Development of Analytical Strategies to Optimize the Use of Photovoltaic Water Pumping Systems

An optimization approach

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Declaration

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

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Abstract

The introduction of solar-powered water pumping systems has become a viable alternative for farmers for irrigation and water supply around the world. However, access to water in the most remote areas of the world is limited. To ensure a reliable water supply, solar-powered water pumping systems need to be efficient and sustainable. This thesis examines the development of analytical strategies to maximize the effectiveness of the use of photovoltaic systems in water pumping systems. As a result, the thesis focuses on developing accurate models of the subsystems of solar-powered water pumping systems. The goal is to have reliable models in order to obtain the best subsystem efficiency solutions. Therefore, a model for the simulation of PV arrays and the motor-pump unit is developed and implemented in a Matlab environment. When the behavior of the subsystems is accurately modeled, it is possible to prioritize and maximize the total efficiency of the system by the correct choice of components. However, the comparative analysis showed that the efficiency is strongly related to the environmental circumstances of the investigated locations. As a consequence, not every location is suitable for standalone solar-powered water pumping systems and potentially needs a backup power source to avoid oversizing the PV array. In addition to the critical analysis of the results, potential bottlenecks, such as space and location constraints, are identified. On the basis of this analysis, tasks for future work and potential extensions of the models are introduced.

Keywords: PV water pumping, Solar-based water pumping system, Irrigation, Energy efficiency

Resumo

A introdução de sistemas de bombagem de água alimentados por energia solar tornou-se uma alternativa viável para os agricultores no que respeita à irrigação e ao abastecimento de água em todo o mundo. No entanto, o acesso à água nas zonas mais remotas do mundo é limitado. Para garantir um abastecimento de água fiável, os sistemas de bombagem de água alimentados a energia solar têm de ser eficientes e sustentáveis. Esta tese examina o desenvolvimento de estratégias analíticas para maximizar a eficácia da utilização de sistemas fotovoltaicos em sistemas de bombagem de água. Como resultado, a tese centra-se no desenvolvimento de modelos precisos dos subsistemas de sistemas de bombagem de água alimentados por energia solar. O objetivo é dispor de modelos fiáveis para obter as melhores soluções de eficiência dos subsistemas. Assim, é desenvolvido e implementado em Matlab um modelo para a simulação de sistemas PV e da unidade motor-bomba. Quando o comportamento dos subsistemas é modelado com precisão, é possível estabelecer prioridades e maximizar a eficiência total do sistema através da escolha correcta dos componentes. No entanto, a análise comparativa mostrou que a eficiência está fortemente relacionada com as circunstâncias ambientais dos locais em análise. Consequentemente, nem todos os locais são adequados para sistemas autónomos de bombagem de água alimentados por energia solar e necessitam potencialmente de uma fonte de energia de reserva para evitar o sobredimensionamento do conjunto PV. Para além da análise crítica dos resultados, são identificados potenciais constrangimentos, tais como limitações de espaço e de localização.

Palavras-chave: Bombagem de água fotovoltaica, Sistema solar de bombagem de água, Irrigação, Eficiência energética

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List of Symbols

The next list describes several symbols that will be later used within the body of the document

$_{i}$	Ef ciency
I_{l}	Light current (Also:Photocurrent)
P_{p}	Peak power
R_{sh}	Parallel Resistance
R_{s}	Series Resistance
A	Area
a	Diodes ideality factor
G	Solar irradiance
g	Gravity acceleration
G^{r}	Irradiance at STC
I_{mp}	Current at maximum power
I_{sc}	Short circuit current
K	Kelvin
k	Bolzmann constant
P_{i}	Power
Q	Water ow rate
T	Temperature
T^{amb}	Ambient temperature
T^{r}	Temperature at STC
V_{mp}	Voltage at maximum power
V_{oc}	Open circuit voltage
vt	Thermal voltage
	Density
V	Volume of water tank

List of Acronyms

AC Alternating current

AP Acidi cation potential

ARDP Abiotic resource depletion potential

BOS Balance of system

DC Direct current

DWP Diesel water pumping

FRDP Fossil resource depletion potential

GWP Global warming potential

HTP Human toxic potential

ICC Initial investment cost

LCA Life cycle assessment

LCC Life cycle cost

MBE Mean bias error

MPPT Maximum Power Point Tracking

NOCT Normal operating conditions temperature

NREL National Renewable Energy Laboratory

PV Photovoltaic

PVWP Photovoltaic water pumping

RMSE Root mean square error

SPWPS Solar powered water pumping system

STC Standard Test Conditions

TDH Total dynamic head

Chapter 1

Introduction

1.1 Background

1.1.1 Challenges

The United Nations has set an important objective: to ensure the availability and sustainable management of water and sanitation for all people around the world. This imperative has become a pressing global issue driven by population growth, ongoing urbanization, and the growing demand for water from agriculture and other sectors. These trends have led to the unfortunate reality that billions of people do not have access to clean water. The challenges associated with water scarcity are further compounded by climate change, aggravating the situation [49]. Today, more than 1.1 billion people lack access to clean water, and estimates suggest this gure could increase to up to 3 billion by 2025 [56]. This problem is of great concern because freshwater plays a crucial role in the maintenance of the health of ecosystems and is essential for human survival [25]. Access to clean water is not just a fundamental human need. It directly results in improved health and overall well-being [49].

Water scarcity

Water scarcity is a fundamental problem. To highlight the severity Figure 1.1 is introduced. The graphic provides insight into global water stress levels. The regional disparities in these challenges are particularly evident. Northern Africa is experiencing levels of critical water stress that exceed 100%, while southern and central Asia is grappling with stress levels that exceed 75% [49]. This phenomenon is strongly related to intense irrigated agriculture and people competing for water in highly populated areas, especially where water resources are scarce due to climate conditions. To highlight the footprint of the agricultural sector Figure 1.2 is introduced. The graphic shows that the sector contributes greatly to the global level of water stress. The in uence of agricultural activities in the form of water withdrawal is particularly strong for the regions of Central, Eastern, and Western Asia, as well as for Northern and Western Africa, contributing between 75% and 100% to water stress [16].

Figure 1.1: Level of global water stress [16]

Figure 1.2: Level of global water stress due to the agricultural sector [16]

The excessive utilization of water resources creates shortages in available water supply. The resulting alterations in the global water cycle are induced by profoundly water-intensive activities, which are aggravated by climate change. Predominantly, groundwater extraction is the method of withdrawal [25]. Two major concerns need acknowledgment and proactive mitigation:

1. Resource Depletion: Resource depletion occurs when water extraction surpasses the source's regeneration over time. This may result in the unavailability of the source for future use.

2. Competition for freshwater: When there is competition for the water source, the extraction or use of one user can in uence the availability of other users. This hinders the access to the source for all potential users [25].

Carbon footprint of the agriculture sector

Another challenge is the carbon footprint of the agriculture sector. Agriculture, forestry, and other land use are responsible for approximately 24% of global anthropogenic greenhouse gas emissions [26]. The sector is vulnerable to climatic changes due to its dependence on climatic conditions. The industry is

faced with these dif culties in ensuring the availability of food, agricultural income, jobs, and ecological bene ts. However, the sector can play an important role in contributing to the global strategy to adapt to climate change. This means that the agricultural sector is part of a global solution that includes mitigation policies and adaptation strategies to climate change, which ultimately lead to more inclusive and sustainable outcomes [22]. The stated facts are a clear indicator that agriculture is set to reduce its greenhouse gas emissions to overcome the challenges the sector faces on a global scale.

1.1.2 The role of Solar-Powered Water Pumping Systems

The question arises of what measures can mitigate the facts as stated.

1. How is it possible to ensure access to fresh water even in the world's most remote areas?

2. How is it possible to do so in an environmentally friendly way to mitigate the impacts of climate change?

3. How can this be applied to the agricultural sector as one of the drivers of water scarcity and climate change?

A promising answer to these questions may be the role of solar-powered water pumping systems. To enable access to water in the most remote areas in the world where water is still needed, solar-powered water pumping systems can help. These remote areas of the world usually have limited access to electricity, so solar-powered water pumping systems have become an important factor in ensuring the supply of fresh water [52]. Additionally, fuel transport for conventional water supply systems can be cost-intensive and linked to a large logistics effort, making solar-powered water supply solutions a relevant technology [53]. In addition, solar energy is an abundant and environmentally friendly energy source, available almost everywhere worldwide, making the technology usable almost everywhere [50]. The environmental bene t of using solar-powered water pumping systems is connected to the global energy transition effort, which leads to an exponential expansion of renewable energy sources worldwide. Consequently, by using a renewable source to power the water supply, the effects of climate change can be mitigated [53]. This is because solar-powered water pumping systems have several advantages over conventional pumping methods, such as being cheaper and exhibiting reduced pollution in both, noise and emissions [52]. Additional advantages such as long service life, independent fuel chain supply, low maintenance, and easy scalability describe this technology, making it an environmentally friendly and reliable solution [53]. Agriculture serves as a supplier of food and raw materials [51]. In agriculture worldwide, irrigation is a well-established and necessary practice [50]. However, agriculture is considered one of the main water users on a global scale, resulting in a use of 60% to 90% of the total available water, depending on the region and other factors. According to Velasco-Muñoz et al., the question of sustainability has become more prominent in recent years in research. Researchers are more focused on issues of climate change, environmental impacts, innovation in irrigation technology, water use ef ciency, and many more in agriculture. These trends are a clear indicator of the direction of future innovation [51]. Originally, irrigation systems in agriculture were designed to run on conventional energy. However, the introduction of solar-powered water pumping systems can be a viable alternative for farmers. This technology increases the ef ciency of water use while simultaneously contributing to socio-economic development. In general, it is an easy-to-implement and environmentally friendly solution for the irrigation of elds [50].

