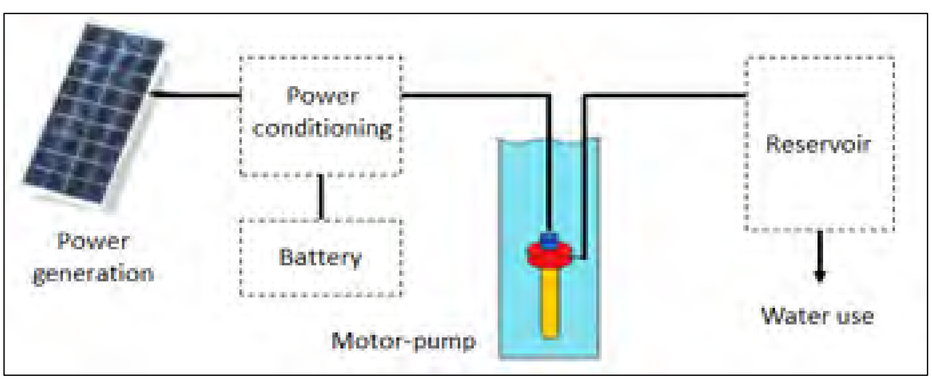

Figure 1.1: Block diagram of PVPS
Adapted from Aliyu & al;, 2018

1.1.1 Photovoltaic array

PV array is the only power generator in a standard off-grid PVPS. Its role is to convert sun irradiance into electricity thanks to the photovoltaic effect inside semiconductor cells. This conversion results in the production of a DC current. Even though a current is produced, it can not be considered electronically as an ideal current generator because the internal structure of the cell interacts with the current generated, thus preventing a linear behavior. This property makes PV array output widely dependent on the load at the terminals and often justifies the need for power electronics. Typical maximum efficiencies of such arrays are about 15-20 %.

1.1.2 Motor pumps

The motor and the pump are often put together in a same device, but the analysis and understanding of the functioning of the whole are easier when they are investigated separately.

1.1.2.1 Electrical Motor

As photovoltaic pumping implies electricity as the energy source, only electrical motors are discussed here. In this case, the electrical motor is the part which converts electricity into mechanical movement, namely the rotation of a shaft, thanks to electromagnetic interactions between stator and rotor.

Numerous architectures exist for electrical motor, allowing it to take alternative current (AC) or direct current (DC), to vary the relation between torque, rotational speed, angular position, internal resistance, back electromotive force (e.m.f.), etc. Nearly all the technologies of electrical motors can be used for pumping water, but some are more common like the Permanent Magnet DC (PMDC) motor, which has the advantage of being compact and brushless, or the series wound DC motor, which has the advantage of having a high torque at the start of the motor (Beaty, 2006). Asynchronous AC motor are also used, because of their low cost and long lifespan, but their efficiency and power density are markedly lower. Moreover, for some data availability reasons discussed further in 1.2.3.1, AC motor pumps are left out of the scope of this work.

1.1.2.2 Pump

The motor is then connected to a pump to transform the mechanical rotation power into pressure drop between the inlet and the outlet. Two main types of pump can be used in PVPS: the displacement pump (DP) and the centrifugal pump (CP).

a. Displacement pump

The displacement pump, or positive displacement pump, works by trapping a certain volume of water and by forcing it to move from the inlet to the outlet. In this type of pump, the flow rate Q is proportional to the rotational speed. This type of pump has the advantage that the flow rate is not much sensible to the head, making it particularly suitable for deep wells (N. Chandrasekaran, B. Ganeshprabu, & Dr. K. Thyagarajah, 2012).

b. Centrifugal pump

The mechanical load exerted by the fluids in centrifugal pumps is well adapted to PV power because the torque varies in the same way than the output flow rate. Therefore, when the input power is low, the pump can still work, lowering the rotational speed and thus pumping less water. This type of pump is more suitable for low-head application, with negligible friction head (Cheremisinoff & Cheremisinoff, 1989).

1.1.3 Power electronics

The power electronics deal with the conversion of the electricity produced by the PV arrays. It can change the type of current from DC to AC and vice-versa (respectively named inverter and rectifier), or just convert a current from one voltage to another (converter). DC/DC converters used in PVPS usually work together with a MPPT, which allows to continuously get the maximum power output from the PV array. As AC motor pumps are not considered in the scope of this work, MPPT converter is the only power electronic system considered herein.

1.1.4 Energy storage

Here, the term energy storage is taken in a large sense and relates not only to battery storing electricity under chemical form, but also to reservoirs storing water at high elevations, allowing its use at any time of the day. An energy storage is not always necessary in a PVPS. Nevertheless, in some cases it can allow to use water when it is really needed, therefore resulting in a lower need.

As soon as an energy storage is considered, the notion of Load Losses Probability (LLP) can be used to evaluate the correct sizing of the energy storage. It represents the probability for the system to be unable to meet the demand and can be applied on systems with reservoirs in the same way than on systems with batteries (Hamidat & Benyoucef, 2009 ; Khatib & Elmenreich, 2016). The LLP is defined as the ratio between the lack of water and the total water volume required over a year.

1.2 Modeling of a PVPS

Understanding the outline of the global functioning of a PVPS is unfortunately not enough to ensure an efficient sizing. For correctly sizing a PVPS, it is first necessary to be able to predict correctly the output of the system. This section focuses on how the different components of the system are modeled in order to eventually constitute a complete PVPS model. For each step, the uncertainty coming from the data or the model are highlighted, if available. A summary of information needed, and models used in the modeling of a PVPS are described in Figure 1.2.

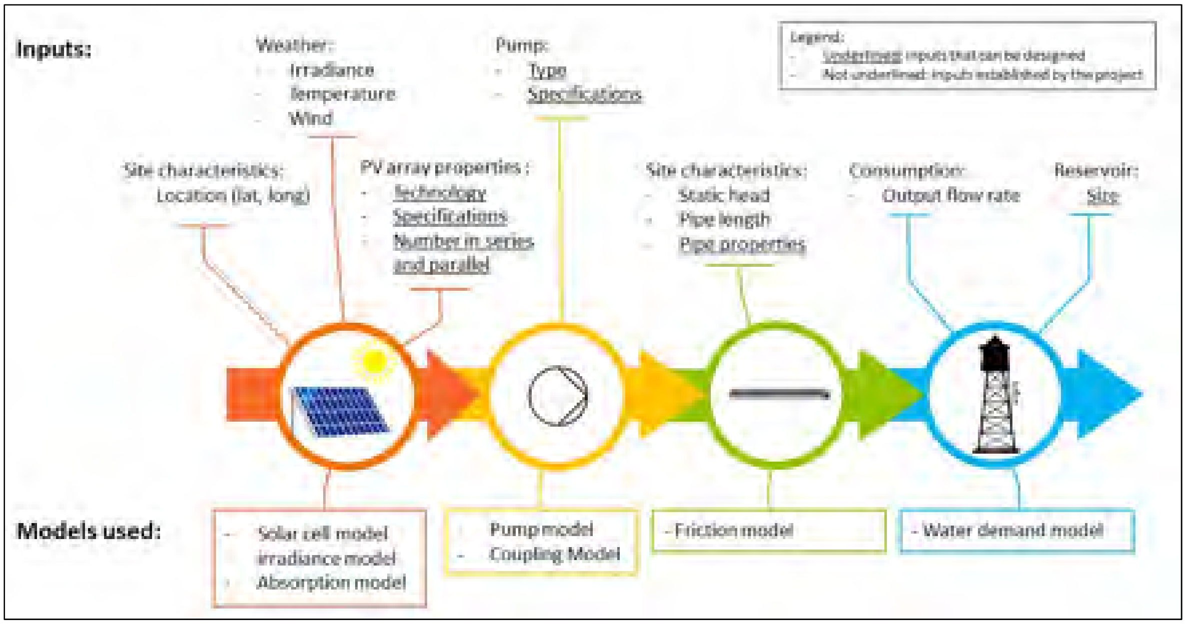

Figure 1.2: General inputs and models used in a PVPS modeling process

1.2.1 Fixed input data

1.2.1.1 Weather files

One of the main input data used for the simulation of a PV system is the weather file containing the irradiance data. For calculation time reasons, the weather files used cover no more than one year, and give different values such as temperatures, irradiance, and precipitation on an hourly basis. The way to summarize weather characteristics in a one-year file depends on the purpose of the weather file. For example, it can be constructed for representing a typical year - like TMY (Typical Meteorological Year), IWEC (International Weather for Energy Calculations) and CWEC (Canadian Weather for Energy Calculations) files - which thus reduces the presence of extreme conditions in the data (Wilcox & Marion, 2008). Therefore, this type of file should not be used in a case of worst-conditions sizing. Note that TMY files were developed by the NREL based on the algorithm created by Sandia National Laboratories, and this algorithm became a standard also used in IWEC and CWEC construction (CWEC, 2016 ;

Skeiker, 2007). On the opposite, special data can be built for representing extreme weather condition on one year, but these weather are not as common. (Nik & Arfvidsson, 2017)

Even before being processed in a one-year data, the data can be obtained by different means, yielding different biases in the final result. Three main families of data gathering strategies can be drawn: direct measurement, which are usually processed in Typical Year (TY) weather files; space interpolation, which uses the measurement files of the closest locations around to interpolate the weather of the considered place; and satellite observation, which relies on some indicators measured by meteorological satellites like the clearness index to infer the irradiance on the ground level (Al-Mofeez, Numan, Alshaibani, & Al-Maziad, 2012 ; Kumar & Umanand, 2005).

(Monteoliva, Villalba, & Pattini, 2017) studied three TY weather files coming from either satellites or ground stations measurements for the region of Mendoza in Argentina. They found that the mean yearly Global Horizontal Irradiance (GHI) could vary up to 8.3% between the data and could vary up to 15% in the case of Direct Normal Irradiance (DNI) and Diffuse Horizontal Irradiance (DHI) taken aside.

(Remund, 2008) processed the same analysis between data coming from ground measurements and from space interpolation given by the software Meteonorm. He found that the relative error on GHI values was comprised between 3.1% and 11%. For DHI and DNI, the mean relative errors were respectively 7.3% and 5.4%.

(Skeiker, 2007) ran a similar analysis by comparing TY weather files constructed from the same weather data records but with different algorithms. The researcher found that different algorithms could induce a relative difference between each other up to 8% for GHI data. Eventually it is stated that the algorithm inducing the smallest relative error is the one from Sandia National Laboratories.

(Kou, Klein, & Beckman, 1998) compared the throughput of a PVPS according to two hourly weather files, one coming from measured data (TY weather data) and the other generated from clearness index following a procedure proposed in the first edition of (Duffie & Beckman, 2013). It is found that the Root Mean Square Error (RMSE) in flow rate output between the two simulations ranges only from 3 to 6%. Nevertheless, this fairly good relative difference has to be considered with care because the authors used a pump model which was found to introduce important uncertainties as discussed in 1.2.3.1. In this same research work, the use of monthly averaged weather data is shown not to be suitable for PVPS simulation as it can widely underestimate the total volume pumped. Previously discussed results are gathered in Table 1.1.

Table 1.1: Relative difference in irradiance data in literature

Authors	Type of files compared	Relative difference
(Monteoliva et al., 2017)	Direct measurement vs satellite observation	0 - 8% on GHI 0 - 15% on DHI & DNI
(Remund, 2008)	Direct measurement vs space interpolation	3.1 – 11 % on GHI mean of 7.3% for DHI mean of 5.4% for DNI
(Skeiker, 2007)	6 Direct measurement methods used for creating TMY files	0 – 8% on GHI
(Kou et al., 1998)	Direct measurement vs satellite observation	3 – 6 % on flow rate Q

From the above it should be noted that weather files can bring significant errors, and therefore the choice of the weather file should be of prime interest in the modeling of a PVPS. In the following work, in order to reduce the relative error, only TY weather files based on the Sandia algorithm and relying on ground direct measurements are used (namely TMY, IWEC and CWEC files).

1.2.1.2 Site characteristics and consumption file

The site characteristics usually consist of the static head in the well, the horizontal distance between water source and reservoir, and the site location. As vertical head is a critical input for the PVPS output (Li, Jin, Akram, & Chen, 2017 ; Muhsen et al., 2017) and the water level is variable in a well through a year, it is often considered as the lowest water level of the well. In nearly all papers on PVPS modeling, the water demand is represented by an hourly file stating the output flow rate retrieved from the reservoir every hour. It is determined by the daily needs in water for a community or a farmer. This approach seems acceptable in the case where the water pumped is for domestic consumption which is about the same every day. However, such a daily profile may be oversimplified in the case of agriculture needs.

(Glasnovic & Margeta, 2007) paved the way for a new way to take into account variable consumption and variable water level into the well. In this work, focused on agriculture applications, the researchers considered the consumption as dependent on the weather, particularly on the rain fall, which reduces the need of water for the plants, and on the sun, which increases the need of water through evapotranspiration. In this study, the type of soil is also considered, influencing the soil moisture and the water infiltration, respectively linked to the water need and to the variable head in the well where the water is pumped. With this method the researchers are able to ensure that the phreatic table will not be depleted. They also find the counterintuitive outcome that the most critical months for sizing in Croatia are July and August, that is to say the months with the most important irradiance, resulting in higher evapotranspiration from crops.

1.2.2 PV generation modeling

The modeling of PV generation is a complex domain but has been already well investigated by researchers during the last three decades. Nowadays, some models are widely used and have been implemented in some ready-to-use tools like the Python package *pvlib-python* (Holmgren, Hansen, & Mikofski, 2018). This package provides classes and functions simplifying the use of many models applying to solar cell, irradiance, absorption, module temperature and others. As the PV generation modeling is not the core of this work, the coming section is aimed at giving an overview of the possibilities included in *pvlib-python*. This overview focuses only on the models that were considered as the most commonly used in literature, and that are used by default in the results found in CHAPTER 3

1.2.2.1 Irradiance models

Classic irradiance data gives the irradiance on a horizontal plane: these are usually named diffuse horizontal irradiance (DHI) and global horizontal irradiance (GHI). To get the actual irradiance on a tilted plane, an irradiance model is then needed. The irradiance models proposed in *pvlib-python* are the following: isotropic, Klucher, Hay-Davies, Reindl, King and Perez. Detailed explanations for each model can be found in (Duffie & Beckman, 2013).

The isotropic model is the default one in *pvlib-python* and is widely used in related literature, mostly because it is easy to use with formulas that can be calculated by hand. It assumes that the direct normal irradiance (DNI) comes from the point where the sun is in the sky and then the DHI is spread evenly, in a isotropic way, through the rest of the sky. (Loutzenhiser et al., 2007) found that the isotropic model had a relative error of 14% between predicted and measured irradiance on a vertical surface. Then, the more the surface tilt approaches the horizontal position, the less the relative error is. In the same paper, it is also stated that Perez model seems to be the best, with a maximum of 9% relative error. Nevertheless, as the isotropic model is still more commonly used in the literature reviewed, it is kept as the default irradiance model in order to ease the comparison with previous works.

1.2.2.2 Absorption models

Irradiance models allows to evaluate the incident irradiance on the array, but then two coefficients are needed to get what is called the effective irradiance, that is to say the irradiance practically available for the solar cell to convert.

The first coefficient is the incidence angle modifier (IAM). It can be obtained by 5 different models in *pvlib-python*: ASHRAE, physical, Martin-Ruiz, interpolation, SAPM. The default IAM model is the physical model, also described in (De Soto, Klein, & Beckman, 2006), and relying on some very common physical equations for the transmission of light like the Fresnel Laws. The second coefficient is the spectral modifier. This spectral modifier comes from the difference in the spectral profile of light depending on the quantity of air and water vapor the light has to go through before arriving on the PV cell. This modifier is empirical and is found from databases giving coefficients for each cell material available depending on air mass and air humidity.

(De Soto et al., 2006) state that IAM and spectral modifier are significant only for incidence angles superior to 70° and 80° respectively. At these angles, it is unlikely that a PVPS would still pump water, so these absorption models might not be of special concern.

1.2.2.3 Cell temperature models

The cell temperature model is used in *pvlib-python* to determine the temperature of the solar cells as a function of incident irradiance, air temperature, wind speed, materials of the module and mounting (open rack, roof-top, insulated-back). Three models are proposed: SAPM, PVSyst, and Faiman. The model used by default is the PVSyst model (PVsyst, s.d.) which considers default values for the silicon, and retrieves the required data from the module parameters contained in CEC or Sandia Module Database.

1.2.2.4 Solar cell models

Three solar cell models are implemented in *pvlib-python*: the empirical model developed by the Sandia National Laboratories (King, Kratochvil, & Boyson, 2004), the theoretical five parameters single-diode model (SDM) of (De Soto et al., 2006) and the six parameters SDM derived from De Soto's work and developed at the California Energy Commission (CEC) (Dobos, 2012).

The most common model is the five parameters SDM developed by (De Soto et al., 2006). As it is directly used by the direct coupling model in order to find the operating point between PV array and motor pump, this model deserves a focus. It represents a PV cell as an electrical circuit composed of one direct current generator producing a photocurrent I_L, one diode subjected to a current I_D with a saturation current I_0 and an ideality factor parameter a, and two resistances, one in parallel R_{SH} and one in series R_S. The equivalent circuit is in Figure 1.3 and the corresponding equation giving the current in the load at the terminals of the cell is equation 1.1.

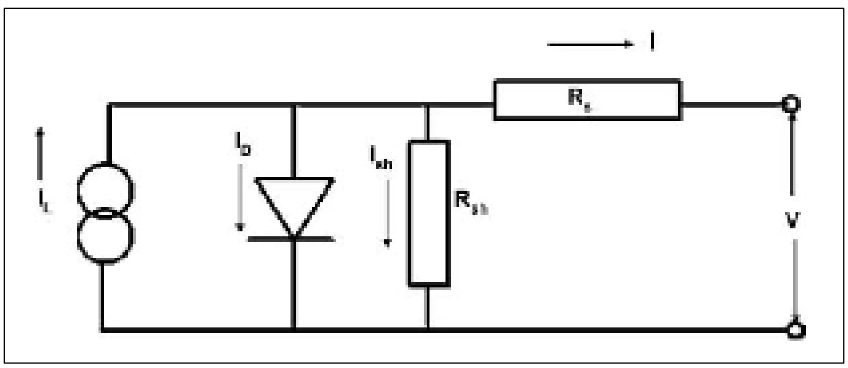

Figure 1.3: Electrical equivalent circuit of SDM
Taken from De Soto (2006)

$$I = I_L - I_0 \left(exp \frac{V + IR_S}{a} - 1 \right) - \frac{V + IR_S}{R_{SH}} \quad (1.1)$$

$$\text{With } V = I * R_{load} \quad (1.2)$$

This model has been popularized since De Soto & al showed the five unknown parameters previously mentioned can be easily found from typical manufacturer's datasheets. The manufacturers minimum input data needed are I_{SC}, V_{OC}, I_{mpp}, V_{mpp} and α_{SC}, usually given at STC conditions. It is then processed in a system of five nonlinear equation, all coming from boundary conditions on equation 1.1, with five variables unknown, and returns the values of

$I_{L,ref}$, $I_{0,ref}$, $R_{S,ref}$, $R_{SH,ref}$, and a_{ref}. Later (Shannan, Yahaya, & Singh, 2013) measured the relative error between measured and predicted output power of the De Soto SDM and found that it was inferior to 1% for cell temperature between 0°C and 50°C.