1.2 Objectives

The research question of this thesis results in the following:

- ”What is an effective strategy for optimizing the energy ef ciency and overall performance of solar-powered water pumping systems across diverse environmental conditions, and how can this strategy be tailored to speci c geographic locations to ensure sustainable and reliable water supply?”

The research question is addressed by developing analytical strategies to optimize the use of photovoltaic systems in water pumping systems. As a result, the thesis focuses on developing accurate models of the subsystems of solar-powered water pumping systems, enabling us to prioritize and optimize the total ef ciency of the system. The objective is added by implementing operating ranges of the system for any given location, enabling usage of the technology almost everywhere around the world. In detail, this means that the rst step is to implement an accurate model for the photovoltaic array, which illustrates the behavior of photovoltaic panels that can be exposed to different external in uences. The idea is to have a reliable model of a photovoltaic array, which allows us to identify the best subsystem ef ciency solutions. In addition, a motor-pump model is developed. The motor-pump model is supposed to take into account external parameters such as the needed height and the required out ow. The idea behind the model is to illustrate possible motor-pump set combinations that demonstrate the best subsystem ef ciency. Both models are implemented in Matlab. When both models are linked, it is possible to obtain an optimized component selection algorithm that focuses on maximizing energy ef ciency from the source of energy to the actual use of water.

1.3 Thesis Structure

This thesis is divided into six chapters:

- Chapter one: Introduction
  This chapter serves to highlight the motivation, as well as the objective and structure of the thesis.

- Chapter two: Main Principles of Photovoltaic Water Pumping Systems
  This chapter comprehensively reviews the main principles related to photovoltaic water pumping systems. It introduces the components, the supporting structures, the reliability, and optimization approaches of the system from an economic point of view, and gives information on the existing software used.

- Chapter three: Methodology
  Chapter three is the essential part of the thesis. With the introduction of the original methodology for sizing a photovoltaic water pump system, we developed a new methodology to establish operating ranges. The important design parameters of the system, including all different subsystems, are introduced.

- Chapter four: Modelization
  This chapter looks at the elaborated methodology and models the individual subsystems. A model for the photovoltaic array and the motor-pump unit of the system is introduced. The coupling model of both individual models is developed at the end of the chapter.

- Chapter ve: Case Studies and Results
  Chapter ve includes two case studies for different locations in the world, one in Portugal and the

other in Germany. The idea is to validate the methodologies and models developed and to present and analyze the results.

- Chapter six: Conclusions and Future Work
  The last chapter serves as the conclusion of the thesis. Potential bottlenecks are identi ed and the results are critically questioned. On the basis of this analysis, the tasks for future work, potential extensions of the models, and the methodology are introduced.

Chapter 2

Principles of photovoltaic water pumping systems

2.1 Components

The rst step is to introduce the components used in the systems studied in this research. There are several con gurations for SPWPS. They form an integration of various subsystems, including electrical, mechanical, and electronic components [33]. The classi cation of the technology can be seen in Figure 2.1.

Figure 2.1: Classi cation of SPWPS [33]

The distinction is made between solar thermal, solar photovoltaic, and solar photovoltaic and thermal

systems, the so-called hybrid systems. Each division can be subdivided according to the technology. Isolated standalone solar photovoltaic systems for water pumping are of great importance for areas with limited access to the electricity grid and electricity in general. The use is related to the ability to provide bene ts for remote locations, such as continuous water supply. This plays a vital role in improving the livelihoods in these areas. When direct-driven approaches are used, conversion losses of inverters are prevented. This is the most simple form of running solar-powered water pumping systems. Therefore, the different components always depend on the given load, the nature of the supply, and the converter /MPPT con guration. The other form of standalone system is battery-driven systems. However, in direct-driven DC con gurations, the additional costs related to the DC pumps possibly erase the bene t of reducing the conversion losses. The technology strongly depends on the circumstances in which the system is operating. The ultimate goal is to create a system that includes subsystems that focus on maximizing ef ciency, including the highest energy conversion combined with the maximum water output [33].

System description

A representative system is shown in Figure 2.2. The gure shows one possible con guration of a SPWPS. In practice, the systems can vary in con guration. The different possible con gurations with a focus on the components are explained in the following paragraph. It is important to note that the different layouts strongly depend on geographical and on-site conditions. These factors include mainly location, temperature, solar insolation, water requirements, ow rate, ow head, etc. [33].

Figure 2.2: Representative solar powered water pumping system [20]

This system can be subdivided into working principles. The two main working principles of SPWPS are summarized in two ow charts: Figure 2.3 shows the DC con guration with direct coupling of a SPWPS for irrigation, while Figure 2.4 shows the AC con guration, respectively. Both systems convert solar energy into electrical energy and, subsequently, into mechanical energy [52]. These systems are considered generalized representations, meaning other possible con gurations may exists.

Figure 2.3: Generalised representation of a SPWPS for irrigation DC - coupled - Modi ed and adapted from [52]

Figure 2.4: Generalised representation of a SPWPS for irrigation AC - coupled - Modi ed and adapted from [52]

Although the gures demonstrate the core principles, they do not cover the full range of potential components that could be incorporated into the setup, including technologies such as MPPT, battery backup systems, and various others, which will be discussed in the following paragraph.

System components

Depending on the con guration, the various components of the system are:

1. PV array

   The PV array is the power source of the irrigation system [35]. The array consists of PV modules connected in parallel or in series depending on the voltage and current output needed in the system. The PV cells convert sunlight irradiance into electricity[52]. The PV energy is considered a non-linear power source, which means that both the output current and the output voltage depend on the radiation level and temperature to which the panel is exposed to [28].

   Photovoltaic Effect

   In a PV cell there is a conversion process that converts the energy received from the sun into electricity [53]. A solar cell is a p-n junction [5]. The working principle of the solar cell can be

broken down into three fundamental procedures, which are better explained by using the graphic shown in Figure 2.5. The gure shows the fundamentals of the photovoltaic effect.

Figure 2.5: PV Effect [53]

The photovoltaic effect is initiated by the absorption of photons from sunlight. In the p-n junction, this generates charge carriers, called electron-hole pairs. If this energy is higher than the band gap energy of the material of which the semiconductor is composed, then an electron is used to excite another electron at the valence level to the conduction band. Inside the p-n junction, the n-type material is at a higher energy level than the p-type material. Consequently, when the photon is absorbed, the electron from the valence band of the p-type material is excited to the conduction band of the n-type material. The resulting excess energy is later dissipated in the form of heat in the semiconductor material. When the electron reaches the conduction band, the electron moves further to the n-type side, whereas, parallel to this, a positive charge hole is created on the p-type side because of the electric eld in the junction. This separation creates a potential difference across the p-n junction, which means that the separated electrons can drive an electric circuit. As a consequence, an electric current is generated. When the electrons pass through the electric circuit, the holes are recombined [5].

This process occurs in each individual photovoltaic cell, which as a consequence, has only a small voltage and current. To generate a higher amount of voltage and current, photovoltaic cells are put together in various forms, such as different series and parallel con gurations. This enables the industry to produce solar panels with various electrical characteristics [53].

Types of PV solar cells

Solar panels consist of multiple solar cells connected in series or in parallel depending on the power output[5]. Different types of solar cells are based on the primary active materials used. The technologies are divided into four generations. The rst generation are thick crystalline lms. These include monocrystalline and polycrystalline gallium arsenide (GaAs) and silicon technologies. The technology changed to thin- lm solar cells in the second generation of photovoltaic cells. These mainly include the development of the rst generation by drifting towards thin- lm technologies, with its most prominent representatives such as microcrystalline silicon, amorphous silicon, or copper indium gallium selenide. The third generation describes emerging technologies such as more recent chemical compounds like organic solar cells. The fourth generation con-

sists of a hybrid approach. Low cost and exibility in the formation of thin- lm polymers combine with the durability approaches of innovative inorganic materials, such as nanostructures. All of the mentioned technologies vary in their characteristics because of the nature of the materials. This results in different band gaps, electrical performances, and ef ciencies. However, the most used technology is silicon-based solar cells, which contribute to more than 80% of the installed worldwide capacity, while having a market share of 90% [37].

2. Additional components
   Additional components describe the BOS. These components may include any kind of wiring between components, switches, mounting structures, etc. The BOS is responsible for making sure that the SPWPS is properly installed and that the operation is working without errors [53].

3. Control system/MPPT
   The control system in SPWPS is complex due to the variety of energy conversion units. Controllers must not only consider regulating the voltage on the side of the PV array, but also control the motor output speed, maintain water ow while facing external in uences such as atmospheric conditions, and potentially shut down the system in unfavorable conditions [33]. The controller regulates the voltage between the PV array and the motor to meet the motor load requirements[35]. Several control systems are based on MPPT technologies, such as fuzzy logic approaches, arti cial neural networks, incremental conductance, etc. Of the mentioned controllers, only a few have been implemented and tested in SPWPS, mostly fuzzy logic controllers [33].

4. Power converters
   The power converter unit is a crucial component of the SPWPS setup [33]. Depending on which type of motor and con guration of the system is used, an inverter or converter may be necessary. The characteristics of the PV array are non-linear, resulting in the challenge of extracting the maximum available power [33]. Naturally, there are changes in insolation on the PV array, which consequently leads to the output voltage of the PV array uctuating [18]. The PV array can only achieve the maximum power output at a very speci c voltage and current level [19]. The power converter unit regulates voltage levels and works simultaneously with the MPPT to interface with the electricity grid (only if the grid is connected, not for isolated systems) and to correct the power factor[33]. There are different power converter con gurations. On the DC side, the two conventional converter types are buck and boost converters [18]. Generally, for SPWPS, almost 30% of the converters used are boost converters, followed by almost 20% for buck-boost converters and nearly 12.5% for buck converters [33]. Typical values of inverter ef ciencies vary between 80 and 90%, with a tendency to increase [13].

5. AC/DC Motor
   The motor converts the electrical input of the PV array into mechanical energy to drive the water pump [35]. There are several pump system con gurations on the market. The different characterization can be seen in Figure 2.6, which shows a classi cation of all electrical machines commonly used for SPWPS.

Figure 2.6: Different types of commonly used electrical machines for solar water pumping systems adapted from [18]

The primary factor in deciding between an AC or DC motor is the ef ciency of the system, cost, availability, size, and power input. The key advantage of DC motors is that they do not need any inverter and can directly utilize the generated DC power. AC motors, in contrast, tend to have lower system ef ciency due to conversion losses [52].

The types of electrical machines used for SPWPS can be categorized according to their application. The electrical machine is either a DC or AC machine. The DC machines are subdivided into brush DC and brushless motors, and the AC machines are subdivided into common induction and synchronous motors. The different motors show different characteristics in terms of suitability in SPWPS. For smaller applications of water pumping, the motors con gured in DC can be directly connected to the PV array. When the application of water pumping becomes larger, DC motors become increasingly more expensive due to the necessity of commuting tools and compensation windings. Additionally, they reduce reliability and increase potential maintenance costs, especially in the humid environment where the pump operates. Brushed permanent magnet DC motors usually use a power of up to 5 kW in photovoltaic pumping systems, while brushless DC motors are not very common, as they need advanced control and feedback loops. AC motors instead outweigh DC motors in relevance when it comes to pumping applications. The primary bene ts of these items are their affordability, durability, availability in a variety of power levels, high power density, and minimal maintenance. However, the disadvantages lie in the necessity of a control system (inverter), the need for a high starting current, low starting torque, and ef ciency drops at low loads. In general, there is no preferable electrical machine for SPWPS. The speci c application and its requirements decide the selection. The author also states that pump manufacturers may sometimes not even have the option to select the type of electrical machine because the motor and pump are already one unit in the same casing [18].

6. Water pump

   The water pump is used to transfer water from its source to the point of use or storage. [35]. Pumps convert the kinetic energy received from the motors into hydraulic energy. They are classi ed according to application, operating principle, depth, ow rate, capacity, costs, market availability,

and many more [33]. The key parameters of the water pump are based on the discharge rate and the head of water. Depending on the water source, the pumps can be categorized into three applications: submersible pumps, oating pumps, and surface water pumps. In submersible and oating pumps, the motor and the pump are combined into one device, while in surface water pumps, the two components are kept apart.[52]. The pump head ow curve is described as follows:

$$H(Q) = H_o \quad C_1 Q \quad C_2 Q^2 \tag{2.1}$$

where H = total head, H_o = pump idle head, C_1 and C_2 = head factors. The pump manufacturer individually provides these parameters with the characteristic curves of the pump. Additionally, the head is described by the total pressure difference across the pump. Introducing the characteristics of the system representing the resistance of the pipes as a function of the work point H (Q):

$$H(Q) = H_s + C_s Q^2 \tag{2.2}$$

where H_s = system idle head and C_s = head factor [6].

7. Storage

   Energy storage is necessary to guarantee that the irrigation system is constantly supplied with energy and to store any additional power produced by the PV array. This helps to overcome periods with little solar radiation, such as cloudy days, or no solar radiation, such as at night [35]. The importance of energy storage when used in combination with renewable energy production is undeniable. In this sense, the required form of energy is mostly electrical energy, but other forms of energy storage allow the conversion of electrical energy into a different form and reconvert it. Energy can be stored in mechanical, electrical, thermal, or chemical ways. For pump applications in the literature, mostly mechanical storage in pumped hydro and chemical storage in batteries are being considered. The most important factors in choosing the right energy storage technology are related to geographical, economic, social, and political circumstances. Furthermore, the application for end-use determines the best energy storage options, as the authors of [47] have shown. In addition, it was found that the use of a combination of energy storage optimizes and harmonizes power productivity. Furthermore, the effect of intermittency could be diminished. The case study analyzed different scenarios for water production in which different combinations of storage methods showed optimal results in the desired parameters, such as the most economical solutions [47].

2.2 Support structures including design, loads, and modeling

Solar pumping systems must be installed safely and according to the equipment manufacturer's instructions to be reliable. The described systems are mostly offered as a complete system package, including the PV array, the pump controller, the water pump, and the corresponding wires and cables. Only the hydraulic system is to be designed separately [14].

The mounting structure provides resilience and protection for the solar panels. The typical structure consists of stainless steel, galvanized mild steel, or aluminum, depending on the site's environmental conditions, topography, and others. The design of the system should be able to bear the load of the photovoltaic panels and any external forces. Depending on the site, earthquake risks must also be considered. It is important to clarify that the structures that support solar panels must have the ability to provide resistance and resilience against these in uences. External weather in uences on the mount-

ing structures and solar panels can be wind, snow, and hail. The type of mounting structure that must be selected depends on the present in uences. These types include ground mount, pole mount, roof mount, and ground screws [53].

According to the manufacturers' data sheets, solar panels have many key characteristics. For example, the Mono S4 innovation Powerline N panel from the German manufacturer Solarfabrik is reliable and secure to withstand hail up to 25 mm in diameter and up to speeds of 23 m/s. Furthermore, the panels can handle up to 5400 Pa of snow load, corresponding to 550 kg/m^2. The information can be obtained from the datasheet which can be found in Appendix A.Wind loads, instead, are mostly subject to the supporting structure of the PV array. Several statics calculations ensure the statics in free-standing PV plants. The manufacturer ensures the withstanding from individual terrain statics, individual system statics based on regional load values to the load assumptions according to DIN EN 1990 (Eurocode 0), DIN EN 1991 (Eurocode 1), DIN EN 1993 (Eurocode 3), DIN EN 1999 (Eurocode 9) and other or corresponding. It is important to note that these assumptions vary depending on the manufacturer of the support structure and according to the support structures used [43]. For example, the PVMAX-S Energy Kit from Schletter manufacturer is described as the following. This kit allows for the installation of up to 22 solar panels in a free-standing space. The inclination angle is xed here at 20 degrees. The manufacturer ensures wind loads of up to 28,0 m/s and snow loads of up to 1,58 kN/m^2 [43].

Researchers showed that wind loads above the natural level in uence the support structure and the panel can suffer structural damage. During potential hurricanes or strong wind speed phenomena, panels face substantial stress regardless of where they are mounted. Experiments were conducted to measure wind speeds of up to 260 km/h, which generated up to 4196.4 Pa, resulting in delamination, also known as peeling stress. This has a detrimental impact on the longevity of solar panels [29].

In addition, there are several researches on the in uence of the layout of the PV array and its wind loads. Information on wind loads at the installed plant site PV is essential for design and support structures as Somekawa et al. state. The authors also mention that the geometry of the module eld and its arrangement signi cantly in uence their loads. The result showed that the larger the panel slope, the higher the upward wind load. Furthermore, longer columns installed are more resistant to upward wind loads than shorter columns. Another conclusion was that the wind loads on the support structure are independent of the array arrangement, which means that the manufacturer's limits will be used. The experiments also showed that wind load calculations are very complex due to spatial variation of the wind force, concluding that individual sites and locations may differ subsequently due to the geographical features of the site [45].

2.3 Reliability

To further underscore the importance and opportunity of SPWPS for irrigation, it is necessary to emphasize their reliability. Research by Mexican authors included inspection and survey of up to 46 SPWPS assessed in several regions of Mexico, where more than 206 SPWPS have been installed in pilot systems in the late 1990s of up to 101kW capacity. The SPWPS have been installed in collaboration with the Mexican Renewable Energy Program. As previously described, the system con gurations have been typical, using a PV array, a pump, a controller, an inverter if needed, and overcurrent protection. The results in terms of reliability and user acceptance after a 10 year period showed that user acceptance was good or excellent for more than 85% in terms of cost effectiveness, reliability, and productivity. Regarding component reliability, it showed zero failures in the PV modules at all sites. However, most of the failures of SPWPS were due to technical defects. 54% of all defects occurred due to pump failure, 21% with inverters or controllers, 17% were well-related failures (e.g., due to droughts), and 8% were

dismantled due to theft or other reasons. In general, 60% of all the sites surveyed were still reliable and functioning properly after up to 10 years of operation [12].
Other approaches in the literature used to evaluate the reliability of SPWPS are Markov models and frequency-duration techniques. The Markov approach considers systems with n numbers of components, either repairable or non-repairable, and either series, parallel or combinations. As a result, reliability indices such as failure rates, repair rates, unavailability, etc. are evaluated. The frequency-duration method is another method to obtain basic reliability indices. Using state transition diagrams, sets of states are described as contributing either to the success state or failure state. The weakness of these reliability methods is that systems that exceed parallel and series con gurations cannot be calculated. According to the authors, the inverter is the most critical component for failure in the tested and calculated SPWPS [44], which underlines the research presented from Mexico in the previous section. To conclude the reliability of solar water pumping systems, typical values of the expected lifetimes of the components are shown in the following Table 2.1. Components with the longest lifetime of up to 25 years are the borehole, the solar panel, and civil infrastructure, which, for example, describes the mounting structures of the panels. It is essential to note that the system can last longer than its expected lifetime and not cease to function after that period. The system can be resized when the rst components, such as the pump and inverter, must be changed and replaced [53].