1.2.2.5 PV module database

The PV module database is not a model but is another important feature of *pvlib-python*. Indeed, the package can access two databases of PV modules: the CEC modules database and the Sandia Modules database. The CEC modules database comes from NREL's System Advisor Model (SAM) (Blair et al., 2014) and is the one used in this work. It is updated on a regular basis and provides many details and specifications on the PV modules, like the maximum power in STC, the six parameters of Dobos's SDM (can be directly used by De Soto's SDM as well), cell material, size of the module, number of cells, etc. As of January 2020, more than 21000 PV modules are indexed in this database.

1.2.3 Motor pump modeling

The motor pump modeling is one of the two key parts of PVPS modeling, along with PV generation modeling. However, contrary to the PV generation case, the existing literature does not agree on the models to use for modeling pumps, and different papers use different approaches on that topic. The following section synthetizes the two main approaches: empirical and theoretical, and describes the corresponding models found in the literature. Motor pump models are more thoroughly described than previous PV models because their implementation represents an important part of the originality of the developed software. In the following work and in part of the literature, motor and pump are considered as a whole, mounted in a same machine, and therefore the terms *motor pump* and *pump* can be used interchangeably.

1.2.3.1 General strategy

Electrical motor pump modeling is a vast subject as many different technologies of motors exist, relying on different electrical principles and assemblies. Moreover, the data provided by pump manufacturers can differ widely, preventing the researchers from constructing a simple and practical model for motor output prediction. The purpose of modeling the motor-pump group is to link the input electrical power to the water discharge. To his end, two equations are needed:

- The first equation is the I-V relation of the motor:

$$I = f_1(V, TDH) \tag{1.3}$$

Indeed, as the main resistance to the shaft rotation is the behaviour of the liquid in the pump casing, and as the speed of the rotor influences the electromagnetic field of the electrical circuit, the total dynamic head (TDH) is a major variable in the electrical function f_1. Equation f_1 is used in cases of direct-coupling between PV array and pump, in order to find the operating point by comparing the *I-V* relations of the PV array and of the pump.

- The second equation is the discharge-power relation of the motor:

$$Q = f_2(P, TDH) \tag{1.4}$$

Where Q is the output flowrate of the pump in m^3/h or L/min.

In equations 1.3 and 1.4, the current I, the voltage V and the power P can be replaced by each other as they are constantly linked by:

$$P = I * V \tag{1.5}$$

In most cases the pumps are designed to be connected to an ideal voltage source, that is to say a source with constant voltage and from which infinite power can be drawn. For common pumps connected to the grid this assumption is correct as the range of use is often way below the limits of the grid. In this case, the first function f_1 is simplified in $I = f_{1,\, V=k}$ (*TDH*). And as *P* and *I* can be replaced by each other, *P* is function of *TDH*, and the output flow rate becomes only dependent on TDH: $Q = f_2$ (*TDH*). These simplifications result in the common specifications for pumps as illustrated in Figure 1.4. Here, function f_2 alone is enough for predicting the pump output, and the information on the power *P* is given on an indicative basis to forecast the energy cost of the pump. The efficiency curve can be found from these two, and therefore is not of prime importance.

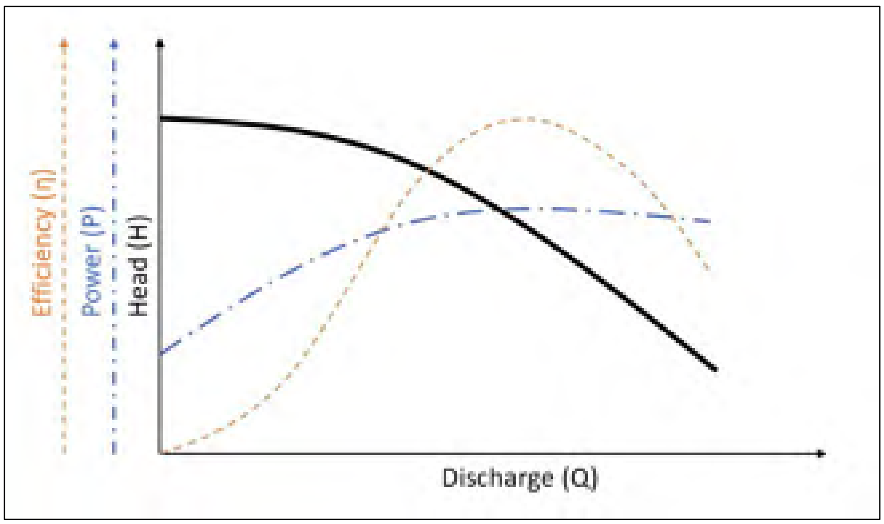

Figure 1.4: Standard characteristics given for an electric motor pump

In the case of a pump connected to a finite power source, like a PV array, the operation of the motor pump is different. It depends on *V* and *I*, and none of the function f_1 of f_2 can be simplified. Therefore, specifications need to be given at different voltage, resulting in more complete specifications as shown in Figure 1.5. Similar curves must be provided for power.

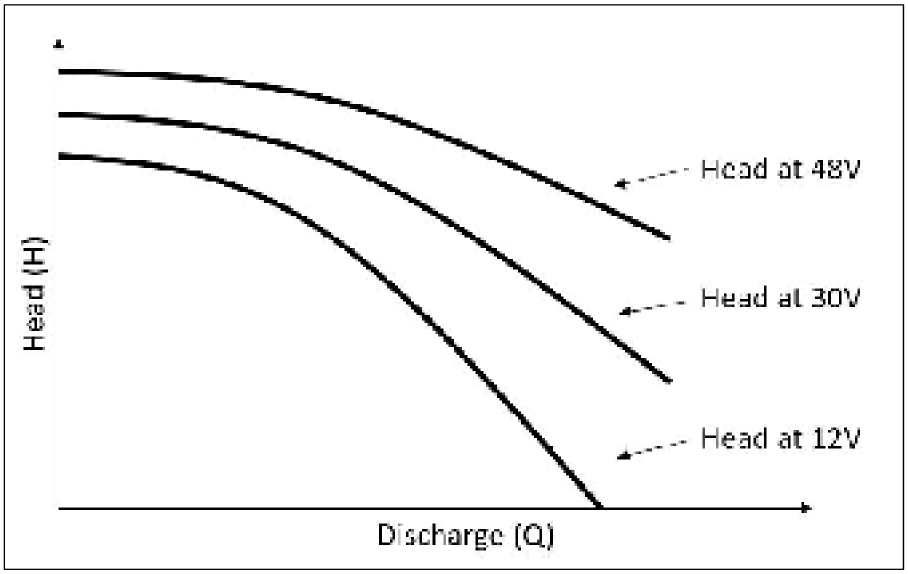

Figure 1.5: Specifications needed for PV array connection

As AC motor pumps are often designed to be connected to the AC grid, they typically include restricted specifications at only one given voltage. On the opposite DC motor pump are mainly designed to work on batteries or PV arrays, so specifications are given for multiple voltages. This work focuses on DC motor pumps because it is the only category for which manufacturers provide sufficient data in order to build a model with a finite and variable power source. AC motor pumps could be investigated in future work.

1.2.3.2 Empirical approaches

These approaches consist in fitting curves for the existing pump data, and then to use these curves to interpolate and extrapolate extra points. Therefore, the pump data must be complete enough to ensure a correct curve fitting. This complete data can be given by the manufacturer of the pump or can be obtained by some tests run on the pump prior to the modeling or sizing. As the manufacturer rarely give enough data, except some companies like (SunPumps, s.d.), the researchers have to carry out tests on the pump before the study in most cases (Hadj Arab, Benghanem, & Chenlo, 2006 ; Hamidat & Benyoucef, 2008 ; Jafar, 2000). Once the pump data is complete enough, the following approaches can be applied.

A typical pump datasheet can be found in Figure 1.6. It contains the flow rate Q and the current I drawn for different voltage and for different head. In total, it gives a certain amount of points (TDH, V, I, Q) that can be used later. In Figure 1.6, three voltages and seven heads are given, resulting in 21 points (TDH, V, I, Q).

Aquatec SWP-6000 Submersible Pump Performance

Pressure		Flow @ 12 Vdc			Flow @ 24 Vdc			Flow @ 30 Vdc		
FT. HEAD	PSI	GPM	LPM	AMPS	GPM	LPM	AMPS	GPM	LPM	AMPS
0	0	2.10	7.95	0.80	4.00	15.14	2.00	5.00	18.92	2.00
20	9	1.75	6.62	1.70	3.80	14.38	2.50	4.70	17.80	2.50
40	17	1.60	6.05	2.40	3.40	12.87	3.30	4.50	17.03	3.10
60	26	1.40	5.30	3.00	3.20	12.11	3.50	3.90	14.76	3.70
80	35	1.30	4.92	3.50	3.10	11.73	4.30	3.70	14.00	4.30
100	43	1.20	4.54	3.90	2.90	11.00	4.80	3.50	13.25	4.60
120	52	1.10	4.16	4.40	2.80	10.60	5.10	3.30	12.50	5.00

Figure 1.6: Typical DC pump datasheet
Taken from www.aquatec.com

a. Kou's model

(Kou et al., 1998) determine the function *V*=f_1 (*I, TDH*) and *Q*=f_2 (*V, TDH*) from manufacturer's data. To obtain these two functions, they fit the data with a 3rd order polynomial with cross terms. The resulting multivariate polynomial functions f_1 and f_2 have the form of equation 1.6.

$$z = z_0 + a_1 * x + a_2 * x^2 + a_3 * x^3 + b_1 * y + b_2 * y^2 + b_3 * y^3 + c_1 * x * y + c_2 * x^2 * y + c_3 * x * y^2 + c_4 * x^2 * y^2 \quad (1.6)$$

As the functions f_1 and f_2 are third order polynomials on *I* and *TDH*, it means that the pump data needs to provide information for at least four different voltages and heads, and needs to have a total of at least 16 points (*TDH, I, V, Q*) in order to yield a correct curve fit.

Jahnig (Jahnig D., Klein S.A., & Beckman W.A., 1998) investigated this model for validation. He found a significant discrepancy between expected flow rates and measured flow rates. The relative error is around 20-40% for high irradiance and could even be infinite for irradiance levels below 550W/m^2. The authors explain the difference by incorrect data given by the pump manufacturer, but the author did not investigate the model with corrected pump data, so it is not possible to decorrelate the error from the model and the error from the incorrect pump data. It is also stated that at least 10% of the discrepancy comes from the four parameters single-diode model used for PV prediction. As this single-diode model is now outdated, some improvements could be expected with Kou & al.'s model.

The same model is used later by (Martiré, Glaize, Joubert, & Rouvière, 2008) for modeling f_2 only. In their paper, the authors fit an affinity law in order to get an algebraic equation more convenient to use. Equation f_1 is useless in this case as the electric power is processed through a MPPT. Indeed, it is considered that the electric power is always maximised. The resulting relative errors between predicted and measured flow rates are about 15% in the morning, and stabilize around 5% during the day, at the time the pump operates in steady state.

b. Hadj Arab's model

Hadj Arab (Hadj Arab et al., 2006) and Djoudi Gherbi (Djoudi Gherbi, Hadj Arab, & Salhi, 2017) propose another empirical model for modeling the pumps. Even though their research relies on data obtained by tests made on the pump in their laboratory, it can also be used on manufacturer's data if the data set is complete enough. This model proposes to use a linear equation for I-V curve of pump, corresponding to f_1:

$$I = a + b * V \tag{1.7}$$

The flow rate Q is dependent on voltage V through a quadratic equation, corresponding to f_2:

$$Q = c + d * V + e * V^2 \tag{1.8}$$

Eventually, all coefficients *a, b, c, d, e* are dependent on *TDH* following either a quadratic (Hadj Arab et al., 2006) or cubic equation (Djoudi Gherbi et al., 2017):

$$\begin{aligned} a &= a_0 + a_1 * TDH + a_2 * TDH^2 + a_3 * TDH^3 \\ b &= b_0 + b_1 * TDH + b_2 * TDH^2 + b_3 * TDH^3 \\ c &= c_0 + c_1 * TDH + c_2 * TDH^2 + c_3 * TDH^3 \\ d &= d_0 + d_1 * TDH + d_2 * TDH^2 + d_3 * TDH^3 \\ e &= e_0 + e_1 * TDH + e_2 * TDH^2 + e_3 * TDH^3 \end{aligned} \qquad (1.9)$$

In order to apply the model to a pump, the data requires at least three voltages and four different heads, for a total of at least 12 points (*TDH, P, Q*) and 8 points (*TDH, I, V*), or 12 points (*TDH, I, V, Q*). The model has been tested by the researchers on two centrifugal and two positive displacement pumps. When considering a quadratic equation for the variation of the coefficients with head, the relative error between model and measures remains below 14% for all heads on centrifugal pumps, and below 5% for positive displacement ones. When the input data of the model is reduced to the minimum of nine points, the model still manages to fit the measurements, adding only a maximum of 5% to the relative error. When considering a cubic equation for the variation of the coefficients, the relative error diminishes below 10% for all heads on centrifugal pumps and remains below 4% for positive displacement pumps. In this case the input data needs to be complete, as a higher order of polynomial regression obviously requires more data points for the fitting.

c. Hamidat's model

Hamidat A. proposed another model for modeling a pump coupled to a PV array through a MPPT (Hamidat & Benyoucef, 2008). The study only considers a MPPT setting, therefore, as mentioned earlier, f_1 is not needed. The equation for f_2 is still required and is given by equation 1.10.

$$P = a + b * Q + c * Q^2 + d * Q^3 \qquad (1.10)$$

This equation links the electric power *P* with a polynomial function taking the flow rate *Q* as the relevant variable. This form is however not convenient for determining the output flow rate according to the power produced by the PV array. Authors thus decide to use Newton-Raphson's root finding method to get *Q* from *P*. The coefficients of the polynomial are dependent on the *TDH* following a cubic equation such as in equation 1.9, therefore minimum pump data in this case include four different heads, and 16 points (*TDH, P, Q*).

Their model is then used to run simulations for four locations with two different motor pumps with different head but is not compared with actual measurements. The relative error cannot be assessed then. This model is also used in (Gualteros Martinez, 2017) but without assessment of the model validity either.

1.2.3.3 Theoretical approach on DC motor pumps

The prediction of the output of motor pump can also be carried-out by analysing the electrical architecture of the motor used. This approach is used by (Khatib & Elmenreich, 2016) and is briefly discussed in the following section.

DC motors can be modelled electrically as a resistance, an inductance and a voltage generator put in series (N. Chandrasekaran et al., 2012 ; Tantos, 2011b). This voltage source is surrounded by a magnetic field Φ which is produced from permanent magnet or from electromagnets fed in electricity by the system. In the latter case, the magnetic field is produced by an inductance L_f, whose internal intensity I_f and voltage V_f can be dependent or not on V_a and I_a. The standard representation can be found in Figure 1.7.

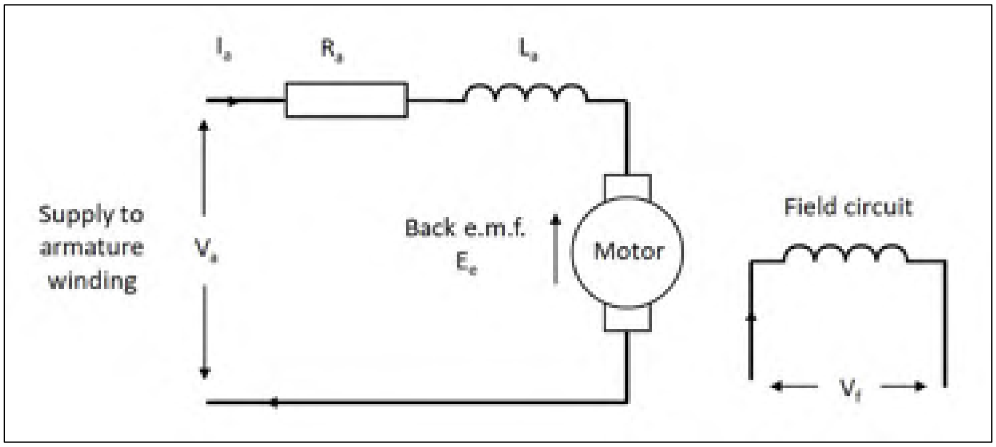

Figure 1.7: Electrical model of a DC motor-pump
Adapted from N. Chandrasekaran (2012)

In this model the resistance R_a and inductance L_a are intrinsic properties of the motor armature, R_a accounts for the wire resistance and the brushes resistance. Stationary operation is assumed and as the motor is run by DC current, it is possible to put aside the transitional effects and not to consider L_a nor the inertia of the mechanical load.
The voltage in the armature is:

$$V_a = I_a * R_a + E_g \quad (1.11)$$

The reverse voltage E_g is induced by back electromagnetic force (e.m.f.) and is proportional to the angular speed of the shaft and to the magnetic flux:

$$E_g = K_E * \Phi * \omega \quad (1.12)$$

The motor torque T_m is linked to the armature through:

$$T_m = K_m * \Phi * I_a \quad (1.13)$$

Then the output pump torque T_p is often said to be proportional to the squared rotational speed of the shaft.

$$T_p = K_p * \omega^2 \leftrightarrow T_p * \omega = P_{meca} = K_p * \omega^3 \quad (1.14)$$

However, it has to be noticed that this proportional relation is an affinity law, therefore assuming that the efficiency, included in *K*, is constant with *ω*. (Martiré et al., 2008) state that this approximation is correct on relatively small motors, but underline the fact that the efficiency is dependent on the flow rate, and as the flow rate is dependent on the head and the rotational speed, it is equivalent to say that the constant *K* must be dependent on *TDH*. Hence:

$$T_p = K_p(TDH) * \omega^2 \tag{1.15}$$

As a result,

$$V_a = R_a * I_a + K_E * \sqrt{\frac{K_m}{K_p(TDH)}} * \Phi^{\frac{3}{2}} * \sqrt{I_a} \tag{1.16}$$

Equation 1.16 gives a direct relationship between the voltage and the current, which is the first function wanted f_1. Second equation f_2 comes from the conservation of energy between electrical and mechanical power (Khatib & Elmenreich, 2016).

$$Q * \Delta p = P_{meca} = \eta_{mp} * P_{elec} \tag{1.17}$$

$$\leftrightarrow$$

$$Q = \eta_{mp}(Q) * \frac{P_{elec}}{g * \rho * TDH}$$

Where Δp is the pressure difference between input and output of pump in Pa.