Table 2.1: Expected lifetimes of solar water pumping components [53]

Component	Expected lifetime (years)
Borehole (if needed)	20-25
Pump	5-10
Inverter/ Control box	5-7
Solar module	20-25
Civil infrastructure (e.g., module supports)	20-25
Water tank - cement	15-20
Water tank - plastic	5-10

2.4 Economic analysis

An economic standpoint is necessary to show the competitiveness of economic parameters against conventional drives. Due to the severe drop in the prices and inverters of PV modules, which represent more than 60% of the initial capital cost, in recent years, the economic viability of SPWPS has increased dramatically. When compared to conventional drives, two key differences are observed. SPWPS have much higher initial costs but lower life cycle costs due to the absence of fuel costs and lower operating and maintenance costs [8].
Figure 2.7 gives indicators of the two technologies compared. For PVWP, the initial investment costs (ICC) consist mainly of the PV modules and the inverter. In general, the ICC of PVWP are substantially higher than the ICC for DWP. Contemporaneously for LCC, the opposite is noticeable. Here, the costs of DWP exceed the costs of PVWP. The data raised for the comparison is from 2015 [8].
To validate the development, more recent data is needed. Data for rooftop systems with a nominal power rating of 10 - 100 kW_p in Germany between 2006 and 2019 show that the average end-customer price, also called the net system price, is decreasing to almost 1000 €=kW_p. Furthermore, the data show that the module costs account for less than half of the total investment costs, decreasing to only 39% for the modules and 61% for the BOS [54].
The BOS describes all components of the PV array that are not directly related to the solar panel. It

encompasses a wide range of essential components beyond inverters and racking. It includes cables, wires, switches, enclosures, fuses, ground fault detectors, and other critical elements [38] [17]. The BOS is a vital part of all solar applications, as it supports and optimizes the overall performance of the PV system [17]. It ensures a safe and ef cient installation and operation of the entire setup [53]. Compared to other technologies, the operating costs of a PV power plant are very low, approximately 1% of the initial investment costs [54].

Figure 2.7: Comparison of the ICC and LCC of PVWP and DWP in 2015 [8]

Figure 2.8 shows the historical development of the PV module prices for all market-relevant crystalline silicon and thin- lm technologies up to 2018. The graphic emphasizes that every technology of PV panels has seen a signi cant decline in price in recent years. The price in USD/W has decreased by a factor of 5-6 between 2010 and 2018 for certain technologies, which means that the price has decreased from 2.5 to 3.0 USD/W to around 0.5 USD/W. At the end of 2018, low-cost PV panels reached prices of 0.22 USD/W [27].

This trend is mainly due to the increase in total capacity combined with the development of connected products and improved manufacturing processes. Prices in Europe vary compared to the world market due to antidumping measures initiated by the European Commission [54].

Another research has studied and compared gasoline-fueled water pumps with SPWPS in the Philippines for selected crops. Studies have shown that SPWPS have higher initial investment costs regardless of the crops grown. However, they become more economical over time as a result of their low maintenance expenses. The study found that for a 20-year period, the cost of pumping 1 m^3 of water using SPWPS was 1.35$, whereas it cost 5.44$ per m^3 when using gasoline-fueled pumps [36].

The authors Mérida Garc´a et al. underscore the importance of PV technologies in the agricultural sector, seeing it as a cleaner and more pro table source of energy compared to traditional energy. LCA of SPWPS has been compared with other predominant energy sources in PV irrigation systems, grid electricity and diesel engines. Again, the PV system showed the highest initial costs, which is the cheapest option for the investigated 30-year period. Furthermore, the energy payback time of SPWPS was estimated between 0.5 and 3.1 years. The authors rst introduced environmental LCA. The indicators introduced were GWP, ARDP, AP, HTP, and FRDP. The SPWPS showed the lowest GWP and overall the best performance for all the parameters examined except ARDP, where it showed the highest value. Environmental factors are linked to the phases of operation. The greatest environmental impact is observed in the installation stage for SPWPS, showing a decreasing impact with further operation [32].

Figure 2.8: Monthly average PV panel prices of market relevant technologies and manufacturers between 2010 and 2018 [27]

2.5 Existing software

The existing software in the literature is mainly from solar pumping or PV module manufacturers and common software. The main softwares used are as follows:

1. PVSyst :
   A commonly used software for solar pumping is the PV software PVsyst or equivalent software. The software simulates and tests several PV scenarios. The software features system design and system sizing paired with optimization and economic evaluation features. Furthermore, it allows the user to pair the PV system with a pumping system. By including several parameters such as the hydraulic characteristics of the source, the water tank, the hydraulic circuit, and the water requirements, it can help to select the pumps, PV modules and controllers and optimize and simulate them in combination [39].
2. Matlab and Matlab Simulink :
   Several researchers use Matlab or Matlab Simulink to create models for the desired systems. These models help to build and integrate different components.
3. HOMER - Hybrid Optimization of Multiple Energy Resources :
   Homer is a useful tool for modeling and calculating parameters using accurate values of PV, inverters, batteries, and their costs. The development and testing has been done by the NREL [4]. HOMER software is suited for system veri cation for optimal technical and cost-effective solutions. Models and simulations are used to design hybrid systems, either hybrid microgrid or grid-connected systems, ensuring the best possible solutions in combination with renewable or non-renewable power generation, storage, and load management [24].
4. COMPASS by Lorentz :
   Pump manufacturers also have software for SPWPS. The software presented comes from the pump manufacturer Lorentz and it helps plan and simulate the design for SPWPS systems for the required water needs. As the leader in the solar pumping market, the COMPASS tool allows access to a detailed simulation depending on the site location [30].
5. SAM - System Advisor Model :

SAM software is an open source techno-economic tool that enables decision making for the renewable energy industry. It is published by NREL and allows the user to model renewable energy systems in addition to nancial models [42].

6. RETScreen :
   RETScreen is a clean energy management software platform by the government of Canada. It allows several services in the sector of renewable energy, such as planning, monitoring, and reporting [41].

Chapter 3

Methodology

3.1 Original Methodology of sizing

To dimension and optimize the photovoltaic water pumping system, the theoretical aspects of sizing must be clari ed. Without knowing the parameters of the different subsystems, it would not be possible to achieve adjustments between them. Figure 3.1 shows the ow chart to design a SPWPS. Each component has its unique parameters that are of major importance when it comes to the initial choice of components for each subsystem.

Figure 3.1: Flowchart of design of a SPWPS, adapted and modi ed from [11]

The parameters of the subsystems must be identi ed to optimize SPWPS. As Figure 3.1 shows, the system parameters will be described in three different stages. The original methodology is to assume

that the water need is known or possible to be calculated. The three stages are:

1. Water demand
   The assessment of water needs describes the following crucial parameters. The desired water ow rate indicates the pump's required out ow to satisfy the demand. This out ow is strongly connected to the total dynamic head, which describes the necessary pressure requirements. Furthermore, the water storage system is an important parameter when assessing the water demand [11].
2. Motor-pump
   The motor-pump is usually one unit and combines the electrical machine with the pump. It mostly comes with speci c ow rate curves and corresponding power curves. These parameters are necessary to identify the hydraulic power needed, as well as the ef ciency of the subsystem[11].
3. PV array
   The PV array is the power source of SPWPS. This means that solar irradiation and temperature are of great importance. The PV array as a subsystem contributes to overall system ef ciency[11].

Introducing these theoretical parameters is the rst step towards creating and modeling the system, which has to be further enhanced by incorporating load speci cations to determine the variables and nally achieve the results. This process includes selecting the appropriate components to complete the setup.

3.2 Design parameters

To modify and optimize the original methodology when selecting the solar water pumping system, a detailed clari cation of the design parameters must be introduced. These parameters include the water demand, the motor-pump unit, the photovoltaic array, and the power converter unit and will be introduced in the following paragraphs.

3.2.1 Water demand

The water demand and the corresponding water output Q are a design parameter that must be known or estimated in advance [11].The height that the pump must overcome is referred to as the total dynamic head (TDH) and can be described as:

$$TDH = \text{Static Head} + \text{Discharge Head} + \text{Friction Head} \tag{3.1}$$

losses. This is the total of the static head, the discharge head, and the head losses due to friction.[35] [19].
To better visualize and explain the total dynamic head Figure 3.2 is introduced. It shows an overview of the nomenclature of the pump parameters described. The graphic represents a submersible pump system, but the theory can be applied to other pump technologies.
The static head is the vertical distance to the source depth. When water is taken from a water aquifer, it can also be called the dynamic water level since the head is dynamically decreasing due to the draw-down. The discharge head describes the vertical distance above ground level to the storage tank that, when elevated, allows use through gravity. The friction head describes the friction of the water against the insides of the pipes. It usually represents 10% of the static head plus the discharge head [55].
In addition, the storage system plays a vital role. Water storage must be sized properly according to water needs. The literature recommends storing enough water for at least 2 to 3 days of supply, which

means:

$$V_{min} = 3 \text{ days } Q \tag{3.2}$$

where:

- Q = total daily demand (m^3/day)

The hourly demand patterns and the total daily demand must be satis ed independently from any variations in insolation and temperature over time[55].