$\eta_{mp}(Q)$ can be fitted with polynomial, as in (Martiré et al., 2008), found from $\eta_{mp}(P_e, TDH)$ in MPPT coupling cases, or from $\eta_{mp}(I, V, TDH)$ in direct coupling cases. If not enough data is given, it can be considered as constant, even though it adds substantial uncertainty on the output.

The values of K_p and K_m can be found sometimes in manufacturer datasheets. If not available, they can be computed from the specifications given or by running some tests on the pump (Tantos, 2011a). The method described by Tantos consists in using four particular operating points: no-load, stall, maximum efficiency and maximum output power. These points are typically given at rated voltages and in stationary conditions. But sometimes pump manufacturers do not give these points and modeling the motor cannot be done with the theoretical approach of Tantos. (Kolhe, Joshi, & Kothari, 2004) use a similar approach for the motor but considers a more advanced model for the centrifugal load, taking into account the moment of inertia and the viscous torque constant of the pump, resulting in a different form for f_2. Even so these data are very rare in manufacturer datasheet, therefore it has been decided not to include the Kolhe model in the scope of this work. According to the figure 11 in (Kolhe et al., 2004), the relative error on overall efficiency between prediction and measurements ranges from 27% at 300W/m^2 to 7% at 700W/m^2.

Above theoretical approach can be used to model different types of motor. In the scope of this work, one is particularly investigated because it is more widely described in the literature reviewed: the permanent magnet DC motor. In the case of such a motor, the magnetic field Φ is constant in any conditions, which simplifies further the equations. Equation f_1 becomes:

$$V_a = R_a * I_a + K_E * \sqrt{\frac{K_m}{K_p(TDH)}} * \sqrt{I_a} \tag{1.18}$$

$$\leftrightarrow$$

$$V_a = \alpha * I_a + \beta(TDH) * \sqrt{I_a}$$

Equation f_2 can be used normally afterward (equation 1.17). This model has the advantage of requiring less information on pumps. First, it needs the electrical architecture of the motor, and then in the merest case where K_p is considered as constant with TDH, only 2 (I, V) points and 1 (Q, P, TDH) point are needed, or only 1 (Q, P, TDH) point if coupled with a MPPT.

1.2.3.4 Operating range of the pump

In the previous papers, researchers always assume that the motor pump works in stationary operation. However, to improve the accuracy of the empirical and theoretical approach, transitional effects should be taken into account. These transitional effects happen typically in the morning at the start of the motor, and more generally for high variations in irradiance during the day, for example in the case of variable partly cloudy conditions. Most studies on PVPS modeling consider a very sunny weather, with very smooth irradiance variations through the day, avoiding the researchers to address these transitional effects. It can be noticed that (Martiré et al., 2008) report their largest relative errors between prediction and measurement in the morning, right after the pump begins to operate.

Being able to model unsteady operations would allow to better predict the exact moment when the pump starts and when it stops. To consider this, more information is needed: the starting voltage and current, and the maximum power acceptable. These characteristics can originate from the motor pump itself or from the integrated controller, if existing.

Nevertheless it is unlikely that pump manufacturer datasheets give such characteristics, and other strategies must be used. The most evident is the prior testing of the pump to gather the required information, but such strategy requires to have access to a test bench.

The second strategy is to analyse the motor with a theoretical approach. (Singer & Appelbaum, 1993) investigated the starting characteristics of a DC motor with this approach, and find that the starting current I_{st} could be linked to the rated current I_{rated} for the four main electrical architectures of DC motor. For example, for PMDC motor it is found that $I_{st} = 1.2 * I_{rated}$. Thanks to this work, the consideration of the range of functioning and the starting characteristics could be made simpler, and could be implemented in a model as soon as the pump electrical architecture is known.

1.2.3.5 Summary table

The following table summarizes the previously discussed pump models and their relative accuracy. Relative errors are related to the output flowrate values, unless specified otherwise.

Table 1.2: Summary of pump models

Name and papers	Relative error	Minimum Data size required	Coupling method applicability
Kou model **(Kou et al., 1998) and** **(Jahnig D. et al., 1998)**	20 – 40%	16 (TDH, I, V, Q) points + 4 different V + 4 different TDH	Direct / MPPT
Hadj Arab model **(Hadj Arab et al., 2006)**	< 5% for DP < 14% for CP	9 (TDH, I, V, Q) points + 3 different V + 3 different TDH	Direct / MPPT
Hadj Arab model **(Djoudi Gherbi et al., 2017)**	< 4% for DP < 10% for CP	12 (TDH, I, V, Q) points + 3 different V + 4 different TDH	Direct / MPPT
Hamidat **(Hamidat & Benyoucef, 2008)**	Not Assessed	16 (TDH, P, Q) points + 4 different V + 4 different TDH	MPPT
Theoretical **(Mokeddem, Midoun, Kadri, Hiadsi, & Raja, 2011)**	Not Assessed	2 (TDH, I, V) points + 1 (TDH, P, Q) point + Electrical architecture	Direct / MPPT *
Theoretical model for f_1 **(Kolhe et al., 2004)**	7 – 27% on motor-pump efficiency	2 (TDH, I, V) points + 1 (TDH, P, Q) point + Electrical architecture	Direct / MPPT *
Theoretical model for f_2 **(Martiré et al., 2008)**	5 – 15%	6 (TDH, P, Q) + 6 different Q at a given TDH	MPPT

* Starting characteristic consideration possible without additional data

1.2.4 Hydraulic circuit

The terminology used to refer to the different heads in a hydraulic circuit is not standardized among all papers. In this work, the following terminology is used: friction head (FH) refers to the head caused by the friction in the pipes, dynamic head (DH) refers to the variable level of water at the water source, static head (SH) refers to the total vertical head in the system, thus including the dynamic head, and total dynamic head (TDH) is the maximum global head seen by the pump. The different head are summarized in Figure 1.8.

Except (Glasnovic & Margeta, 2007) and (Campana, Li, & Yan, 2013), all researchers working on PVPS consider static head as constant in time, with no dynamic head. The main reason for this is that the dynamic head is difficult to predict and depends on complex geological systems, often out of the field of the researchers in PVPS, who are mainly specialized in mechanics and electronics. However, it has to be noticed that it may be a major omission in the modeling of a pumping system as discussed in 1.2.1.2.

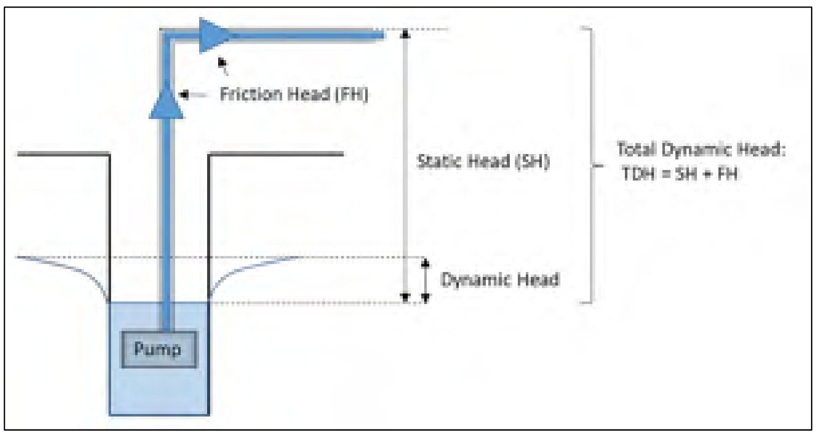

Figure 1.8: Diagram of heads in a pumping system

Concerning the computation of friction head, this field of fluid mechanics is well developed, and some models are very commonly applied. For example, the Darcy–Weisbach equation (Douglas, 2005) is often used in PVPS modeling along with the fluid and pipes properties to evaluate the head due to friction effects in the pipes (Khatib & Elmenreich, 2016 ; Mokeddem et al., 2011). The Darcy-Weisbach equation needs a friction factor which has to come from other relations dependant on the regime of the fluid in the pipe. Hagen-Poiseuille and Colebrook equations can be used respectively for laminar and turbulent flows with a not significant relative error (Bell, s.d.) for a PVPS case.

These fluid models are already implemented by researchers in different packages available online. Notably, the open-source project *fluids* (Bell, s.d.) proposes a ready-to-use package written in Python and implementing many fluid models and standard pipes and fluids properties.

1.2.5 Global modeling procedure

After having detailed the modeling of the different part of the system, a last focus should be put on how to link all these models to eventually reach the prediction of output water flow rate. Two cases can be drawn: the modeling with a MPPT converter between PV array and pump, or the modeling without it.

1.2.5.1 MPPT coupled modeling

Using a MPPT is the easiest coupling method to model, and the most widely used because it can bring significantly better water output for the PVPS (Aliyu et al., 2018 ; Muhsen et al., 2017). It consists in simply considering the total power produced by the PV array, with no consideration of current and voltage, and to use it as input power for the pump. The power can be reduced by a given percentage to take into account the losses in the conversion. This MPPT coupling is used in (Gualteros Martinez, 2017 ; Hamidat & Benyoucef, 2008 ; Meunier et al., 2019).

1.2.5.2 Direct-coupling modeling

The direct coupling method is for systems including no power electronics between PV array and the pump. This type of system can be preferred in order to simplify the set-up in the perspective of having a more reliable PVPS in time or to lower the cost. Such systems often use PMDC motor pumps for load-matching and reliability reasons (Djoudi Gherbi et al., 2017 ; Kolhe et al., 2004 ; Mokeddem et al., 2011). In this case the I-V operating point between PV array and the pump must be found. It can be defined as the intersection between the I-V curve of the PV array and the I-V curve of the pump (represented by the function f_1 described in 1.2.3.1.) as shown in the Figure 1.9. This figure shows the issue of load-matching: the PV array and pump I-V curves can sometimes not intersect or can intersect far from the maximum power point of the PV array. In this case the power produced by the PV array is not maximised and it results in a low output from the PVPS.

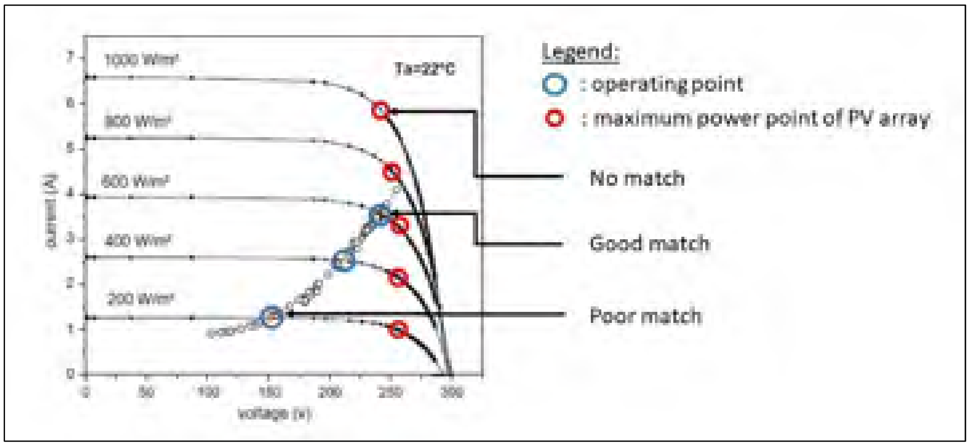

Figure 1.9: Operating point in direct-coupled systems.
Adapted from Mokeddem & al.

In terms of costs and output flow rates, no global comparison between direct and MPPT coupled systems was found in the literature. It can be noticed that (Mokeddem et al., 2011) reported pump efficiencies up to 25% on a PMDC pump directly coupled, whereas (Hamidat & Benyoucef, 2008) stated that efficiencies up to 40% are reachable for the same type of pumps, suggesting that direct systems cannot be as efficient as MPPT systems. However this is highly dependent on the match quality between pump and PV array, therefore this difference in efficiency cannot be generalized in any way. The following research tries to address this question by running comparisons on a big set of pump and locations.

1.2.5.3 Friction head and total head computation

If the water level is considered as fixed, as discussed in 1.2.4, a static head can be selected for each location, and only the friction head coming from pipes friction and fittings has to be added to obtain the TDH. In most cases, if the pipes are correctly sized, the TDH should not vary widely over the constant SH. Therefore, for each pumping system, a simplified function

$I = f_{I,TDH=k}(V)$ can be found. This simplified function is implicitly assumed in the work of (Hadj Arab et al., 2006) and (Hamidat & Benyoucef, 2008).

If this approximation cannot be done, TDH should be computed from discharge Q with a function $TDH = f_3(Q)$. Then it is possible to iterate on f_1, f_2 and f_3 until converging to the TDH researched, or to try to integrate f_3 into f_2 so as to avoid the necessity of looping until convergence (Meunier et al., 2019).

1.2.5.4 Global relative error

The following table summarizes the different relative errors that correspond to each model previously discussed and used through the whole simulation of a PVPS.

Table 1.3: Summary of minimum and maximum of typical relative errors for models used in PVPS modeling

Model	Minimum relative error	Maximum relative error
Weather file construction	0–8% (measurement-based data)	20% (satellite-based data)
Irradiance on tilted plane	0-9% (Perez)	0-14% (isotropic)
Absorption model	Nonsignificant	0-5% around 70°
Cell temperature	Not assessed	
Single Diode	Nonsignificant	0-2% at -25°C
Pump model	0-4% (Hadj Arab's model on displacement pump previously tested in laboratory)	20-40 % (Kou's model on centrifugal pump with manufacturer data)
Friction head model	Nonsignificant	Nonsignificant
Water demand model	Not assessed	

It can be noticed that the expected relative errors of each model depend on the situation in which the model is used. It is particularly true for pump modeling, where few papers present relative error assessment, and even when given, it is strongly linked with the other factors of the study (data size of pump specifications, sunny location, electrical architecture, etc.). Therefore, a special focus should be put on evaluating the performance of each pump model on a same experimental set-up.

1.3 Sizing procedures

As detailed in 1.2 the prediction of a PVPS output still needs investigations to determine what is the best way to make an accurate prediction, in particular which pump model to use to this end. Still, some researchers worked in parallel on the sizing of such systems.

As represented in Figure 1.10, sizing is basically the reverse process of modeling. The output of the modeling, water flow rate in this case, becomes the input of the sizing; and the inputs like PV array and pump become the expected output. Therefore, the sizing process uses the same models than the modeling process to be able to choose the best elements during the sizing. This highlights the need of an accurate modeling to ensure a correct sizing.

The standard fixed inputs for the sizing are the water consumption, the weather files and the site characteristics. Then the variables to size of a PVPS are numerous, and the sizing should ideally be made on any of these variables, like PV array size, tilt, PV module, coupling method, motor-pump, reservoir size… But all these variables interact between each other, resulting in huge complexity. To simplify the problem, it has to be assumed some values, and therefore to focus the sizing on a few variables only. The sizing methods can be gathered in two groups: the intuitive and numerical methods. The intuitive method allows to size a good number of variables but always with neglecting a lot of interaction between the elements of the system, resulting in a poor output prediction, whereas numerical methods often restrict the number of variables to size but use a more reliable analysis based on whole iterative simulations. The global structure of the methods is described in Figure 1.10, and each of them are explained further in the next sections.

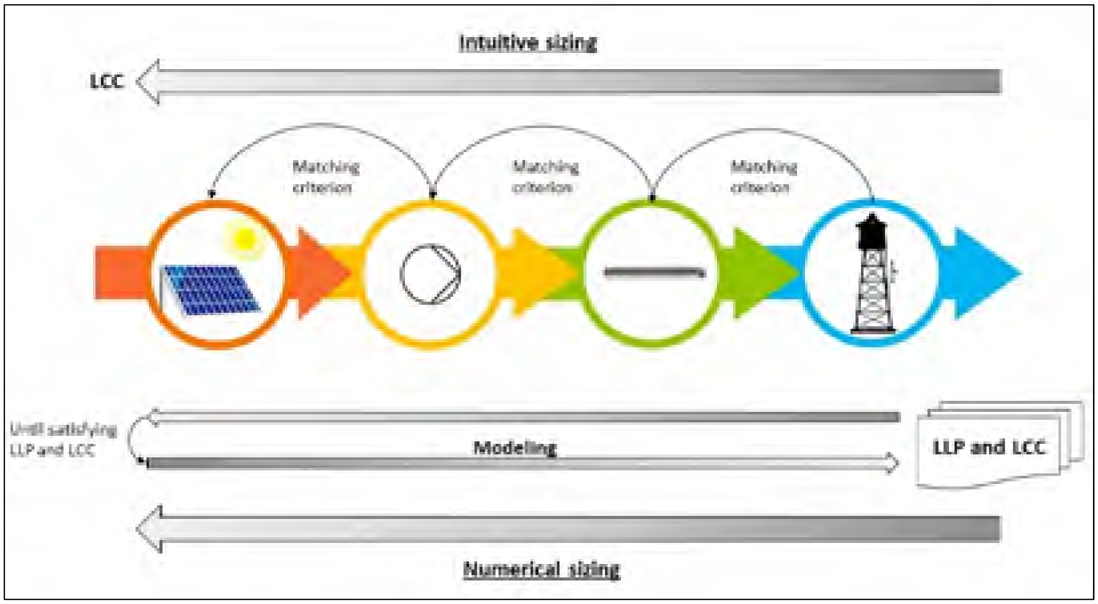

Figure 1.10: Diagram of modeling and sizing principles

1.3.1 Intuitive methods

Intuitive method refers to any sizing method where each component and variable is selected following some simple principles linking the different specifications and components to each other. The research using these methods often consider the worst month, which is not necessarily easy to find as detailed in 1.2.1.2, or monthly average data. The Life Cycle Cost (LCC) can be used in these methods to find the more cost-efficient option. LCC is the cost of the system including the initial investment, the operational costs during its whole lifespan and the end of life value. The LCC can be computed using different method, including more or less details in the assessment of the different costs, but it is often considered as the same than the Net Present Value (NPV) of the project, thus including the discounted cash flows through time.