Figure 3.2: Total dynamic head determination [35]

3.2.2 Hydraulic system - Motor-pump unit

The hydraulic energy required for a speci c water demand and total dynamic head is given by [11]:

$$P_H = Q \quad TDH \quad g \tag{3.3}$$

where:

- Q = water ow rate (m^3=h)
- = liquid density = water density (1000 kg=m^3)
- TDH = total dynamic head (m)
- g = gravity acceleration (9:81m=s^2)

Using this equation, we can accurately estimate the power requirements for a pumping system to meet speci c water demands, allowing us to select appropriate pumps and optimize the system's ef - ciency. For a centrifugal pump, the relationship of parameters resulting in pump ef ciency is determined by the following equation [6]:

$$_{pump} = \frac{P_H}{P_{pump\ in}} = \frac{Q \quad H \quad g}{P_{pump\ in}} \tag{3.4}$$

where:

- $P_{pump\ in}$ = pump input power (W)
- H = TDH (m)

The pump input power describes the mechanical input power from the electrical machine to the pump, which then further describes the relationship between the hydraulic output power and the mechanical input power as the pump ef ciency [34]:

$$_{pump} = \frac{P_H}{P_{m\ in}} \tag{3.5}$$

where:

- P_p = hydraulic output power (W)
- $P_{m\ in}$ = mechanical input power (W)

The pump's ef ciency is a critical factor in assessing the pump's performance and is an important consideration in pump selection and system design. Higher pump ef ciency indicates better energy utilization and reduced losses in the pumping system.
The motor-pump unit is then determined by introducing the ef ciency of the electrical machine. It is represented as [18]:

$$_{EM} = \frac{P_{m\ out}}{P_{sup}} = \frac{P_{m\ out}}{I_o\ \ V_o} \tag{3.6}$$

where:

- $P_{m\ out}$ = mechanical output power P_{shaft}
- P_{sup} = supplied power by PV array (or power converter - depending on con guration)
- I_o = output current (A)
- V_o = output voltage (V)

The formula considers both the mechanical and electrical output power, allowing us to introduce the ef ciency of the electrical machine $_{EM}$. It helps to evaluate the effective utilization of the energy generated by the PV array to achieve the desired mechanical output power on the pump shaft. Additionally, maximizing the ef ciency of the electrical machine also indicates better energy utilization and reduces energy losses in the overall system.

3.2.3 Power converter

Depending on the system con guration, a power converter must be introduced. To obtain the energy losses, the ef ciency can be described as [9] (modi ed nomenclature):

$$_i = \frac{P_{out}}{P_{DC}} \tag{3.7}$$

with:

- P_{out} = output power (W)
- P_{DC} = input power (W)

The ef ciency of the converter $_i$ connects the input power of the PV array to the output power of the converter. The ef ciency of DC / AC inverters generally varies between 86 and 96% and shows a notable drop when the power is signi cantly lower than the rated power of the inverter [9]. In solar-powered pumping applications, the ef ciency of the power converter is also a factor that impacts overall energy utilization and system performance.

3.2.4 PV array

The PV array is an important component of SPWPS, especially for optimization. Solar irradiation availability and temperature are key parameters that in uence system ef ciency. Solar irradiation G is the solar radiation per unit of area, often described in W=m^2=day. It results from solar irradiance G (W=m^2), which shows the rate at which the radiant energy is incident to the surface area over time. Total solar radiation is also called global radiation on a horizontal surface. It includes beam radiation, solar radiation without the effect of scattering in the atmosphere, and diffuse radiation, which describes radiation received after a direction change due to scattering of the atmosphere[15].

Figure 3.3: Example of Solar irradiance on a given site over time [55]

Figure 3.3 gives a representative course of solar irradiance over a day. Solar irradiance varies since the position of the sun to the surface changes over the day. Typically, the irradiance rises from sunset until noon, where we ideally have incident solar irradiance. After there is a decline again due to the increased scattering and atmosphere, the sun has to penetrate. Solar insolation can also be described as sun peak hours. Several in uences affect solar irradiance on the PV array, including latitude, atmospheric clarity, humidity, and seasonal variations[55].
To have a more comprehensive understanding of the PV array, several parameters are established in the following paragraphs.
The capacity of the PV array and the corresponding number of PV panels (N_{PV}) can be expressed as:

$$N_{PV} = \frac{P_{EL}}{G \quad {}_{PV} \quad A_{PV}} \tag{3.8}$$

where:

- P_{EL} = electrical energy requirement (W)
- G = solar irradiance (W/m^2)
- ${}_{PV}$ = PV ef ciency (%)
- A_{PV} = area of the PV array (m^2)

Knowing the panels' characteristics, the overall PV array capacity can be expressed as:

$$P_{PV} = N_{PV} \quad W_{P,PV} \tag{3.9}$$

where:

- $W_{P,PV}$ = maximum power output of the panel (W) [35]

The PV power output is directly dependent on the irradiance and the temperature of the cell. Power output varies according to the operating point, which is the main parameter for the ef ciency of the PV systems. This means that the power output has to be further characterized to [9]:

$$P(G;T) = \frac{G}{G^r} \quad P_p \quad [1 + \quad {}_{P_p} \quad (T \quad T^r)] \tag{3.10}$$

where:

- P_p = peak power corresponding to maximum DC power output (W_p)
- ${}_{P_p}$ = peak power temperature coef cient (% / ºC)
- G^r = irradiance at STC G^r = 1000 (W/m^2)
- T = current cell temperature (K)
- T^r = temperature at STC cell temperature ${}^r_m$ = 25 °C (K)

The advantage of the mathematical model for the power output is its simplicity, making it easy to understand, implement, and connect the input parameters. However, a major drawback is providing access to other crucial variables of interest, such as the maximum power voltage and current [9].
To obtain the needed current temperature of the cell, the relationship of NOCT, the irradiance (G), and the ambient temperature (T_{amb}) is given as [9]:

$$T_{cell} = T_{amb} + G \quad \frac{NOCT \quad 20}{800} \tag{3.11}$$

where:

- T_{cell} = cell temperature (K)
- T_{amb} = ambient temperature (K)

The NOCT is usually a parameter provided by the manufacturer in the datasheet of the solar panel. This method is a simpli ed approach to estimating the panel temperature and in uence on the power output at a given operating point. The Ross model has shown that this method is an approximation and shows some errors compared to the experimental data [9].
To be able to compute the overall ef ciency of the system, the ef ciency of the PV array is described as [18]:

$${}_{pv} = \frac{I_o V_o}{G A_{pv} n_s n_p} \tag{3.12}$$

where:

- n_s = cells connected in series (n)
- n_p = cells connected in parallel (n)
- V_o = output voltage (V)
- I_o = output current (A)

The resulting ef ciency of the panel can then be simpli ed to:

$${}_{pv} = \frac{P(G;T)}{G \quad A_{pv}} \tag{3.13}$$

This equation establishes a connection between the output power, P(G, T), derived from the output voltage V_o and output current I_o and the solar irradiance per unit area of the PV array [9].
The ef ciency of the PV array is a crucial parameter in determining how effectively sunlight radiation is converted into electrical energy, and it is an essential factor in the calculation of the overall ef ciency of a solar-powered water pumping system. By maximizing the ef ciency of the photovoltaic array, more electrical power can be generated from the available solar energy, contributing to the overall effectiveness of the system.

3.2.5 Summary

By combining the ef ciencies of the PV array of Equation 3.12 with the ef ciency of the electrical machine in Equation 3.6 and the ef ciency of the pump in Equation 3.4, we have a total ef ciency of the system of SPWPS:

$$_{total} = \quad _{pv} \quad _{EM} \quad _{pump} \tag{3.14}$$

when there is no power converter involved [18]. When there is a power converter present, then Equation 3.14 is added by Equation 3.7, which allows us to obtain the total ef ciency of the system, including all subsystems:

$$_{total} = \quad _{pv} \quad _{EM} \quad _{pump} \quad _{i} \tag{3.15}$$

This formula describes the ratio of hydraulic power output to the input solar power [13].
The main objective of optimizing the total ef ciency of the system is to achieve the maximum hydraulic power output using the available solar power input by selecting suitable components. This ensures that the system operates with minimal energy losses, resulting in high ef ciency and sustainability.

3.3 Proposed Methodology for optimization

After establishing the parameters of the subsystems, the design and choice of components are possible. However, to optimize the SPWPS, it is mandatory to prioritize the ef ciency of the system. It is possible to create and introduce operating ranges of the system when the water demand is unknown. This means that all possible combinations of motor-pump units connected to a PV system can be identi ed. The xed variable for the PV array will be the location that includes the speci c temperature and irradiance. For the motor pump unit, the TDH must be known to identify all possible pumps. In doing so, the original methodology of dimensioning is changed. Figure 3.4 shows the proposed methodology considered for this work for the development of the different operating ranges of the SPWPS.
It can be classi ed into six major parts. The rst task is to create an accurate model of the photovoltaic array. By doing so, it is possible to obtain the power produced by any photovoltaic panel in any location under given environmental conditions. The power output of the model, created by the PV array, is used as the power supply of the system. The next step is to create a counterpart for the power consumer. A model for the motor-pump unit is being established. This model includes the input parameter TDH and nonmandatory input parameter out ow Q. The model serves to nd every possible combination of motor-pump units that satisfy the conditions while calculating and maximizing their ef ciency. The goal is to identify the power that the motor absorbs from the PV supply. After both models have been created, it is possible to combine them. The motor demands power to satisfy certain heights and out ows. These powers are now matched with the PV model, with a focus on the overall ef ciency of the system. The next step is to determine the solar resources available for the given site. By introducing the temperature and the irradiance for the investigated location, it is nally possible to generate PV panel setups with the corresponding motor-pump units. This step introduces a crucial secondary parameter, the area A of the PV array. The space can be an important parameter for sizing and usually needs to be considered. The area of possible setups is shown, yet ef ciency is the key parameter of this work. The outcome allows us to assess the water needs that can be met. Working with these possible combinations of components and their corresponding out ows, it is now possible to create operation ranges of the system for the investigated locations.

Figure 3.4: Flowchart for the development of different operating ranges for the SPWPS

Chapter 4

Modelization

4.1 Proposed PV model

4.1.1 One-diode ve-parameter model

This part aims to form and present the theoretical framework for modeling a photovoltaic system to determine the useful output power of the array. The electrical model used is shown in Figure 4.1. The model referred to is commonly known as the one-diode ve-parameter model, also known as the single-diode model with ve parameters. The one-diode ve-parameter model is a widely used approach in the modeling of photovoltaic systems and takes into account the various losses present in a PV panel [9].

Figure 4.1: Equivalent circuit of the photovoltaic solar cell used in the 1 Diode 5 parameter model from [7]

The relationship of the current and the voltage in a solar panel is given as [9] (Equation has been modi ed due to nomenclature):

$$I = I_L \quad I_D \quad I_{sh} = I_L \quad I_o[\exp(\frac{V + IR_s}{a \quad vt}) \quad 1] \quad \frac{V + IR_s}{R_{sh}} \tag{4.1}$$

where:

- I = operation current
- I_L = light current (A)
- I_D = diode current (A)
- I_{sh} = shunt current (A)
- I_o = saturation current (A)
- R_s = series resistance ( )
- R_{sh} = shunt resistance ( )
- V_t = thermal voltage (V)

Many of the parameters shown in Equation 4.1 depend on irradiance and temperature. Generally, they are searched for STC. The manufacturer of the PV panel provides the following variables to the conditions mentioned above, as we can see in Table 4.1. The parameters include not only the short-circuit current and the open-circuit voltage, but also the maximum operation current and voltage. In addition, they provide valuable information on the temperature coef cients of both the current and voltage. Next to the parameters given, Table 4.2 shows the model's ve unknown and desired parameters. The table provides information on photoelectric current, saturation current, series resistance, shunt resistance (parallel resistance), and diode ideality factor in a PV panel.

Table 4.1: Given parameters by the manufacturer as found in datasheets in Appendix A

Parameter	Name	Unit
I_{sc}	Short circuit current	(A)
V_{oc}	Open circuit voltage	(V)
I_{mp}	Maximum operation current	(A)
V_{mp}	Maximum operation voltage	(V)
$_{V}$	Temperature coef cient of V	$(\frac{V}{K})$
$_{I}$	Temperature coef cient of I	$(\frac{A}{K})$

Table 4.2: Five unknown parameters resulting from [9]

Parameter	Name	Unit
I_L	Photoelectric current	(A)
I_0	Saturation current of the diode	(A)
R_s	Series resistance	( )
R_{sh}	Shunt resistance	( )
a	Ideality factor of the diode	-

The tables highlight the input parameters on one side and the output parameters on the other. To obtain these parameters accurately, a precise model is essential. This requirement drives the development of a tool designed to extract the photoelectric current, saturation current, series resistance, shunt resistance (parallel resistance) and diode ideality factor from the PV panel and will be shown in the next paragraph.

4.1.2 Implementation in Matlab

Given that information, the model is implemented in a Matlab environment. The goal of the model is to retrieve the individual I-V and P-V curves of the different panels, as shown in the datasheet of the PV panel. An I-V curve is a graphical representation of a PV panel's current and voltage relationship, whereas the P-V curve shows the relationship between the output power and the corresponding voltage. When the characteristic curves are obtained, it is possible to identify the operating points with a given irradiance and temperature. The ultimate goal is to intersect the operating points of both the PV panel and the motor-pump unit to maximize the ef ciency between the components. The ow chart that illustrates the implementation process is presented in Figure 4.2. The methodology comprises six distinct steps, which form a well-de ned algorithm to extract the characteristic curves of various PV panels under varying environmental conditions.

Figure 4.2: Flowchart of the implementation into Matlab

Creation of database

A concise database that includes PV panels sourced from various manufacturers, each with different electrical characteristics, has been created. The panels used in this research are presented in Table 4.3. This table includes all the essential parameters required for accurate calculations, including the maximum power points and the temperature coef cients for current and voltage. The corresponding datasheets can be found in Appendix A.

Table 4.3: PV panel speci cations

PV Panel	V_{mp}	I_{mp}	V_{oc}	I_{sc}	P_{mp}	p	Pp	Voc	Isc	NOCT
LC-50-12M	17.2	2.9	22.5	3.2	50	11.69	-0.50	-0.35	0.09	48.00
NU-180	23.7	7.6	30.0	8.37	180	13.7	-0.485	-0.347	0.053	47.50
KC200GT	26.30	7.61	32.9	8.21	200	-	-	-0.123	0.0318	-
A-255P	30.90	8.26	37.3	9.12	255	15.71	-0.3845	-0.29	0.0681	46.00
A-260P	31.00	8.39	37.4	9.27	260	16.01	-0.3845	-0.29	0.0681	46.00
A-265P	31.05	8.54	37.5	9.42	265	16.32	-0.3845	-0.29	0.0681	46.00
A-270P	31.10	8.69	37.6	9.58	270	16.63	-0.3845	-0.29	0.0681	46.00

User interface

Once the database is successfully implemented, a user-friendly interface is incorporated to allow the user to select the desired panel for investigation. A pop-up in the command window allows the user to enter the number of the desired panel from the previously created database, where each number corresponds to a panel in the list chronologically. In this section of the code, a space has been implemented to enable the addition of new PV panels. This functionality ensures that the code remains up-to-date and adaptable for future research and analysis and can be easily extended.

Stornelli's iterative algorithm for 5 parameter determination

Consequently, the data from the selected panel is passed to an algorithm created by Stornelli et al.. The authors introduced a simpli ed iterative method to extract the ve unknown parameters. The algorithm is split into two parts. The initial step is to identify the optimal ideality factor of the diodes, followed by the calculation of R_p in the second part to improve the precision of the estimation model. The proposed method is validated and shows minimal errors between the resulting characteristic curves obtained and those from the manufacturer's datasheet [46]. After slight adaptations and modi cations to the proposed algorithm, the implementation is carried out within the Matlab environment. As a result of the implementation, we obtained the ve unknown parameters speci c to the selected PV panel. A potential output of a PV panel of the database is shown in Table 4.4.

Table 4.4: Representative output for panel A-255P

A	I_0 [nA]	I_{PV}	R_s[m]	R_p[ ]
1.27	46.56	9.13	96.68	84.94

Newton-raphson method

The next step is to create a user interface in which the input consists of three input parameters. Namely, the amount of curves desired to plot (n_i) together with the corresponding temperatures (T_i) and irradiances (G_i). After obtaining these parameters from the user, it is possible to use the Newton-Raphson method using the voltage, current and power parameters. This method uses the expansion of the Taylor series where:

$$f(x) = f(x_0) + f^{0}(x_0)(x \quad x_0) + \frac{1}{2}f^{00}(x_0)(x \quad x_0)^2 + ::: = 0 \tag{4.2}$$

An initial guess close to the real root of the equation allows us to make (x-x_0) small enough, which results in the general formula:

$$x_1 = x_0 \quad \frac{f(x_0)}{f^{0}(x_0)} \tag{4.3}$$

As a result, to calculate the point x_{n+1}, we nd the intersection of the tangent line to the function f (x) at x_n with the x-axis as we can see in gure Figure 4.3. The Newton-raphson Method guarantees convergence when applied to a particular interval [a, b], which contains the root of the function f(x). For this convergence to occur, it is essential that both f(x) and its derivative f'(x) show continuity within this interval. Additionally, the condition f( ) = 0 must be satis ed, where represents the true root of the function. These requirements ensure the effectiveness of the Newton-Raphson method in nding the root within the speci ed interval[40].

Figure 4.3: Graphical illustration of newton-raphson method [40]

For the designed model, we use the initial guess $I = I_L$. In this step, the algorithm accumulates and stores the data for each desired curve in V, I, and P. The voltage array used is larger according to the temperature and irradiance input where $V_{oc} > V_{oc}^{r}$ and shows an interval of $\frac{V_{oc}}{100}$ that ensures a true and precise representation.

I-V and P-V curves

The nal step involves plotting the results that have been obtained. Characteristics V-I and P-V of the selected panels for the desired temperatures and irradiances are plotted. An example output is shown in Figure 4.4. The graphs illustrate how the electrical parameters vary with changes in temperature and irradiance and can be seen for irradiances of 200, 400, 600, 800, and 1000 (W/m^2).