(Campana et al., 2013) used an intuitive method to size a whole system. They start by assessing the water need with a dynamical model, and then adapt an intuitive method for the selection of the other components. Basically, the components are arbitrarily chosen as long as they match the needed load. They use a factorial experimental design to evaluate the best configuration between a fixed or two-axis tracked PV array, AC or DC pump, and three different PV array sizes (1.8 kW_p, 2.1 kW_p, and 2.4 kW_p) used. It results in a 12 experiments design, from which they find that the fixed 2.1 kW_p array with the AC pump was the more cost-efficient option. However, no comparison with experimental system exists, therefore the result is only theoretical and the oversizing or undersizing of the PVPS cannot be measured.

(Ebaid, Qandil, & Hammad, 2013) also used an intuitive method and then compare with experimental data. Even if the researchers found that the system was eventually oversized of 38%, the LCC was still under the fossil fuel powered system.

The intuitive method allows to size quite all possible variables and components in the system, but the interactions between the components are not taken into account and nothing ensures that the resulting PVPS is not oversized or undersized.

1.3.2 Numerical methods

Numerical sizing methods realize complete modeling of different PVPS, until finding an optimized set-up. To select which set-up are better than the others, the following criteria are mainly used: the Load Losses Probability (LLP) and the Life Cycle Cost (LCC) (Muhsen et al., 2017). LLP is defined as the ratio between the lack of water and the total water required. The numerical method has this advantage over intuitive method that it can compute the LLP of a system as the complete modeling is made. Therefore, it avoids having oversized systems due to the sizing method. Still if the water demand, weather conditions, or any model (pump, PV, coupling, etc) used are wrong, the system can be incorrectly sized, but it is independent of the sizing method.

The experimental design can be factorial experiments (Bouzidi, 2013) or can follow a given algorithm, optimizing step-by-step the set-up (Hamidat & Benyoucef, 2009 ; Kaldellis, Spyropoulos, Kavadias, & Koronaki, 2009). The variables possible to size are numerous for a

PVPS, and sizing all these variables at the same time would result in a huge computational complexity and computation time. To simplify the problem, researchers often only consider a restricted number of variables. In reviewed literature the variables sized in the case of numerical method are the number of PV modules and the size of the energy storage (Bakelli, Hadj Arab, & Azoui, 2011 ; Bouzidi, 2013 ; Hamidat & Benyoucef, 2009 ; Kaldellis et al., 2009 ; Martiré et al., 2008).

Among the previously cited studies, Bouzidi realizes a quite complete analysis for these two variables. He sizes different systems based on LLP and LCC, and uses a factorial approach by computing LLP and LCC for each combination into his variables set of values. He shows the strong link between the number of PV module and the size of the reservoir, and concludes that given his very sunny location, it is more cost efficient to increase the number of PV modules than the size of the reservoir. The optimum size of the reservoir is found to be only half of the water volume consumed in one day. It is to note that the modeling method used in this research is basic and theoretical, considering the fact that the motor-pump is only modeled by a constant efficiency. Therefore, the predicted output flow rate may be very uncertain, but the comparative analysis on PV array size and reservoir size is still relevant to assess the effect of these variables.

1.4 Research problem

As discussed in 1.2 and 1.3, PVPS simulation is not entirely mature yet, especially considering the pump model. Still a lot of research papers exist on PVPS, sometimes applying to simulation cases, sometimes to experimental set-up, but often they cannot be generalized to other contexts. For instance, many researchers study different interactions between variables or sizing methods, but using different underlying models. This prevent them to draw solid conclusions, and finally to strengthen the accuracy of the domain. Hence, an effort should be put on trying to create more links between the papers, make these researches converge, eventually to find which models are more accurate than the others or which sizing methods are to be generalized against others.

The proposed solution is the creation of a simulation tool implementing some of the models found in the literature, with a special focus put on the flexibility and extensibility of the package.

CHAPTER 2

METHODOLOGY

To address the research problem, it is chosen to develop a software tool aggregating some of the available models found in the literature, and providing classes and functions to model a photovoltaic pumping system (PVPS) output. The advantage of such a software would be the possibility to easily change the models and the specifications of the set-up, so as to facilitate and accelerate the modeling and sizing of PVPS, and hopefully to eventually standardize some modeling and sizing processes. One other advantage of opting for an integrated software is the high reproducibility of any studies made with it.

2.1 Philosophy of the package

2.1.1 Accessibility and flexibility

As the project of aggregating the existing research on PVPS is potentially huge, and as the software should be flexible enough to adapt to future research, it appears like an evidence that the software must be open-source and must facilitate the participation of other researchers. Therefore, the software is available through the GitHub online platform, and it takes the name of *pvpumpingsystem.*

Python is chosen as the programming language of the software. Python has the advantage of being free, already well settled in the academic research world, easy to learn, and its use is growing so fast that it is expected to become one of the most popular programming language in the world, if not the most (David, 2017). Python also has the advantage of working well on most of the operating systems (OS), including the three mains: Windows, MacOS and Linux. Python is a high-level multi-paradigms language, but among these paradigms the concerned software uses an object-oriented design. It allows to organize the structure of the code in the same way than the structure of the PVPS to some extent. For example, a class object “Pump” exists for representing a motor-pump and gathers all the useful methods for the pumps. The following class objects also have their equivalent physical elements: “Pump”, “MPPT”, “Reservoir”, “PipesNetwork” and the container class “PVPumpSystem” which includes the other classes. The object corresponding to PV array does not follow the exact same structure as it is not directly coded in this software, but comes with the pvlib-python dependency (Holmgren et al., 2018). This PV power part is included in a container class called “PVGeneration” internally relying on pvlib-python functions and class. The naming convention is as follows: classes are named in camel case (first word letter capitalized) and attributes and functions are written in snake case (lower case with underscores). More generally, all the code respects the Python Enhancement Proposal (PEP) 8, which is the style guide for python code writing. This allows to highly increase the readability of the code.

2.1.2 Dependency packages

Programming a whole complex system from zero is a hard task, and the result is very likely to include many bugs and errors. Moreover, the simulation of PV array is a complex domain as well and there is a high risk to implement incorrect or oversimplified PV models. These problems can be solved by relying on already existing packages, designed and recognized by researchers of the field. This approach has the advantage of increasing the internal validity of the software.

To this end, the package “pvlib-python” is used by “pvpumpingsystem” for the whole simulation of PV power generation (Holmgren et al., 2018). As discussed in 1.2.2, this package provides classes and functions to simulate the output of PV generators depending on the PV module, irradiance model, surface materials, weather conditions and more. It is also entirely written in Python, following an object-oriented design as well. Nevertheless, to be fully compatible with pvpumpingsystem package, some modifications had to be done, mainly on the outputs that are aimed to become the inputs of pvpumpingsystem. These modifications were submitted through pull requests on GitHub and were accepted by the maintainers of pvlib-python. The “PVGeneration” class is then added for containing pvlib-python. It aims at making the use of pvlib-python more user-friendly for users of “pvpumpingsystem”. For example, it includes a function finding a PV module in the database without the exact reference name but from an incomplete name.

Then the package “fluids” (Bell, s.d.) is also used together with the module “waterproperties” developed by L. Lamarche at ETS. “Fluids” was developed at the University of New Brunswick and serves the modeling of the friction head in the pipes of the PVPS. This package only provides computation functions and is therefore integrated in the “PipeNetwork” class to provide a class and the methods in the same way than the rest of “pvpumpingsystem” structure. Figure 2.1 summarizes the use of the dependencies in pvpumpingsystem.

The other dependencies used are the classic scientific packages of python which are included in Anaconda distribution: numpy, scipy, pandas, matplotlib, etc.

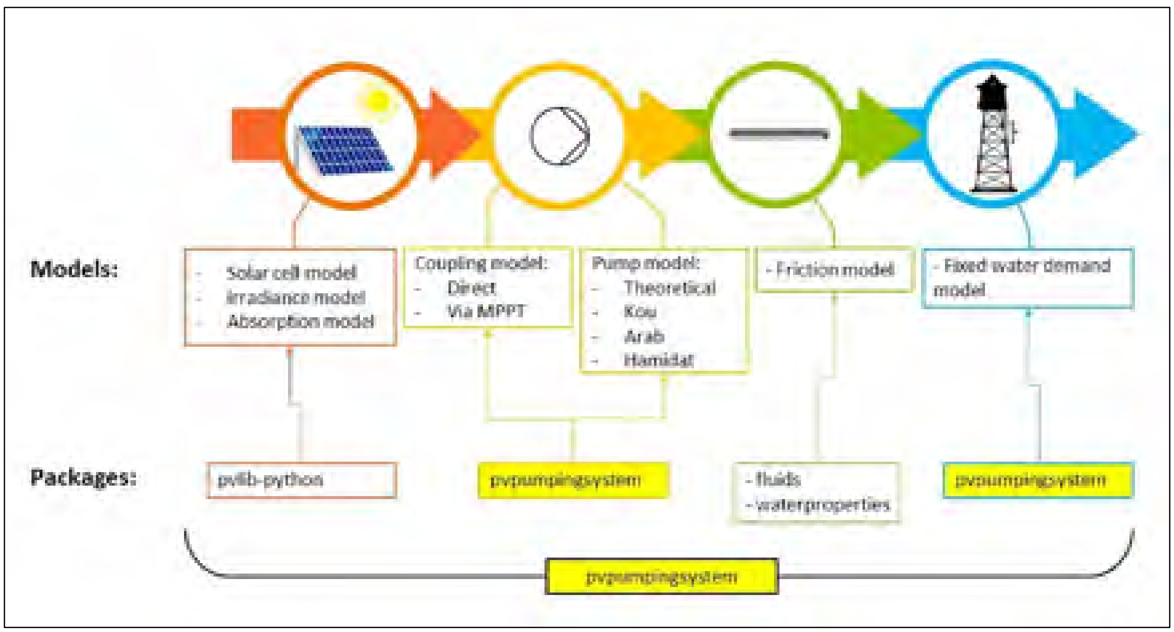

Figure 2.1: Diagram of package usages

2.1.3 Extensibility and continuous integration tools

The continuous integration (CI) is the practice of testing and validating the code written continuously in parallel of the software development. These parallel processes are called workflows and can validate different aspects of the code. In “pvpumpingsystem” package, the CI is done through the GitHub workflows. Two workflows are declared, one on windows 10 OS and the other on the latest Ubuntu OS. Both workflows use python 3.7 and process the following checks:

- Lint errors research with *flake8*. This tool allows to ensure that the code respects the PEP8 conventions, excepting some lint type that can be manually declared in the workflow setup file.
- Tests fulfillment with *pytest*. This tool runs all the tests of the package and ensure that all of them return the expected answer.
- Tests coverage. This tool computes the ratio of lines actually tested by *pytest* in the whole code. The target is set at 70% for full code, and 90% for pull-requests.

The validation of code with the above CI tools is a good way to ensure that new code fits with the former, particularly thanks to the testing facility.

2.2 Integrated models

Different models are implemented in the *pvpumpingsystem* package to enable researchers using that of their choice. The coming section focuses on these available models and how they articulate together.

2.2.1 Pvlib-python models

All models implemented in *pvlib-python* are kept available in pvpumpingsystem, with only one restriction. This restriction is that if the PVPS is direct coupled, the solar cell model must be a SDM (De Soto’s or CEC’s (Dobos)). Indeed, the I-V relation of PV array used to find the operating point has to be determined from the five parameters of SDM in the current implementation of pvpumpingsystem. Implementing a function for getting the I-V relation from Sandia PV Array Performance Model (SAPM) is also possible but has been considered secondary as SAPM is not widely used.

2.2.2 Coupling models

Both direct and MPPT coupling method are implemented in pvpumpingsystem package. They do not use the same data from the PV generation modeling: MPPT coupling uses the total maximum power of the PV generator, while direct coupling uses the I-V relation of PV array. Then, the algorithm used is slightly different in the two cases and results in a longer computation time for the direct-coupling case. The algorithm is portrayed in Figure 2.2. Note that the loop on friction head can be avoided for computation time reasons with the attribute “iteration”.

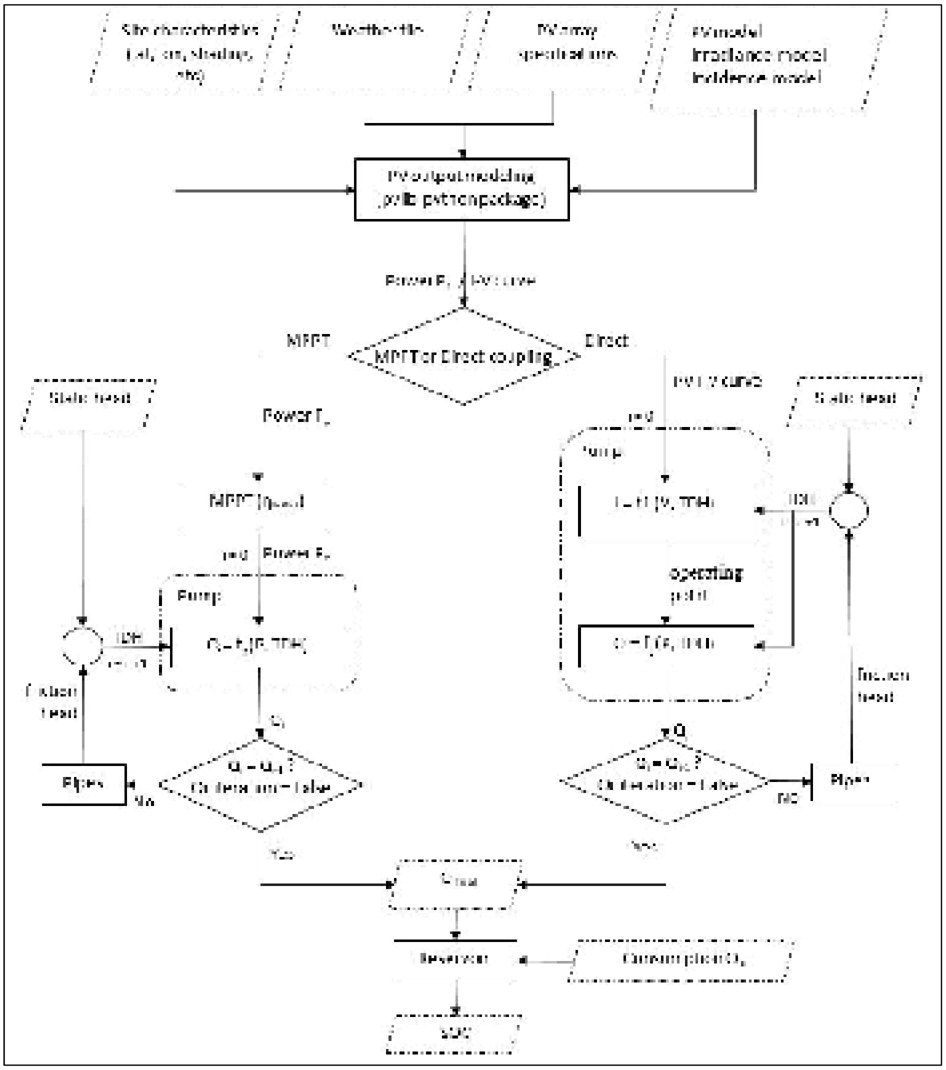

Figure 2.2: Modeling algorithm

2.2.3 Pump models

As discussed in 1.2.3 the pump models are diverse, use different pieces of information and can require more or less information to be used. This package intents to put a focus on making easier the modeling from data manufacturer information only, even if the data size is often restricted. This would allow people or organisations without access to a test facility to model and size better PVPS. In order to know what model can be applied depending on the data size, an attribute 'data_completeness' is added to the Pump objects. It contains information on the number of voltages for which specs are given, the number of points (TDH, I, V, Q), the minimum flow and head given in the specifications and if the electrical architecture of the pump is known. Thanks to this attribute, one can determine which pump model can be applied and an error can be raised if the user asks for a model which is not suitable for the data size. The pump model is selected through the attribute “modeling_method”, which is accessible from Pump class or PVPumpSystem class. The available options for pump models are “hamidat”, “kou”, “arab” and “theoretical” with reference to the above-discussed papers (Djoudi Gherbi et al., 2017 ; Hadj Arab et al., 2006 ; Hamidat & Benyoucef, 2008 ; Kou et al., 1998 ; Mokeddem et al., 2011).

2.2.4 Water demand models

Two types of hourly water demand can be modeled easily with the package. The first is a constant consumption model, which typically represents the consumption coming from a drip irrigation. The second is a repeated flow model, where the user can define the sequence of output flowrate he wants to be repeated all along the simulation. By defining it on a 24h basis, it fits well for a description of a human water consumption throughout the day.

2.2.5 Simulation outputs

Once all the parameters and models chosen, the final modeling or sizing can be run. For this purpose, the PVPumpSystem class method run_model() can be used. It allows to run all the models and to retrieve all possible outputs afterward. For computation time reasons, some other methods allow to run only a part of the model. The two main outputs of a whole simulation are the following: Load Loss Probability (LLP) and Net Present Value (NPV). The latter is equally considered as the Life Cycle Cost (LCC) of the PVPS. It is also possible to retrieve hourly data on the total unused power, the deficit or extra water, the efficiency of the system, the output flow rate, the State of Charge (SOC) of the reservoir, and other details on the PVPS. The possibilities in the output data that can be retrieved, as well as in the input data that can be given, opens doors to the intermediate user for realizing numerous parametric tests. The hourly data can also be printed in graphs for better visualization. Figure 2.3 shows a typical graph representing the water volume and the input flow rate in the tank (equivalent to the pump output flow rate). The water consumption is considered as constant and the time scale corresponds to the first three days of January in Montreal.

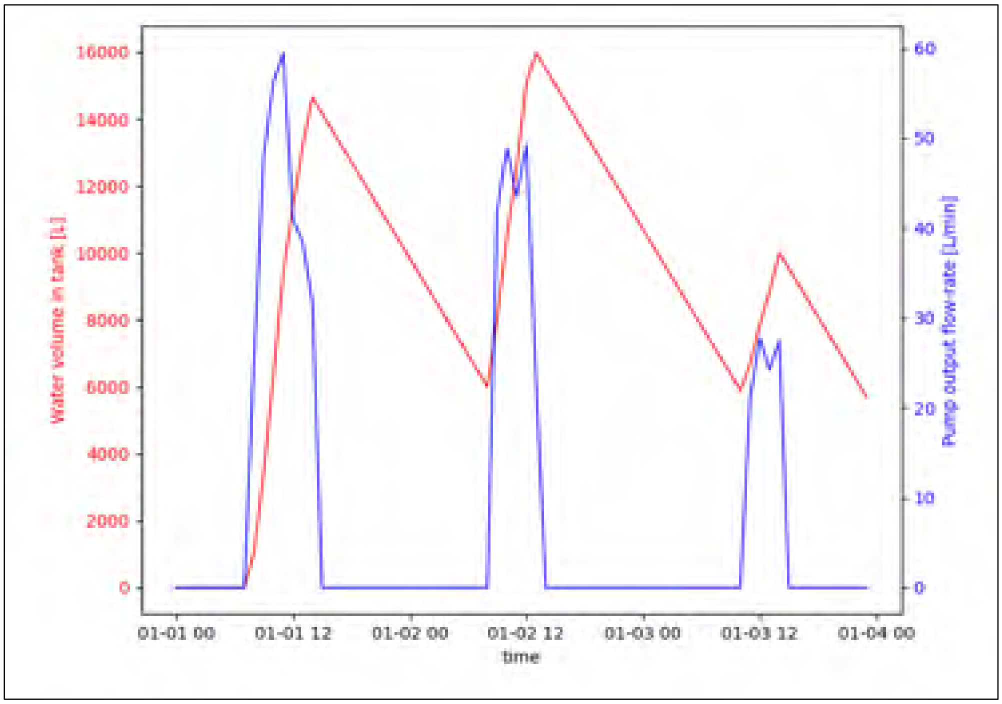

Figure 2.3: Graph of water volume in tank and pump output flow rate for three days of simulation and in the case of a constant water consumption

2.2.6 Sizing models

A factorial numerical sizing model based on LLP and LCC is implemented in pvpumpingsystem under the name “sizing_minimize_npv()”. It allows to choose the most cost-efficient set-up among a PV module and pump database. A factorial analysis is run on each combination of PV module and pump available. For each combination, the number of modules is adjusted so as to ensure an LLP inferior to the minimum LLP acceptable. Knowing the PV module, the number of modules, the pump, and the other components set at the definition of the PVPS, the NPV of the project can be determined. The function eventually chooses the combination with the lowest NPV and returns it as the result.

A summary of the models available in pvpumpingsystem is presented in Table 2.1.

Table 2.1: Main models available through pvpumpingsystem package

Package	**Category of models**	**Options**
Pvlib-python	Weather file type	Hourly measures based (TMY, etc) Satellite-based
	Irradiance on tilted plane	Isotropic, Hay-Davies, Klucher, Reindl, King, Perez
	Solar cell	5 parameters SDM (De Soto) 6 parameters SDM (CEC)
	Absorption	ASHRAE, physical, Martin-Ruiz, interpolation, SAPM
Pvpumpingsystem	Coupling	Direct MPPT
	Pump	Hadj Arab Hamidat Kou Theoretical PMDC
	Sizing	Factorial sizing for pump and PV module selection and number of modules

CHAPTER 3

RESULTS

So far the predictive accuracy of the software is not validated by comparison with experimental data, but as the software consists more in the gathering of previous models of PVPS than in the design of a new model, one can expect the relative error of the software output to stay into a reasonable range, equivalent to the relative error of the worst model used. In the following, it is assumed that the written code does not bring other biases than those internally contained in each model implemented, therefore, the relative error of the final output is a function of the relative error of each internal model. Thereupon, it is relevant to run sensitivity analyses on the different models available. The following chapter presents three comparative analysis on three internal models available in the software: the pump, the coupling method and the weather file type.

3.1 Model fit assessment

Before using “pvpumpingsystem” package, the user may appreciate to have some recommendations on which model to use against others. As discussed in 1.2, this information is already available on most of the photovoltaic models used in “pvlib-python”, but not on the pump. This section provides an assessment of the predictive power of pump models through a comparative analysis of the goodness of fit returned by each model.

3.1.1 Results

A database of 46 DC pumps from the company SunPumps (SunPumps, s.d.), each containing specifications for between 10 and 78 points (TDH, I, V, Q)., is used. These pumps are all permanent magnet brushless DC motor pumps. A curve fit is run on each of these pumps following each model previously described. For the model of Hadj Arab, the Djoudi Gherbi variation is used (12pts needed). The theoretical model uses a mere constant efficiency model for f_2 (as in (Kolhe et al., 2004) implementation), despite the fact that this model is highly simplistic and that the efficiency should be ideally depending on voltage and head.

To assess the goodness of fit, a Normalized Root Mean Square Error (NRMSE) is used. The NRMSE is a statistical tool allowing to compare the Root Mean Square Error (RMSE) between predicted and measured values independently of the absolute value of the quantity measured. The more NRMSE approaches 0, the better the fit is. The NRMSE is defined by:

$$NRMSE = \frac{RMSE}{\bar{y}} = \frac{\sqrt{\frac{\sum_i^N \left(y_i - f(y_i)\right)^2}{N}}}{\bar{y}} \tag{3.1}$$

The NRMSE is computed for each model applied to the 46 pumps, and the results are represented in Figure 3.1. The boxplots presented in this figure follow the Tukey industry standard, that is to say boxes are between first and third quartile and whiskers are minimum and maximum values without considering the outliers. A value is considered as outlier when it lies further than 1.5 times the box length from each tip of it. The bar inside the box is the median, and the cross is the mean.

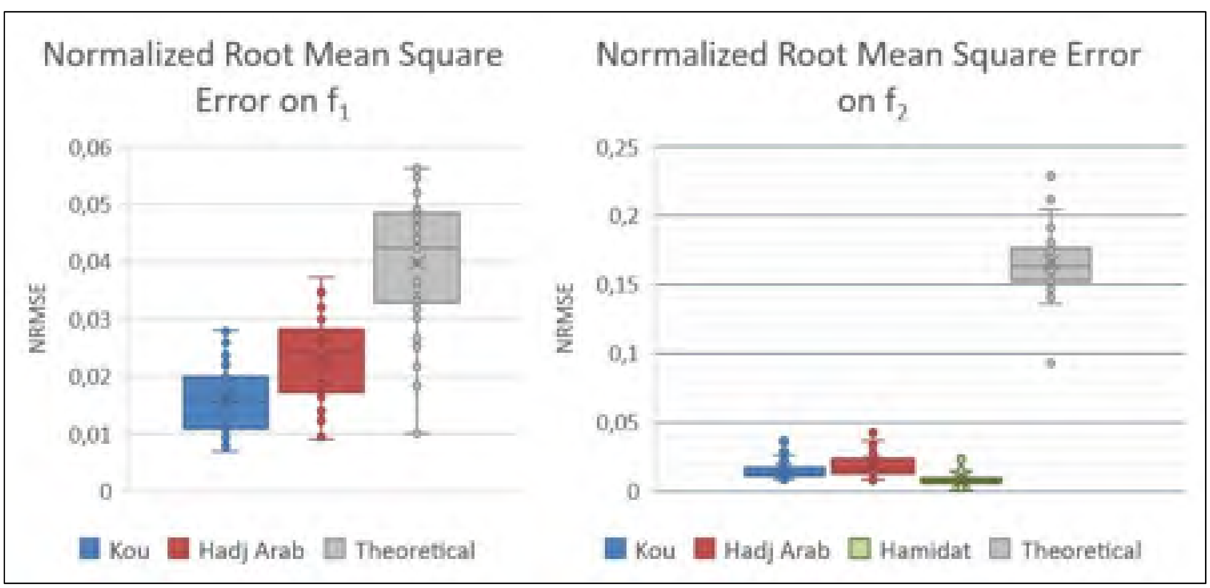

Figure 3.1: Goodness of fit assessment for the pump models

Key values such as minimum, maximum and means along with the standard deviation of the series are gathered in
Table 3.1.

Table 3.1: Key values of NRMSE for the pump models

Models		**Minimum**	**Maximum**	**Mean**	**Standard deviation**	**Data size required**
f_1	Kou	0.0068	0.0280	0.0158	0.0058	16
	Hadj Arab	0.0089	0.0373	0.0230	0.0073	8
	Theoretical	0.0100	0.0563	0.0397	0.0116	2
f_2	Kou	0.0080	0.0363	0.0153	0.0063	16
	Hadj Arab	0.0080	0.0450	0.0200	0.0098	12
	Hamidat	0.0008	0.0231	0.0080	0.0038	16
	Theoretical	0.0928	0.2288	0.1660	0.0225	1

3.1.2 Interpretation

At first sight, it can be noticed that the theoretical model provides a worse fit than the other models in most cases. On function f_2, the NRMSE is around ten times higher than for the other models. It is the logical result of considering a constant pump efficiency over a wide range of output flow rate. Nevertheless, it should be noted that theoretical model returns a reasonable NRMSE on f_1 despite the fact that it requires only two data points. Between the other models, Kou's model seems to be slightly better than Hadj Arab's on functions f_1 and f_2 but proceeding together with a higher number of data points required. If direct coupling is not considered in the simulation, then function f_1 is not needed, and Hamidat's model should be chosen. It requires the same minimum data size than Kou's model (16 points) but leads to NRMSE values twice less than that of Kou. The only drawback of using Hamidat's method is the internal use of a root-finding algorithm, which can ultimately extend computation time. Hadj Arab model does not return the best NRMSE for any function, but with a lower number of data points needed (12), it is a good compromise between data size needed and relative error.

Note that the goodness of fit is here calculated along the whole Total Dynamic Head (TDH) range available to the pump. Nevertheless, the fit can be differently good along the TDH range, and the relative error at a given TDH can differ from the global NRMSE. In a practical case the pump operates around a particular TDH, often more or less equal to the static head (SH). Therefore, the above analysis could be repeated for each project, in order to find which model provides the best relative error at the considered SH and than use this model subsequently.

3.2 Assessment of direct coupling potential

As discussed in 1.2.5, two strategies exist in order to couple the pump and the PV array: with or without MPPT. The latter, also called direct coupling, has the advantage of reducing the initial investment and the operational maintenance on the system. Indeed, a MPPT must be typically replaced every 10 years, whereas the PV modules can last for 30 years (Häberlin, 2012). However, having no MPPT decreases the efficiencies of the PV modules and the pump, resulting in a potentially higher number of PV modules required in the array. Consequently, both coupling methods can theoretically lower the Life Cycle Cost (LCC) of the system. The existing literature does not provide relevant comparisons on the outcomes resulting from both coupling methods; therefore the following analysis aims to bridge this gap. The purpose is to evaluate if one of the coupling methods is particularly more efficient than the other, and to assess the relative decrease or increase in LLP and cost resulting from this option.

3.2.1 Inputs of analysis

The analysis is carried-out for five different locations, each representing a different climate type according to the Köppen climate classification (Peel, Finlayson, & Mcmahon, 2007). The arid and semi-arid climates are represented respectively by Aswan, Egypt and Denver, USA. Mediterranean and tropical climate are represented by Tunis, Tunisia, and Nairobi, Kenya. The four previously cited climate also correspond to dry environments, and therefore to high water pumping needs. The continental climate of Montreal is also used as a basis for comparison.

Figure 3.2 shows the typical irradiance data for each of the five locations, where each curve corresponds to the hourly irradiance averaged for each month.

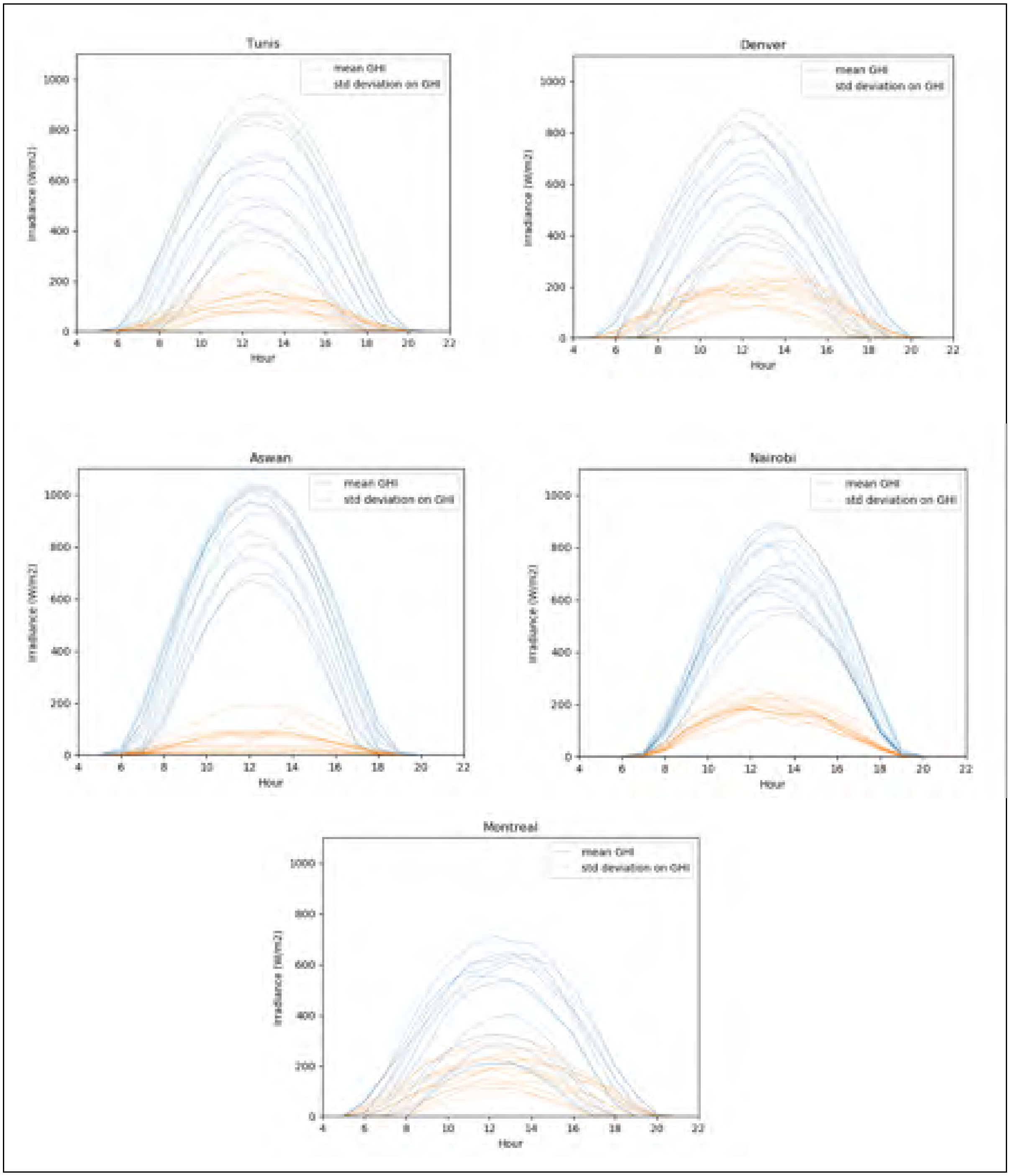

Figure 3.2: Irradiance characteristics of studied locations

This figure shows that the five locations can be qualitatively ranked from the sunnier and more stable climates to the less in the following order: Aswan, Nairobi, Tunis, Denver and Montreal. The weather files used are Typical Year files formatted in EPW format. These files (namely IWEC, CWEC and TMY) are different types of typical weather files, which were said to reduce the representativeness of extreme weather in the file, and thus should not be used for sizing. Nevertheless, as this study aims at comparing two coupling methods using the same file, the weather file does not invalidate the results.

According to (World Health Organization, 2013) an adult person requires 70L per day to ensure a decent water access, that is to say without accounting for water used in agriculture or recreation. In the present analysis the water demand is set at 1750L per day, the water need of a community of 25 people. The consumption varies arbitrarily through the day with peaks around noon and evening as shown in Figure 3.3.

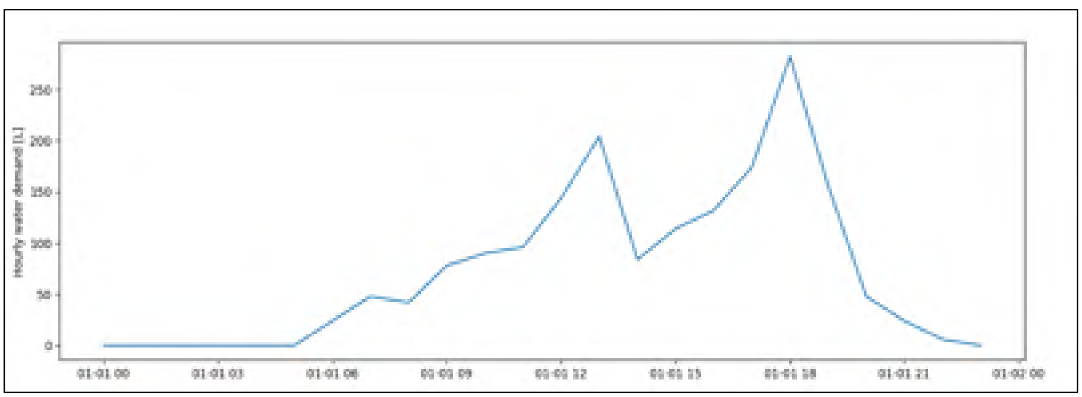

Figure 3.3: Water demand variation in a day

The other fixed inputs to the simulation are given in Table 3.2.