(a) I-V curve (b) P-V curve

Figure 4.4: Representative output of algorithm

4.2 Proposed Motor-pump model

4.2.1 Overview and Flowchart

As a result, to effectively connect the operating points between the components, the panel must be coupled with a suitable motor-pump model. This integration will ef ciently utilize the system and its components under several environmental conditions. To better understand the idea of modeling the motor-pump unit Figure 4.5 is introduced. The graph shows the ef ciency (orange dotted), the power P (blue dotted) and the head plotted against the discharge output ow Q. These characteristics are unique to each motor-pump unit combination and are crucial to identifying the ef ciency of the system.

Figure 4.5: Characteristic curves of an electrical motor-pump unit [48]

The work ow must be clari ed to create a model of the motor-pump unit. A visualization of the implementation is shown in Figure 4.6. The two input parameters of the model are the height H and the Out ow Q. These two parameters are necessary to enable the operation ranges of all possible motor-pump combinations. Parallelly, another input is to digitize the data provided by the manufacturer. This step includes the import of PQ and HQ curves, tables that connect each pump to a corresponding motor, and the motor data itself. The next task is to connect the input parameters with the given data to identify possible motor-pump combinations for the user's requirements. Here, the data between the characteristic curves and the tables are matched. As an output, we obtain all possible out ows Q and powers P satisfying the height. Here, the user input height is the mandatory pressure requirement of the system. This means that the out ow Q will be a variable parameter possibly higher or lower than the user's input. Nevertheless, all possible out ows and combinations of motor-pump sets are shown. Afterward, with the pump ef ciency at the operating out ows, it is possible to identify the load on the motor. Interpolating the ef ciencies with the load on the motor, we will obtain the power the motor absorbs with the highest ef ciency motor-pump combination. This is the power that the motor demands from the source, the PV supply, enabling us to connect the two models. The nal output displays all possible combinations in case the user prefers to choose a different motor-pump combination, not prioritizing the highest ef ciency.

Figure 4.6: Flowchart of developing motor-pump model

4.2.2 P-Q and H-Q Curves

Mathematical model

To properly model the behavior of the pump and connect the input power P to the output ow Q, it is necessary to model the P-Q behavior of the pump. The pump manufacturer often provides P-Q curves for different pumping heights. The proposed mathematical model is given as:

$$P_a(Q) = aQ^3 + bQ^2 + cQ + d \tag{4.4}$$

where a, b, c, and d are the main parameters of the model, describing the cubic function of $P_a(Q)$. These parameters are constant for the given head h [23].
In the literature, approaches exist to extract the desired parameters. As proposed by the authors, the Newton-Raphson method with a constraint for d $P_a(Q) > 0$ can calculate the output ow rate Q. The immediate output ow is given as [23]:

$$Q_k = Q_{k-1} \quad \frac{F(Q_{k-1})}{F^0(Q_{k-1})} \tag{4.5}$$

The model follows the mathematical model Equation 4.4 but adds the height in the form of a function into the equation:

$$P(Q;h) = a(h)Q^3 + b(h)Q^2 + c(h)Q + d(h) \tag{4.6}$$

The parameters a(h), b(h), c(h), and d(h) depend on the given head. These secondary parameters can be obtained by experimental testing, allowing the authors to showcase the parameters for different pump technologies. This approach precedes the general model and is validated with RMSE and MBE [23].

Implementation in Matlab

To obtain these parameters, a Matlab model was created, which contains the following steps:

1. Input of points of datasheet (P, Q)
2. Polynomial curve tting
3. Extraction of model parameters (a, b, c, and d)
4. Characteristic P-Q curve for given head h

The data points decide the accuracy of the proposed curve tting method. The Poly t function in Matlab is designed to nd the coef cients of a polynomial p(x) that best ts a given set of data points y in a least-squares sense. The resulting polynomial has a degree of n and is represented by a set of coef cients stored in descending order of powers. The length of the coef cient array, denoted as p, is n+1. The function p(x) can be represented as [31]:

$$p(x) = p_1 x^n + p_2 x^{n-1} + ::: + p_n x + p_{n+1} \tag{4.7}$$

This method allows to obtain the characteristic P-Q curves for all heights given by the manufacturer. Doing so allows the generated output data to be plotted for different heights and compared to the pump datasheet. Figure 4.7 shows the output of the algorithm of the characteristic P-Q curve of a pump for different heads and the manufacturer's data sheet given. The input points are shown in the circles in Figure 4.7b, and the lines illustrate the corresponding cubic function following Equation 4.4. The corresponding parameters for gure Figure 4.7b can be summarized in the following Table 4.5.

(a) P-Q curve from manufacturer - PS2-600 CS-F4-3 Solar Surface Pump System by Lorentz

(b) Obtained P-Q curve

Figure 4.7: Comparison between the pumps P-Q charts from datasheet and algorithm

Table 4.5: Parameter de nition for P-Q curve of PS2-600 CS-F4-3

Height (m)	a	b	c	d
5	0.42	3.10	12.73	39.73
10	0.09	7.12	18.84	74.61
15	0.05	7.81	32.58	122.90
20	1.02	-0.20	65.57	181.23
25	3.90	-13.85	90.83	272.90

It can be seen that the obtained parameters and curves represent an accurate estimation of the pump curve shown in the datasheet. The datasheet can be found in the Appendix B. The information enables us to describe the P-Q characteristics of the pump accurately.

Special cases

Unfortunately, these representations of the manufacturer are not consistent. Other manufacturers provide the P-Q and H-Q characteristics separately. As a consequence, it is necessary to combine them. The datasheets for the Grundfos SP7 example pump can be found in Figure 4.8a and Figure 4.8b. An input to Matlab is needed to work with the data provided by the manufacturer. To simplify the input of the data, the software PlotDigitizer [3] is used. The software helps to manually import the data points from the data sheet to create a table with coordinate points. These points are digitized and plotted in Matlab. The result can be seen in Figure 4.8c and Figure 4.8d. Having imported the characteristic curves for different pumps, it is now possible to create a connection between the user input, i.e., input H and Q, and the datasheets.

(a) H-Q Curve from Manufacturer [21]

(b) P-Q Curve from Manufacturer [21]

(c) Matlab H-Q Curve

(d) Matlab P-Q Curve

4.2.3 Components selection

Identifying possible pumps from H-Q curve

As input for the motor-pump model, the algorithm uses height H and output ow Q. With reference to the H-Q curves of the pump and according to the user's input, all possible pumps are selected. In the selection process, priority is placed on the needed height H when there is no perfect match between input H and Q. After checking for the ideal match. The height H is kept constant, showing all possible out ows Q that meet the necessary height. These values may vary higher or lower than the original input Q given by the user, but this is unavoidable. This serves to establish the operating ranges later.

Identifying corresponding power from P-Q curve

After identifying all possible pumps with their connected out ow, it is possible to link them to the power they absorb using the P-Q graph. All possible out ows are interpolated with the corresponding power P referring to Figure 4.8d. The algorithm here identi es the input values Q and searches the connected data points where the Q value appears to be in between and performs a linear interpolation to obtain the exact value.
The formula for linear interpolation is given as [10]:

$$y = y_1 + (x \quad x_1) \; \frac{y_2 \quad y_1}{x_2 \quad x_1} \tag{4.8}$$

As a result, we obtain all the combinations of pump types used, the out ow Q, and the power P.

Connecting possible pumps to motors

The manufacturer connects each pump model to a corresponding motor [21]. With this information, it is possible to create a connection between the two characteristic curves. The motor used for each pump type is shown in Table 4.6 for single-phase 1 x 230 / 1x 400 V and in Table 4.7 for three-phase 3 x 220-230 V / 3 x 380-400-415 V. These motors are shown from the same manufacturer and create a small database. The designed rated power of the motor in this example varies between 0.55 kW and 13.0 kW, which means various heights and out ows can be represented. The algorithm connects the pump type to the motor type by its name and creates an output of all possible combinations that satisfy the user's input.

Table 4.6: Single-phase 1 x 230 V / 1 x 400 V motor-pump connection [21]

PumpType	MotorType	Power (kW)
SP 7-3	MS 402	0.55
SP 7-5	MS 402	0.75
SP 7-8	MS 402	1.1
SP 7-12	MS 402	1.5
SP 7-17	MS 4000	2.2

Table 4.7: Three-phase 3 x 220-230 V / 3 x 380-400-415 V motor-pump connection [21]

PumpType	MotorType	Power (kW)
SP 7-3	MS 402	0.55
SP 7-5	MS 402	0.75
SP 7-8	MS 402	1.1
SP 7-12	MS 402	1.5
SP 7-17	MS 402	2.2
SP 7-5	MS 4000	0.75
SP 7-8	MS 4000	1.1
SP 7-12	MS 4000	1.5
SP 7-17	MS 4000	2.2
SP 7-23	MS 4000	3.0
SP 7-27	MS 4000	4.0
SP 7-31	MS 4000	4.0
SP 7-37	MS 4000	5.5
SP 7-42	MS 4000	5.5
SP 7-51	MS 4000	7.5
SP 7-59	MS 4000	7.5
SP 7-37	MS 6000	5.5
SP 7-42	MS 6000	5.5
SP 7-51	MS 6000	7.5
SP 7-59	MS 6000	7.5
SP 7-71	MS 6000	9.2
SP 7-86	MS 6000	11.0
SP 7-100	MS 6000	13.0

Hydraulic ef ciency

- Graphical solution

  Hydraulic ef ciency describes the ef ciency of the pump. It can be obtained from the pump datasheet from the manufacturer and is usually represented in an eta curve. This ef ciency is used to identify the overall ef ciency of the system. A representation of a possible ef ciency curve can be seen in Figure 4.9. It connects the pump's ef ciency to the out ow Q. It is noticeable that the ef ciency peaks between the lowest and the highest possible out ow Q. This means that the most ef cient operating point is not at the maximum out ow.