Table 3.2: PVPS equipment

	Reference	**Price**	**Specifications**
PV module	Canadian Solar CS6P 200P	2.5$/W	V_{OC} = 36V / I_{SC} = 7.7A 30 years lifespan
MPPT	Sun Pump PCA-120-BLS-M2	410$	Output voltage up to 120V 10 years lifespan
Water reservoir	3500VW-POT	1010$	Volume = 3500L Potable water grade
Pipe network	Standard PVC pipes	210$	Static head = 30m Pipes of ¾ in x 500ft Potable water grade

A static head of 30m and total length of pipe of 100m is considered. The maximum tolerated Load Losses Probability ($LLP_{accepted}$) is first set at 1%. For the financial analysis, the discount rate is set at 5% and the yearly operational expenditure (OPEX) at 500 USD. This OPEX corresponds to a yearly 10 hours maintenance cost. Lifespan of pumps and MPPT are considered to be 12 years and 10 years, respectively. In addition to the fixed inputs, the sun pump database of 46 brushless pumps is explored recursively. All pumps are modeled according to the Hadj Arab's model, which was said in 3.1 to be a good compromise between input data size and precision. Each pump is then modeled with the full PVPS at the five locations and with both coupling methods. For each combination, first the PV array layout which fulfils the maximum $LLP_{accepted}$ is computed, and then the Net Present Value (NPV – considered as equal to LCC) is recorded.

It is found that six pumps in the database are not suitable because of limited head range, so the following results were obtained for the remaining 40 suitable pumps. After gathering the list of set up and corresponding NPV, simple comparisons can be made between direct and MPPT coupling cases in order to draw conclusions. A full result sample page for Tunis is available in Appendix I.

3.2.2 Direct systems validity

In the case of Tunis, the 40 pumps can reach $LLP_{accepted}$, provided that enough PV modules are installed in the array and are coupled to the pump through a MPPT. In contrast, only 20 pumps are found to be able to meet the demand if a direct coupling is considered. When comparing the LCC of the PVPS using the 20 pumps which work for both MPPT and direct coupling, it is found that the price of MPPT systems is on average 943 USD lower than for direct coupled systems that cost 19,071 USD along the life cycle. This comes from the fact that direct PVPS need more PV modules than its MPPT counterpart. Nevertheless, as direct systems avoid the cost of MPPT which is repeated three times along the life cycle, it can happen that direct coupling is more cost effective. In the case of Tunis, this happens five times, and the lowest cost, all pumps considered, is for a direct coupled system, with a NPV of 15,159 USD.

After performing the same analysis for Montreal, Denver, Aswan and Nairobi, the results are gathered in Figure 3.4. Locations cited in Figure 3.4 are presented from the least sunny to the sunniest when reading the chart from top to bottom. It is then clear that direct PVPS are found to be more suitable for sunnier locations. In Aswan, the sunniest location, 23 direct systems are found to be able to meet the demand, 13 of which are even less expensive than MPPT coupled systems. In Montreal, only six direct systems are suitable, and none of them are more effective than their MPPT counterpart. The average difference in NPV between MPPT and direct systems ranges from nearly zero for Aswan to 2260 USD for Denver. This last case corresponds to an extra cost of 11% compared to MPPT coupled systems. However, it has to be noted that for all locations except Montreal, the overall least expensive PVPS is a direct system.

The same analysis is run with $LLP_{accepted}$ set at 10%. Note that this value is not reasonable for PVPS aimed at providing drinking water for a community but can be a valid limit when considering agricultural usages. The results are presented in appendix II. With this higher tolerated LLP, the direct systems are found to be even more widely suitable, and the least expensive option is now systematically found to be a direct system.

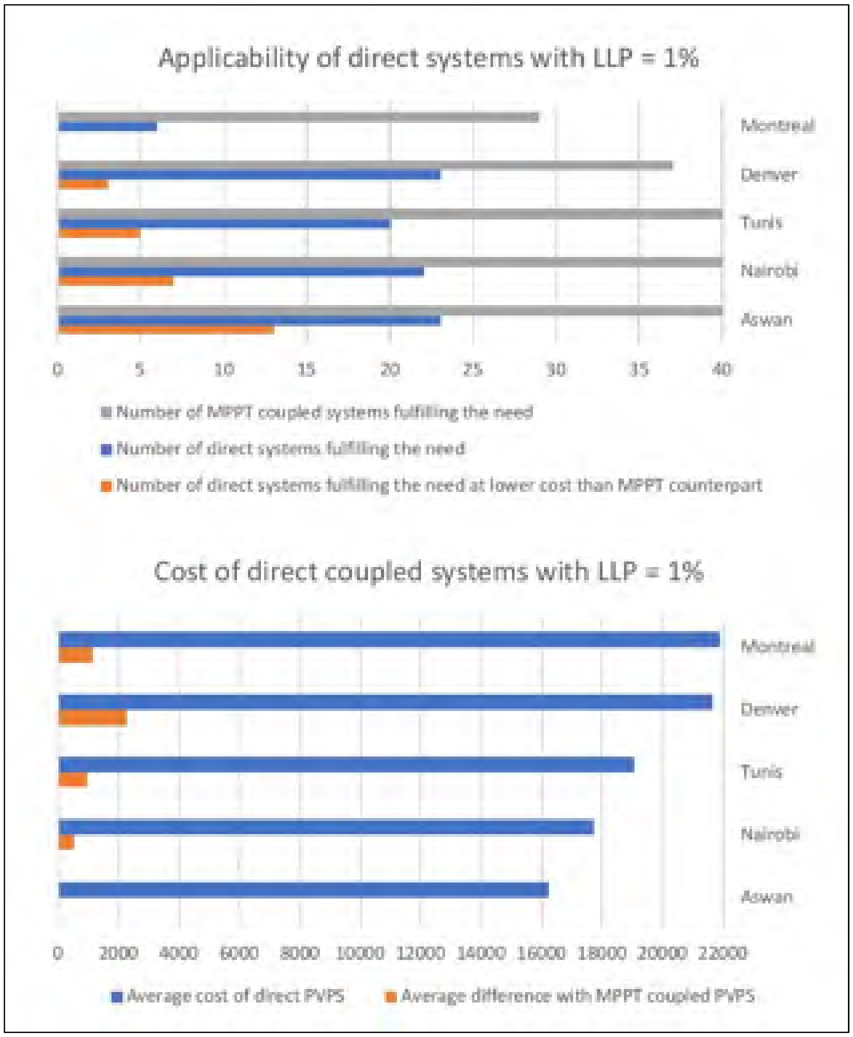

Figure 3.4: Direct systems applicability and cost assessment

3.2.3 Interpretation

This analysis tends to show a high potential in direct coupled PVPS. Indeed, they are found to be the most cost-efficient solution for four over five investigated locations when the $LLP_{accepted}$ is set at 1%, and for all locations when $LLP_{accepted}$ is set at 10%. When $LLP_{accepted}$ is set at 10%, the gain resulting from the choice of direct coupling ranges from 2.5% to 6.6% of total LCC, and decreases to between 2.3% and 5.1% if $LLP_{accepted}$ is 1%.

But this outcome is highly linked with the fact that a wide pump database is explored for the sizing of the PVPS, thus making it more likely to find a pump whose IV curve fits very well with PV array output. If such as database of pumps is not available, MPPT coupled systems are on average less expensive. Previous results show an average extra cost for direct systems ranging from 0% to 11% compared to MPPT coupled systems. This study also shows a greater potential of direct systems in sunny locations. The sunnier the climate is, the more stable the PV array output is, resulting in a higher chance of a good match between the PV generator and the pump.

3.3 Influence of weather file type

As discussed in 1.2.1.1, choosing the appropriate weather database is important for the reliability of the results. For this purpose, Typical Year (TY) weather files may be avoided because it levels the weather characteristics by removing the extreme weather events, whereas these events may be decisive in the sizing of the pumping system. But choosing to use a meteorological record of only one year can lead to the same issue and choosing to use a 20 years file would lengthen proportionally the computation time. Moreover finding real weather records is not easy in every countries, TY files are a lot easier to find under many different name like IWEC (International Weather for Energy Calculation), CWEC (Canadian Weather for Energy Calculation), TMY (Typical Meteorological Year for the US), CTYW (Chinese Typical Year Weather) and many other. The following analysis tries to assess what is the error resulting from the use of TY weather file compared to actual weather files, and if a strategy for mitigating this issue can be found.

3.3.1 Relative error resulting from typical year files

Among the locations studied in 3.2, yearly meteorological records are found to be freely available for Montreal and Denver. For Denver, the data is taken from the NREL Solar Radiation Research Laboratory and covers the year 1991 to 2005 (Andreas, A. & Stoffel, T., 2019). It corresponds to the dataset used for building the last TMY3 weather file for Denver.

Regarding Montreal, meteorological records are available through the website of Environment Canada, under the name of Canadian Weather Energy and Engineering Datasets (CWEEDS). The CWEEDS file used covers the year 1998 to 2014 inclusively and corresponds to the data used for building the CWEC file (CWEC, 2016 ; Natural Resources Canada, 2014). In order to unify the terminology, actual meteorological records are called Weather Year (WY) files in the following.

The PVPS considered for the simulation is the same than the one used in 3.2 and described in Table 3.2, with the difference that the selected pump is 'SCB_10_150_120_BL': a centrifugal DC pump of 1HP. $LLP_{accepted}$ is set at 10%. Resulting outcomes are gathered in Figure 3.5 and Figure 3.6 for Montreal. Figure 3.5 shows the distribution of the total volume of water pumped resulting from the 17 WY files in the form of a boxplot following the same convention than in 3.1, and the equivalent result coming from the CWEC file is shown beside it. The analysis is made for direct coupling and for MPPT coupling, and is also made on the LLP in Figure 3.6.

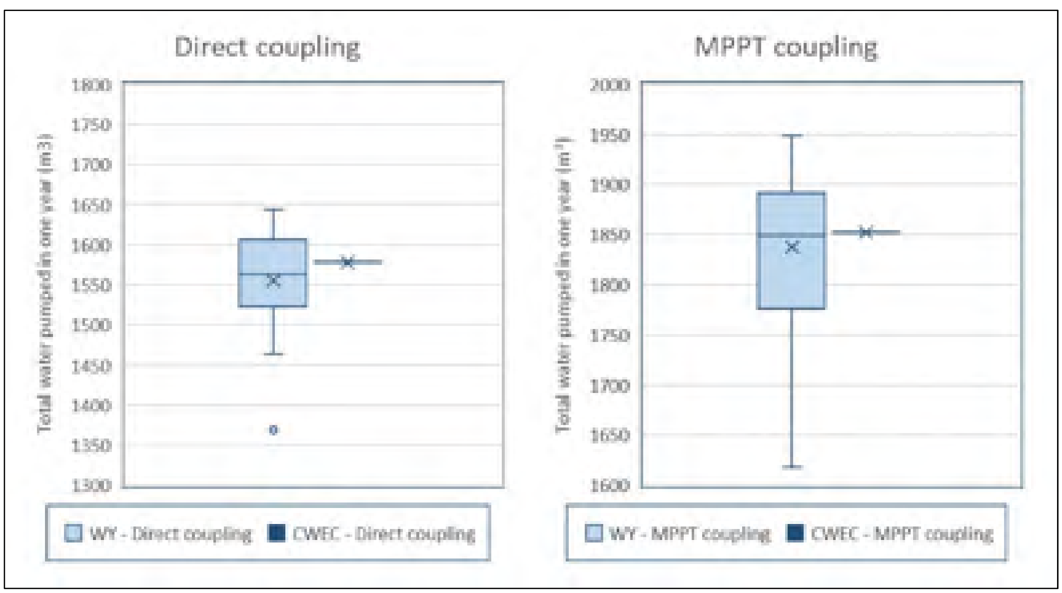

Figure 3.5: Comparison of total volume of water pumped for simulations with WY and CWEC files

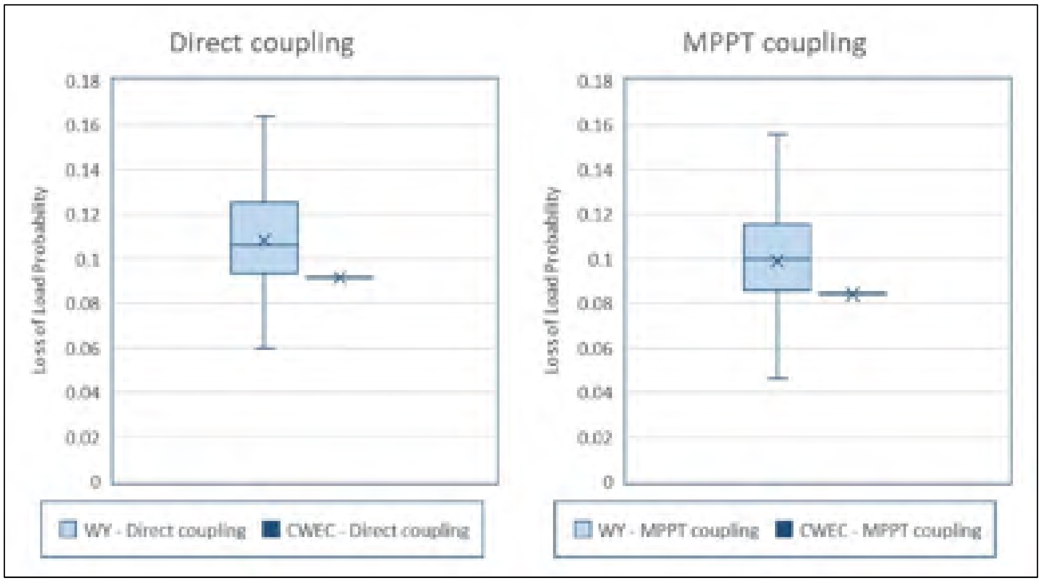

Figure 3.6: Comparison of LLP returned for WY and CWEC files in Montreal

In both direct and MPPT coupling, the total volume of water pumped is more important than the median of the WY files, which logically results in a lower LLP obtained as well. Nevertheless, it can be noticed that the volume of pumped water from CWEC file is located near the median, whereas the LLP value is under the first quartile. The difference in the LLP value between CWEC and WY files is therefore not only explained by the overall quantity of water pumped, but also by the distribution along the year. This is not a surprising outcome as the CWEC file construction is based on an algorithm aimed at levelling the occurrence of extreme weather events, and these events are the same ones that increase the LLP in actual weather year files. Hence, it can be stated that the LLP is significantly underestimated with the use of CWEC file, and the biggest difference between WY and CWEC file is found for the year 2006. When considering this year, the relative error on the volume of water pumped can go up to 15.3% for direct coupling and up to 14.5% for MPPT coupling, whereas relative error on LLP can go up to 44.1% and 46.1%.for direct and MPPT coupling respectively. Concerning Denver similar outcomes are found, but with smaller differences between WY and TMY file. The distributions of resulting LLP are presented in Figure 3.7.

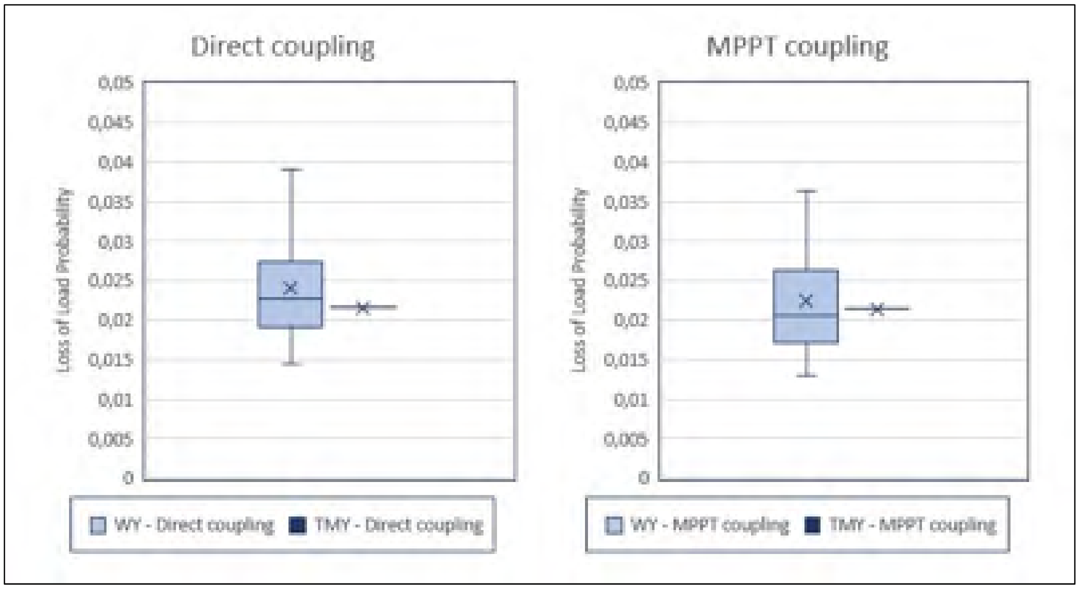

Figure 3.7: Comparison of LLP returned for WY and TMY files in Denver

The LLP of the TMY file is closer to the median and the mean of WY files when compared to Montreal case. This smaller difference can be the logical result of the fact that the weather variability is also smaller in Denver. The worst year is found to be 1995, and the relative error between LLP obtained in 1995 and in TY file is about 44.6% and 41.1% respectively for direct and MPPT coupling, that is to say very close to the figures found for Montreal.

Such relative errors are worrisome if TY weather files are used in order to size critical water pumping systems, and above results should clearly invalidate the use of TY files like CWEC, IWEC or TMY files as it is in such cases.

3.3.2 Safety factor

Nevertheless, as actual weather files are rarely available for most places, it would be interesting to find a way to use TY files in the PVPS sizing. A safety factor is proposed in this purpose. This safety factor can be applied on sizing inputs so as to ensure a sufficient LLP for every year. Applying the safety factor directly on $LLP_{accepted}$ is not possible as it would not work in the case where maximum accepted LLP is near zero. The solution considered here is to apply the safety factor on the water consumption, that is to say to multiply hourly output flow rate by it.

In order to find what would be the value of such a factor, a simple algorithm is used. First, it defines the function described in Figure 3.8. This function sizes the PV array of a PVPS with a CWEC file and with a safety factor higher than 1 considered as the function input. Secondly, it runs a simulation on the sized PVPS, but with the actual weather file of the worst year (2006 or 1995 here) and without safety factor. Then, the function output is the difference between the $LLP_{accepted}$ for the sizing process and the actual LLP resulting from the simulation on actual weather file. The function can then be used in any root finding algorithm in order to find the sufficient safety factor corresponding to the PVPS. In this work, Brent's method (SciPy v1.4.1 Reference Guide, 2020) is used for finding x so as y equals zero.

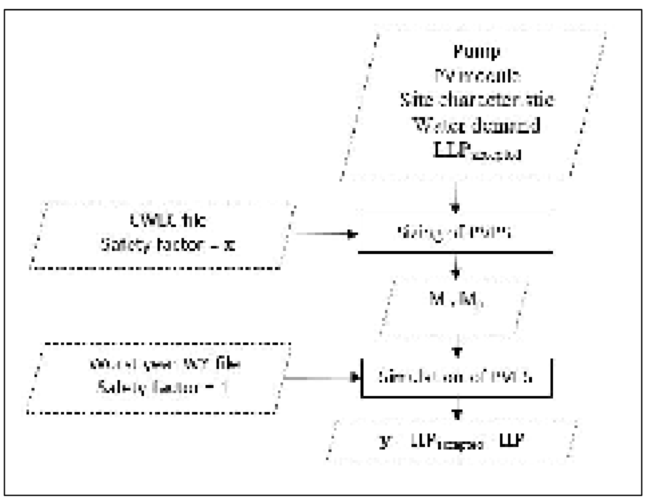

Figure 3.8: Block diagram of function for research of safety factor

This process is used with different $LLP_{accepted}$ values, and the sufficient safety factor is recorded for each. It is found that the safety factor is highly dependant on the accepted LLP, as detailed in Figure 3.9.

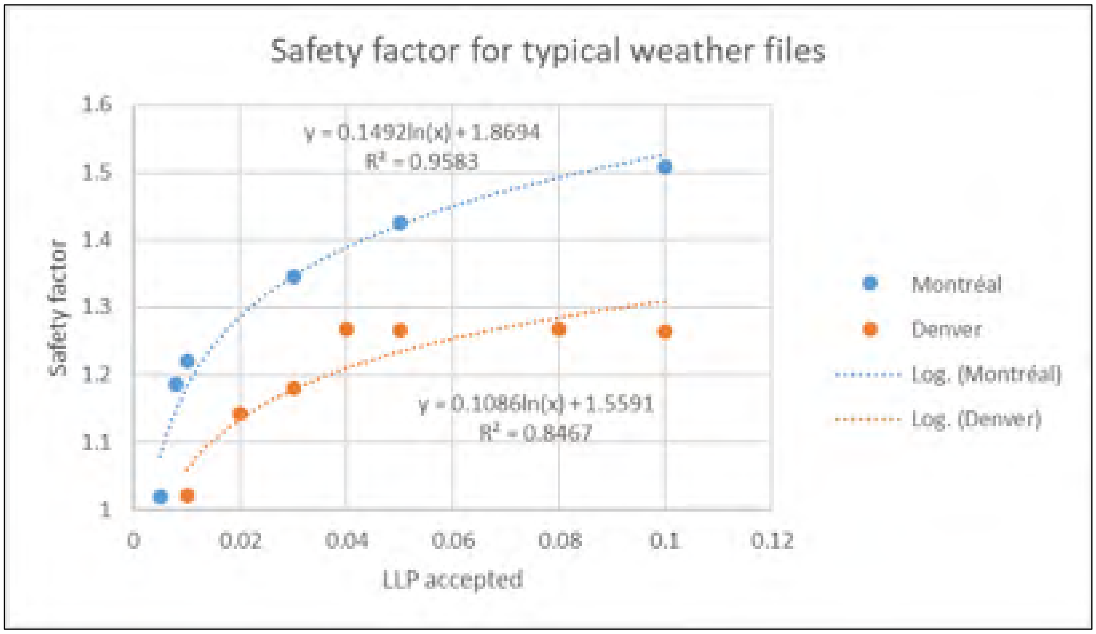

Figure 3.9: Safety factor according to LLP accepted

Interestingly, the more the PVPS is critical - therefore asking for a lower $LLP_{accepted}$ – the less the safety factor needs to be high. This counter intuitive outcome can be explained by the fact that the sizing process with a low $LLP_{accepted}$ already results in an oversize PVPS, therefore making the system more resilient when facing extreme weather events. Figure 3.9 can be used to determine which safety factor to apply depending on $LLP_{accepted}$ during the sizing. It can be expected that the less the local weather variability is, the less the safety factor needs to be important. Therefore, location like Tunis, Nairobi and Aswan would probably not need a safety factor higher that 1.3.

It also can be stated that a safety factor of 1.5 may be used as a general conservative safety factor for all sizing. The result shows that using a higher safety factor would be useless and counterproductive as it would increase the total cost of the system and would reduce the worst year LLP under the $LLP_{accepted}$, which is unnecessary.

CHAPTER 4

DISCUSSION

Pvpumpingsystem, the herein developed software, provides new open source tools for modeling and sizing Photovoltaic Pumping System (PVPS). These tools can help to shed light on some uninvestigated questions in the field of PVPS, and three numerical studies were designed to this end. The results obtained were described in CHAPTER 3, and are discussed and put into perspective in the following in order to underline the contribution of this work among the research field of PVPS.

4.1 Pump models

As discussed in 1.2.5.4 and 1.2.3, pump models for PVPS seems to be the less mature part in the global simulation of PVPS. One contribution of this work is to give a tool for researchers to implement new models for pumps, and to immediately compare with other existing and already implemented model. At the time of writing, four pump models were implemented in *pvpumpingsystem*. Thanks to it, it has been possible to evaluate pumps model through a comparative assessment on function f_1 and f_2. Results tend to show that goodness of fit was expectedly correlated with input data size. A recommendation was made to use Hamidat's model if a MPPT coupling is considered, and to vary the model accordingly to the available data size if data size is lower than 16 data points or if direct coupling is considered.

However, NRMSE values were calculated with the manufacturer specifications as reference, hence it does not necessarily correspond to the average relative error between expectations and measurements on an actual set up. Indeed, the reliability of manufacturer specifications is unknown, and it can be said that the manufacturers even have an incentive to boost the pump specifications in order to be more competitive. Notably, this issue was said to be an important reason for the high relative error in the work of (Jahnig D. et al., 1998 ; Kou et al., 1998). Later research should consider manufacturer data with caution and should try to conduct an assessment on how different are manufacturer specifications, laboratory measurements and field throughput. Moreover, the variability coming from the starting characteristic of the pumps is not assessed and is another direction of research to address in order to improve the accuracy of PVPS simulation.

4.2 Direct coupling potential

The potential of direct coupling was evaluated in 3.2, and was found to be good. Even if the MPPT systems were found to be more cost efficient on average, the least expensive option for each location studied was a direct system. Indeed, if the pump database contains enough pumps, it is likely that the software finds a pump matching well enough with the PV array raw output, and phases out the need for a MPPT. The direct system is therefore cheaper because it avoids the cost of the MPPT. In the simulation this cost is assumed to be repeated twice along the life cycle cost, because of the relatively short lifespan of it. It must be noted that the MPPT lifespan was considered to be 10 years, whereas the PVPS lifespan was considered to be equivalent to the PV modules lifespan, i.e. 30 years. If the MPPT lifespan was considered to be 15 years or more, the MPPT would be replaced only once along the life cycle and MPPT coupled systems would become more cost efficient against direct ones. As the field of photovoltaic technology evolves rapidly, it must be considered that the relative cost difference between direct and MPPT systems can evolve at the same time. The cost efficiency of a well matched direct PVPS can increase if PV module price and lifespan improve faster than for MPPT, and vice-versa.

Another aspect not addressed herein nor in literature reviewed, is the impact of direct coupling on the pump. A pure directly coupled system has no electronics allowing to control the pump input power, therefore it opens the door to voltage and current higher than what the pump was designed for. Therefore, it could cause issues like blown fuse, overheating of armature coils and premature wear of the pump. This potential issue can significantly lower the lifespan of the pump, and eventually make the direct coupling option more expensive than the MPPT option.

From a psychological perspective, it was said that PVPS could face social acceptability challenges as they are perceived as more high-tech than the diesel counterpart (Gualteros Martinez, 2017). On this point, the absence of MPPT can be an asset, as the whole system appears as simpler for members of the community.

4.3 Weather file

As detailed in 1.2.1.1 and 3.3, the weather file type is of prime interest in the simulation of a PVPS. The literature reviewed underlined the fact that some Typical Year (TY) files like TMY and IWEC standards manage to represent a local weather with reasonable relative errors when compared to some other TY construction algorithms or with other data collection methods like satellite or space interpolation. Nevertheless, the average difference on irradiance values between actual meteorological records, called Weather Year (WY), and TY files was not found in the literature. Indeed, as the Sandia algorithm used for constructing TY files selects the most typical months of the dataset with a weighting coefficient of 50% on irradiance, there is little chance that the yearly total irradiance of the TY file differs widely from the average of the WY files used (Wilcox & Marion, 2008, p. 3). But this reasoning is valid for yearly total irradiance only and when the sun power is not critical. As sun power is the only power source for off-grid PVPS, and that PVPS can be used for critical needs like drinking water supply, the difference between TY weather and worst weather year can be crucial.

The non-suitability of TY files as it is for PVPS sizing was demonstrated in 3.3. As it can be expected for irradiance values, the yearly total volume of water pumped varies in a reasonable range between WY and TY files: the maximum relative error is 15%. But in PVPS the distribution of the weather variations matters as well, and this information is captured by the Load Losses Probability (LLP) which is found to vary between 40% and 46% in the worst case. This high relative error was found to be quite stable between MPPT and directly coupled PVPS, and between Montreal and Denver. However, two places are not enough to generalize, and it can be expected that these high relative errors are still dependent on the location. Therefore, such values should not be taken for granted in other places.

Above results were collected by comparing typical year files with the dataset used for building it. As the climate continuously changes towards a warmer and more extreme one, it must be said that there is a high chance that the discussed relative errors are low estimates of what it would be on systems sized nowadays. Indeed, the typical year files can represent correctly the last two decades but is likely to fail to be representative of the two next decades. This uncertainty unfortunately cannot be quantified as of now.

As hourly meteorological records are not available in most of the developing countries where off-grid PVPS are relevant, an attempt is made for enabling the use of TY weather files under condition. This condition is the use of a safety factor applied to the consumption data as a multiplier. For both Montreal and Denver, the sufficient safety factor to apply is found to decrease with the LLP tolerated ($LLP_{accepted}$) during the sizing of the PVPS. This trend is reassuring as it implies that the more the PVPS is critical, the less the safety factor has to be high. This counter-intuitive result comes from the fact that the PVPS is already oversize when a low $LLP_{accepted}$ is considered at the sizing. As a general result, a safety factor of 1.3 is proposed for the sizing of any PVPS whose $LLP_{accepted}$ is under 10% and in climate similar or sunnier than Denver's climate.

However, it has to be reminded that this study considers a water demand not dependent on the weather. If it is a simplification acceptable to a certain extent when considering the water needs of humans, it becomes an oversimplification when considering agriculture where precipitation and evapotranspiration must be taken into account. As a lower irradiance is correlated with greater chances of precipitation, one can expect the safety factor to decrease below 1.3 if this dependence is modeled into the software. This pitfall could be addressed in future work, for example by implementing the work of (Glasnovic & Margeta, 2007) in the software.

4.4 Work limitations

One deception along this work was the impossibility to model any PVPS reported in experimental papers. This is due to the lack of information on the set up, and specifically on the pump, available in experimental papers reviewed. This observation tends to show that PVPS field is affected as well by a reproducibility crisis (Stoddart, 2016), and having a common and open tool for researchers to compare and share their outcomes would be a way to mitigate this crisis. *Pvpumpingsystem* could be used to this end as well, and the herein presented work tries to path the way for it by being fully available in a specified folder called *studies*, contained inside the general package.

Without the possibility of validation through previous experimental papers, and without time for experimental set up, it must be reminded that the tool *pvpumpingsystem* has not been validated with any experimental data so far. If the comparison with experiments is a priority, another way of partial validation was found little time before the end of the present thesis. It consists in running a comparative analysis with *PVsyst* software (PVsyst, s.d.) which can run complete simulation of PVPS as well, and includes the same pumps than the ones used in chapter 3. Having coherent results with *PVsyst* would be encouraging for the validity of *pvpumpingsystem* but does not avoid the need for experimental validation as *PVsyst* is likely to rely on the same models than the ones used herein.

Apart from blind spots previously cited in the three first subsections of chapter 4, an important gap in the proposed software is the absence of any AC pump model. It was justified by the fact that too little information is usually available on these. Nevertheless, AC pumps represent an important part of the currently available pumps on the market, and are generally significantly less expensive than DC pumps, but with lower efficiencies in return. Moreover, DC pumps are often low power pumps, and as soon as a more powerful pump is required, AC pumps appear like inevitable. Around 5 to 10 horsepower seems to be the limit above which DC pumps are unlikely to be available. These AC powerful pumps are typically needed in agriculture, where substantial volumes of water are required. Nevertheless, covering agricultural needs is not the core of this work, as the model used does not consider the precipitation and the evapotranspiration. It can be added that work of (Glasnovic & Margeta, 2007) would be even more useful in the case of powerful pumps because of the risk of water resource depletion associated with higher output flow rate.

On a longer-term perspective, if the proposed software is validated and more widely reviewed, a more user-friendly interface should be considered, in order to make the software accessible to people without a strong technical background.

CONCLUSION

The purpose of the present work was to use a software-based strategy in order to improve the simulation and sizing of Photovoltaic Pumping Systems (PVPS), and eventually to reduce the cost of such systems. Specifically, it was said that the work should:

1. Provide a functional tool to help PVPS installers with sizing.
2. Assess which model to use against others in order to reduce simulation and sizing error.

Both objectives were fulfilled. Indeed, the present work resulted in the design of an open source software named *pvpumpingsystem*, which aggregates various tools for the simulation and sizing of PVPS. The tools mostly consist of direct implementations of models found in reviewed literature. The software is coded in Python following an object oriented and flexible approach, and is made publicly available online on GitHub platform. This approach aims at facilitating participation from other parties interested in pumping system simulation and sizing. *Pvpumpingsystem* is the first software of its kind applied to PVPS in particular. The results concerning the pump models and the weather file influence can then be useful in reducing simulation error and eventually increasing the predictive power of PVPS modeling. They also provide typical relative error assessment helping the PVPS installer to guarantee a certain throughput to the user.

The literature review conducted a global investigation of models used in PVPS simulation and their respective relative errors. It was concluded that pump models and specification completeness of the pumps are key drivers for the accuracy of PVPS modeled throughput. An analysis on goodness of fit yielded by *pvpumpingsystem* software allows for evaluation of the pump models. When enough data is available, Hamidat's model should be used if the pump is coupled to the PV array through a MPPT, whereas Kou's model is recommended in the direct-coupling case, when no power electronics links the PV array and the pump. This direct coupling option was investigated in more detail using the software and then compared to the MPPT coupling. The main outcome is the good potential of direct coupling for decreasing the life cycle cost (LCC) of PVPS. The expected cost decreases were found to range between 2.3%

and 6.6% of the LCC. However, this is only possible provided that the pump input power specifications match particularly well the PV array output characteristics, and that weather is similar to a Mediterranean, arid or tropical climate. If one of the two conditions is not met, then the MPPT coupling option is on average 1% to 11% more cost effective.

Lastly, the influence of the weather file was explored. It was noted that the irradiance variability between typical year files like TMY, CWEC or IWEC, and the actual weather records used for building the mentioned files could yield very significant variations in the yearly Load Losses Probability (LLP) at the PVPS level. The worst relative error on the LLP value resulting from these variations was said to be around 45% for both Montreal and Denver, and for direct and MPPT coupling cases. In order to mitigate the risks of sizing a critical pumping system which would not be able to fulfil the water need in some years, a safety factor is investigated. This safety factor is conceived as a multiplier of the water need and is found to be positively correlated with the LLP tolerated at the sizing (called $LLP_{accepted}$). The value of 1.3 is proposed as a conservative safety factor for any system to be sized with $LLP_{accepted}$ under 10% and located in a sufficiently sunny climate, as defined above.

However, the work research described herein is not without its limitations. First, no comparison with experimental results was undertaken. Therefore, validation and potential correction of the software should be the priority of future research. Subsequently, the research focus can shift to the diversification of *pvpumpingsystem*. Indeed, the proposed software is well suited for domestic water supply systems but may be limited in terms of potential application to agricultural purposes. The two main limitations for it are the absence of AC pumps handling, and the absence of a model for evaluating the water need as function of the weather. These two limitations can be addressed in future work that could be also implemented in *pvpumpingsystem*.

In conclusion, it is hoped that the work presented herein constitutes the first brick of a new tool to improve access to one of the most important resource for humanity: water

APPENDIX I

LIST OF RAW RESULTS FROM MPPT AND DIRECT SIZING FOR TUNIS

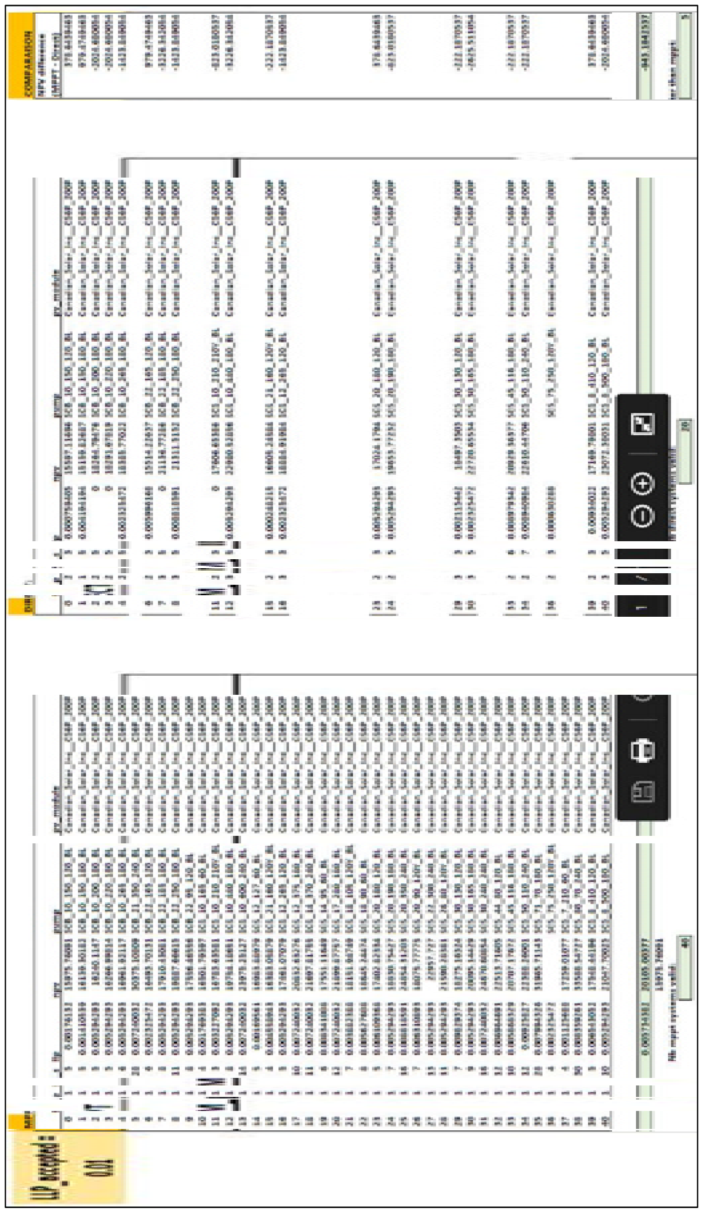

Figure-A I-1: List of raw results from MPPT and direct sizing for Tunis

APPENDIX II

DIRECT SYSTEMS APPLICABILITY AND COST AT LLP = 10%

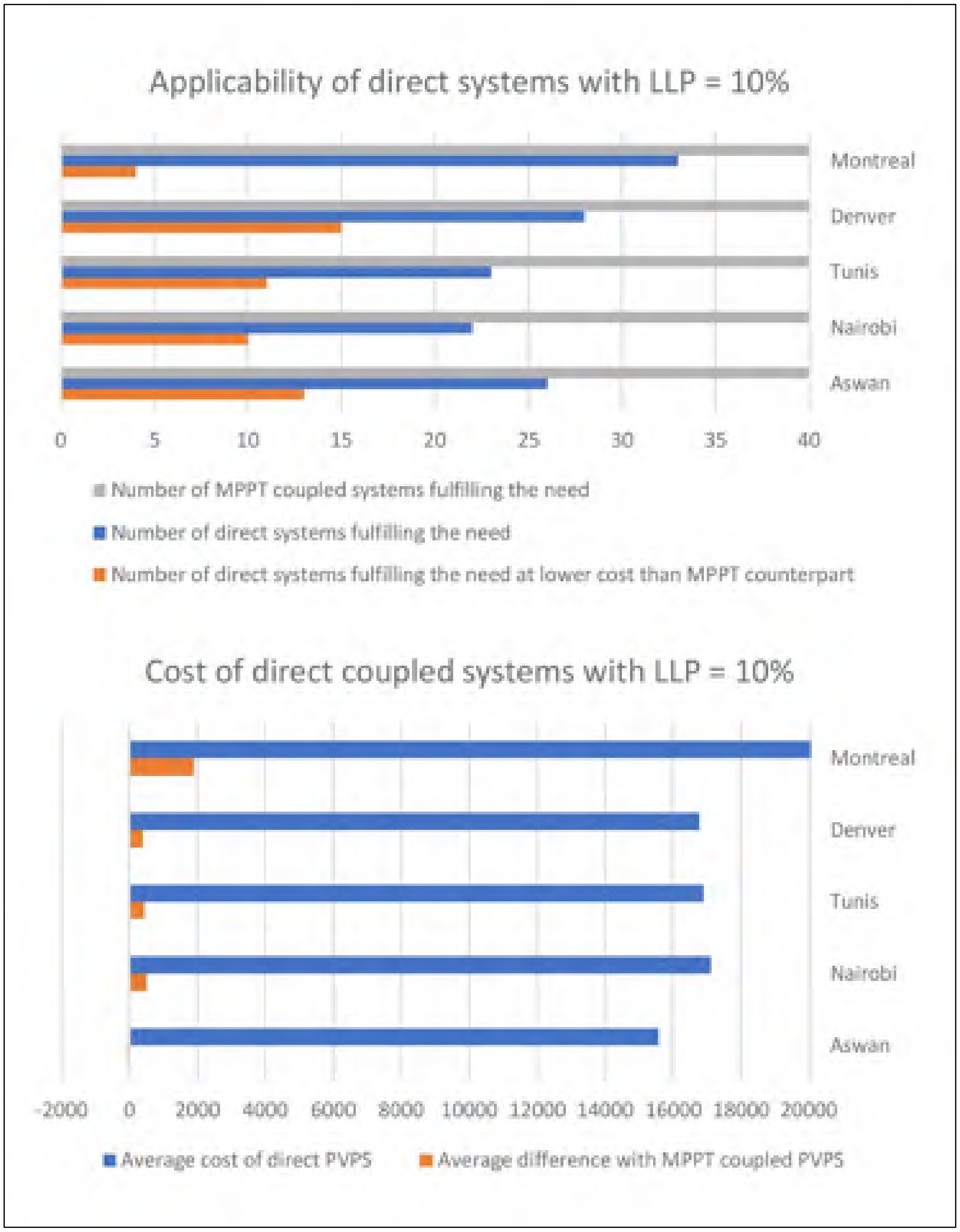

Figure-A II-1: Direct systems applicability and cost at LLP = 10%

LIST OF REFERENCES

Aliyu, M., Hassan, G., Said, S. A., Siddiqui, M. U., Alawami, A. T., & Elamin, I. M. (2018). A review of solar-powered water pumping systems. *Renewable and Sustainable Energy Reviews*, *87*, 61-76. https://doi.org/10.1016/j.rser.2018.02.010

Al-Mofeez, I. A., Numan, M. Y., Alshaibani, K. A., & Al-Maziad, F. A. (2012). Review of typical vs. synthesized energy modeling weather files. *Journal of Renewable and Sustainable Energy*, *4*(1), 012702. https://doi.org/10.1063/1.3672191

Andreas, A., & Stoffel, T. (2019). NREL Solar Radiation Research Laboratory (SRRL): Baseline Measurement System (BMS). https://doi.org/10.5439/1052221

Bakelli, Y., Hadj Arab, A., & Azoui, B. (2011). Optimal sizing of photovoltaic pumping system with water tank storage using LPSP concept. *Solar Energy*, *85*(2), 288-294. https://doi.org/10.1016/j.solener.2010.11.023

Beaty, H. W. (2006). Standard Handbook for Electrical Engineers, 1828.

Bell, C. (s.d.). fluids: Fluid dynamics component of Chemical Engineering Design Library (ChEDL) (version 0.1.75) [Logiciel]. [Python], (S.l.) : (s.n.). Repéré à https://github.com/CalebBell/fluids

Blair, N., Dobos, A. P., Freeman, J., Neises, T., Wagner, M., Ferguson, T., … Janzou, S. (2014). *System Advisor Model, SAM 2014.1.14: General Description* (Rapport No. NREL/TP-6A20-61019). National Renewable Energy Lab. (NREL), Golden, CO (United States). https://doi.org/10.2172/1126294

Bouzidi, B. (2013). New sizing method of PV water pumping systems. *Sustainable Energy Technologies and Assessments*, *4*, 1-10. https://doi.org/10.1016/j.seta.2013.08.004

Campana, P. E., Li, H., & Yan, J. (2013). Dynamic modelling of a PV pumping system with special consideration on water demand. *Applied Energy*, *112*, 635-645. https://doi.org/10.1016/j.apenergy.2012.12.073

Cheremisinoff, N. P., & Cheremisinoff, P. N. (1989). *Pumps/Compressors/Fans - pocket handbook*. (S.l.) : (s.n.).

CWEC. (2016). Updating CWEEDS Weather Files. Repéré à https://drive.google.com/drive/folders/1XxNjhD7SqwtkEd-Bnz3RRNhPEi2kbbO1

David, R. (2017, 6 septembre). The Incredible Growth of Python. *Stack Overflow Blog*. Repéré à https://stackoverflow.blog/2017/09/06/incredible-growth-python/

De Soto, W., Klein, S. A., & Beckman, W. A. (2006). Improvement and validation of a model for photovoltaic array performance. *Solar Energy*, *80*(1), 78-88. https://doi.org/10.1016/j.solener.2005.06.010

Djoudi Gherbi, A., Hadj Arab, A., & Salhi, H. (2017). Improvement and validation of PV motor-pump model for PV pumping system performance analysis. *Solar Energy*, *144*, 310-320. https://doi.org/10.1016/j.solener.2016.12.042

Dobos, A. P. (2012). An Improved Coefficient Calculator for the California Energy Commission 6 Parameter Photovoltaic Module Model. *Journal of Solar Energy Engineering*, *134*(2), 021011. https://doi.org/10.1115/1.4005759

Douglas, J. F. (Éd.). (2005). *Fluid mechanics* (5th ed). Harlow, England ; New York : Pearson/Prentice Hall.

Duffie, J. A., & Beckman, W. A. (2013). *Solar Engineering of Thermal Processes*. (S.l.) : Wiley.

Ebaid, M. S. Y., Qandil, H., & Hammad, M. (2013). A unified approach for designing a photovoltaic solar system for the underground water pumping well-34 at Disi aquifer. *Energy Conversion and Management*, *75*, 780-795. https://doi.org/10.1016/j.enconman.2013.07.083

Glasnovic, Z., & Margeta, J. (2007). A model for optimal sizing of photovoltaic irrigation water pumping systems. *Solar Energy*, *81*(7), 904-916. https://doi.org/10.1016/j.solener.2006.11.003

Gualteros Martinez, S. C. (2017). *Outils d'aides au dimensionnement de systèmes de pompage PV*. ETS Montréal.

Häberlin, H. (2012). *Photovoltaics: System Design and Practice*. Chichester, UK : John Wiley & Sons, Ltd. https://doi.org/10.1002/9781119976998

Hadj Arab, A., Benghanem, M., & Chenlo, F. (2006). Motor-pump system modelization. *Renewable Energy*, *31*(7), 905-913. https://doi.org/10.1016/j.renene.2005.06.003

Hamidat, A., & Benyoucef, B. (2008). Mathematic models of photovoltaic motor-pump systems. *Renewable Energy*, *33*(5), 933-942. https://doi.org/10.1016/j.renene.2007.06.023

Hamidat, A., & Benyoucef, B. (2009). Systematic procedures for sizing photovoltaic pumping system, using water tank storage. *Energy Policy*, *37*(4), 1489-1501. https://doi.org/10.1016/j.enpol.2008.12.014

Holmgren, W. F., Hansen, C. W., & Mikofski, M. A. (2018). pvlib python: a python package for modeling solar energy systems. *Journal of Open Source Software*, *3*(29), 884. https://doi.org/10.21105/joss.00884

IRENA. (2016). *Solar pumping for irrigation: Improving livelihoods and sustainability*.

Jafar, M. (2000). A model for small-scale photovoltaic solar water pumping. *Renewable Energy*, *19*(1), 85-90. https://doi.org/10.1016/S0960-1481(99)00020-8

Jahnig D., Klein S.A., & Beckman W.A. (1998). *Experimental Validation of Photovoltaic Pumping System Models*. University of Wisconsin - Madison.

Kaldellis, J. K., Spyropoulos, G. C., Kavadias, K. A., & Koronaki, I. P. (2009). Experimental validation of autonomous PV-based water pumping system optimum sizing. *Renewable Energy*, *34*(4), 1106-1113. https://doi.org/10.1016/j.renene.2008.06.021

Khatib, T., & Elmenreich, W. (2016). *Modeling of Photovoltaic Systems Using MATLAB*. (S.l.) : Wiley.

King, D. L., Kratochvil, J. A., & Boyson, W. E. (2004). *Photovoltaic array performance model.* (Rapport No. SAND2004-3535, 919131). https://doi.org/10.2172/919131

Kolhe, M., Joshi, J. C., & Kothari, D. P. (2004). Performance analysis of a directly coupled photovoltaic water-pumping system. *IEEE Transactions on Energy Conversion*, *19*(3), 613-618. https://doi.org/10.1109/TEC.2004.827032

Kou, Q., Klein, S. A., & Beckman, W. A. (1998). A method for estimating the long-term performance of direct-coupled PV pumping systems. *Solar Energy*, *64*(1-3), 33-40. https://doi.org/10.1016/S0038-092X(98)00049-8

Kumar, R., & Umanand, L. (2005). Estimation of global radiation using clearness index model for sizing photovoltaic system. *Renewable Energy*, *30*(15), 2221-2233. https://doi.org/10.1016/j.renene.2005.02.009

Li, G., Jin, Y., Akram, M. W., & Chen, X. (2017). Research and current status of the solar photovoltaic water pumping system – A review. *Renewable and Sustainable Energy Reviews*, *79*, 440-458. https://doi.org/10.1016/j.rser.2017.05.055

Loutzenhiser, P. G., Manz, H., Felsmann, C., Strachan, P. A., Frank, T., & Maxwell, G. M. (2007). Empirical validation of models to compute solar irradiance on inclined surfaces for building energy simulation. *Solar Energy*, *81*(2), 254-267. https://doi.org/10.1016/j.solener.2006.03.009

Martiré, T., Glaize, C., Joubert, C., & Rouvière, B. (2008). A simplified but accurate prevision method for along the sun PV pumping systems. *Solar Energy*, *82*(11), 1009-1020. https://doi.org/10.1016/j.solener.2008.05.005

Meunier, S., Heinrich, M., Quéval, L., Cherni, J. A., Vido, L., Darga, A., … Marchand, C. (2019). A validated model of a photovoltaic water pumping system for off-grid rural communities. *Applied Energy*, *241*, 580-591. https://doi.org/10.1016/j.apenergy.2019.03.035

Mokeddem, A., Midoun, A., Kadri, D., Hiadsi, S., & Raja, I. A. (2011). Performance of a directly-coupled PV water pumping system. *Energy Conversion and Management*, *52*(10), 3089-3095. https://doi.org/10.1016/j.enconman.2011.04.024

Monteoliva, J., Villalba, A., & Pattini, A. (2017). Variability in dynamic daylight simulation in clear sky conditions according to selected weather file: Satellite data and land-based station data. *Lighting Research & Technology*, *49*(4), 508-520. https://doi.org/10.1177/1477153515622242

Muhsen, D. H., Khatib, T., & Nagi, F. (2017). A review of photovoltaic water pumping system designing methods, control strategies and field performance. *Renewable and Sustainable Energy Reviews*, *68*, 70-86. https://doi.org/10.1016/j.rser.2016.09.129

N. Chandrasekaran, B. Ganeshprabu, & Dr. K. Thyagarajah. (2012). Comparative Study of Photovoltaic Pumping System Using a DC Motor and PMDC Motor. Piscataway, NJ : IEEE.

Natural Resources Canada. (2014, 14 janvier). Solar resource data available for Canada. Repéré à https://www.nrcan.gc.ca/energy/energy-sources-distribution/renewables/solar-photovoltaic-energy/solar-resource-data-available-canada/14390

Nik, V. M., & Arfvidsson, J. (2017). Using Typical and Extreme Weather Files for Impact Assessment of Climate Change on Buildings. *Energy Procedia*, *132*, 616-621. https://doi.org/10.1016/j.egypro.2017.09.686

Olsson, A., Campana, P. E., Lind, M., & Yan, J. (2015). PV water pumping for carbon sequestration in dry land agriculture. *Energy Conversion and Management*, *102*, 169-179. https://doi.org/10.1016/j.enconman.2014.12.056

Peel, M. C., Finlayson, B. L., & Mcmahon, T. A. (2007). Updated world map of the Köppen-Geiger climate classification. *Hydrology and Earth System Sciences Discussions*, *4*(2), 439-473.

PVsyst. (s.d.). PVsyst 6 Help. Repéré à https://www.pvsyst.com/help/index.html

Remund, J. (2008, 1 janvier). *Quality of Meteonorm Version 6.0*. [Meteotest Report], Bern, Switzerland. Manuscrit soumis pour publication. Repéré à https://www.researchgate.net/publication/241491372_Quality_of_Meteonorm_Version_60

SciPy v1.4.1 Reference Guide. (2020). brentq root finding algorithm description. *scipy.org*. Repéré à https://docs.scipy.org/doc/scipy/reference/generated/scipy.optimize.brentq.html#rcf302ff4bf60-brent1973

Shannan, N. M. A. A., Yahaya, N. Z., & Singh, B. (2013). Single-diode model and two-diode model of PV modules: A comparison. Dans *2013 IEEE International Conference on Control System, Computing and Engineering* (pp. 210-214). https://doi.org/10.1109/ICCSCE.2013.6719960

Singer, S., & Appelbaum, J. (1993). Starting characteristics of direct current motors powered by solar cells. *IEEE Transactions on Energy Conversion*, *8*(1), 47-53. https://doi.org/10.1109/60.207405

Skeiker, K. (2007). Comparison of methodologies for TMY generation using 10 years data for Damascus, Syria. *Energy Conversion and Management*, *48*(7), 2090-2102. https://doi.org/10.1016/j.enconman.2006.12.014

Stoddart, C. (2016). Is there a reproducibility crisis in science? *Nature*. https://doi.org/10.1038/d41586-019-00067-3

SunPumps. (s.d.). Sun Pumps - Providing Solar Pumping Products and Power System. Repéré à https://sunpumps.com/#

Tantos, A. (2011a). How to Read Motor Datasheets. *Modular Circuits*. Repéré à http://www.modularcircuits.com/blog/articles/bridge-to-the-far-side/how-to-read-motor-datasheets/

Tantos, A. (2011b). Motor Modeling. *Modular Circuits*. Repéré à http://www.modularcircuits.com/blog/articles/bridge-to-the-far-side/motor-modeling/

United Nations. (s.d.). Regional focus: Africa | International Decade for Action « Water for Life » 2005-2015. Repéré à https://www.un.org/waterforlifedecade/africa.shtml

Wilcox, S., & Marion, W. (2008). *Users Manual for TMY3 Data Sets*. NREL.

Wong, S. (2019). Decentralised, Off-Grid Solar Pump Irrigation Systems in Developing Countries—Are They Pro-poor, Pro-environment and Pro-women? Dans P. Castro, A. M. Azul, W. Leal Filho, & U. M. Azeiteiro (Éds), *Climate Change-Resilient Agriculture and Agroforestry: Ecosystem Services and Sustainability* (pp. 367-382). Cham : Springer International Publishing. https://doi.org/10.1007/978-3-319-75004-0_21

World Health Organization. (2013). Technical notes on drinking-water, sanitation and hygiene in emergencies. Repéré à https://www.who.int/water_sanitation_health/publications/2011/WHO_TN_09_How_much_water_is_needed.pdf

World Health Organization. (2019). Drinking-water. Repéré à https://www.who.int/news-room/fact-sheets/detail/drinking-water