Figure 4.9: Ef ciency eta curve of example pump Grundfos SP7 [21]

- Calculated solution

  Hydraulic ef ciency can also be obtained by calculation. The solution formula is already introduced

and can be found in Equation 3.4. When rearranged, the formula is brought to a useful form:

$$_{pump} = \frac{P_H}{P_{Power\ from\ P\text{-}Q\ Curve}} \tag{4.9}$$

where:

- $_{pump}$ = ef ciency of pump
- P_H = hydraulic power resulting from Equation 3.3
- $P_{Power\ from\ P\text{-}Q\ Curve}$ = power, which correlates the out ow Q to power P in the datasheet

The amount of energy transmitted from the motor to the pump shaft is represented by the P-Q curve. The ef ciency of the pump in uences this power [53]. Table 4.8 is introduced to compare both approaches. As seen in the table, the graphical solution for ef ciency offers very similar results to the calculated ef ciency. Since both approaches use a graphical component in obtaining the pump's ef ciency, they are rated equal in performance. To better validate, an experimental comparison would be needed. The ef ciencies in the table are shown for an input out ow of 5 $\frac{m^3}{h}$ and a height H = 100m with the corresponding results. This example serves as a visualization of a fundamental observation.

Table 4.8: Comparison of graphical and calculated pump ef ciency

Pump Type	Graphical Ef ciency	Calculated Ef ciency
SP7_31	0.6294	0.6248
SP7_27	0.6682	0.6574
SP7_23	0.6907	0.6824
SP7_17	0.5403	0.5468

Load and ef ciency calculation

Given the power P that the pump absorbs, it is now possible to identify the load on the motor. As supporting material, Table 4.9, Table 4.10, and Table 4.11, are introduced. The tables show the electrical characteristics of each motor. The provided data give information about the motor pump unit used, including the size of the borehole, the rated power, the full-load current, and generally the electrical performance. These include the ef ciency according to the load 50, 75, and 100 as well as the power factor cos ' 50, cos ' 75, and cos ' 100.
The following formula helps to identify the load on the motor [53]:

$$\text{Load} = \frac{P_a}{P_r} \tag{4.10}$$

where:

- P_a = absorbed power
- P_r = rated power

Knowing the load on the motor, it is possible to obtain the ef ciency of the electrical machine $_{EM}$ as part of the overall system ef ciency in Equation 3.15. This is done by interpolating the corresponding ef ciencies connected to the load on the motor as seen in the tables using Equation 4.8. It can be seen that the higher the rated power of the motor, the better its ef ciency will be for the same load in %. The ef ciency of the electrical machine is a crucial parameter to maximize the ef ciency of the entire system.

Table 4.9: Data Motor 3 x 230 V [21]

Motor Type	Size	Power	Full-load current	50	75	100	cos ' 50	cos ' 75	cos ' 100
'MMS 6'	'6"'	5.5	25.0	71	75	76	0.61	0.72	0.78
'MMS 6'	'6"'	7.5	33.5	72	76	77	0.59	0.71	0.78
'MMS 6'	'6"'	9.2	40.5	74	77	78	0.59	0.71	0.78
'MMS 6'	'6"'	11.0	50.0	74	78	79	0.53	0.66	0.74
'MMS 6'	'6"'	13.0	56.0	77	80	80	0.57	0.69	0.77
'MMS 6'	'6"'	15.0	62.5	79	82	82	0.58	0.71	0.79
'MMS 6'	'6"'	18.5	75.0	80	82	82	0.61	0.75	0.81
'MMS 6'	'6"'	22.0	87.0	82	84	83	0.61	0.74	0.81
'MMS 6'	'6"'	26.0	106.0	81	83	83	0.57	0.70	0.78
'MMS 6'	'6"'	30.0	118.0	82	83	82	0.63	0.76	0.82
'MMS 6'	'6"'	37.0	148.0	82	84	83	0.59	0.72	0.81
'MMS 8000'	'8"'	22.0	82.5	80	84	84	0.71	0.80	0.84
'MMS 8000'	'8"'	26.0	95.5	81	84	84	0.76	0.83	0.86
'MMS 8000'	'8"'	30.0	110.0	83	85	86	0.71	0.80	0.84
'MMS 8000'	'8"'	37.0	134.0	83	86	86	0.73	0.82	0.85
'MMS 8000'	'8"'	45.0	168.0	84	87	88	0.62	0.74	0.81
'MMS 8000'	'8"'	55.0	214.0	84	87	88	0.57	0.70	0.77
'MMS 8000'	'8"'	63.0	210.0	87	89	89	0.81	0.87	0.90
'MMS 10000'	'10"'	75.0	270.0	84	86	86	0.72	0.81	0.85
'MMS 10000'	'10"'	92.0	345.0	83	85	86	0.65	0.77	0.82
'MMS 10000'	'10"'	110.0	385.0	85	86	86	0.80	0.86	0.88

Table 4.10: Data Motor 3 x 400 V [21]

Motor Type	Size	Power	Full-load current	50	75	100	cos ' 50	cos ' 75	cos ' 100
'MS 402'	'4"'	0.37	1.40	51.0	59.5	64.0	0.44	0.55	0.64
'MS 402'	'4"'	0.55	2.20	48.5	57.0	64.0	0.42	0.52	0.64
'MS 402'	'4"'	0.75	2.30	64.0	69.5	73.0	0.50	0.62	0.72
'MS 4000'	'4"'	0.75	1.84	68.1	71.6	72.8	0.69	0.79	0.84
'MS 402'	'4"'	1.1	3.40	62.5	69.0	73.0	0.47	0.59	0.72
'MS 4000'	'4"'	1.1	2.75	70.3	74.0	74.4	0.62	0.74	0.82
'MS 402'	'4"'	1.5	4.20	68.0	73.0	75.0	0.50	0.64	0.75
'MS 4000'	'4"'	1.5	4.00	69.1	72.7	73.7	0.55	0.69	0.78
'MS 402'	'4"'	2.2	5.50	72.5	75.5	76.0	0.56	0.71	0.82
'MS 4000'	'4"'	2.2	6.05	67.9	73.1	74.5	0.49	0.63	0.74
'MS 4000'	'4"'	3.0	7.85	71.5	74.5	75.2	0.53	0.67	0.77
'MS 4000'	'4"'	4.0	9.60	77.3	78.4	78.0	0.57	0.71	0.80
'MS 4000'	'4"'	5.5	13.0	78.5	80.1	79.8	0.57	0.72	0.81
'MS 4000'	'4"'	7.5	18.8	75.2	78.2	78.2	0.52	0.67	0.78
'MS 6000'	'6"'	5.5	13.6	78.0	80.0	80.5	0.55	0.67	0.77
'MS 6000'	'6"'	7.5	17.6	81.5	82.0	82.0	0.60	0.73	0.80
'MS 6000'	'6"'	9.2	21.8	78.0	80.0	79.5	0.61	0.73	0.81
'MS 6000'	'6"'	11	24.8	82.0	83.0	82.5	0.65	0.77	0.83
'MS 6000'	'6"'	13	30.0	82.5	83.5	82.0	0.62	0.74	0.81
'MS 6000'	'6"'	15	34.0	82.0	83.5	83.5	0.64	0.76	0.82
'MS 6000'	'6"'	18.5	42.0	83.5	84.5	83.5	0.62	0.73	0.81
'MS 6000'	'6"'	22	48.0	84.5	85.0	83.5	0.67	0.77	0.84
'MS 6000'	'6"'	26	57.0	84.5	85.0	84.0	0.66	0.77	0.84
'MS 6000 '	'6"'	30	66.5	84.5	85.0	84.0	0.64	0.77	0.83

Table 4.11: Data Motor 1 x 230 V [21]

Motor Type	Size	Power	Full-load current	50	75	100	cos ' 50	cos ' 75	cos ' 100
'MS 402'	'4"'	0.37	3.95	48.0	54.0	57.0	0.58	0.68	0.77
'MS 402'	'4"'	0.55	5.80	49.5	56.5	59.5	0.52	0.65	0.74
'MS 402'	'4"'	0.75	7.45	52.0	58.0	60.0	0.57	0.69	0.79
'MS 402'	'4"'	1.10	7.30	62.0	69.5	72.5	0.99	0.99	0.99
'MS 402'	'4"'	1.50	10.2	56.5	66.5	71.0	0.91	0.96	0.98
'MS 4000'	'4"'	2.2	14.0	67.0	73.0	75.0	0.91	0.94	0.96

Final output of the motor-pump model

The algorithm's outcome is a structure that combines various pump types, their respective linked motors, ef ciency ratings, load parameters, output ow characteristics, and details of the power consumption for both the pump and the motor, speci cally for user input. It is separated by a single-phase or three-phase operation to distinguish the setup installations. Knowing the demanded power of the motor-pump unit referring to the highest ef ciency, it is now possible to link both models, the PV and the motor-pump model.

4.3 The PV / Motor-pump coupling model

To link both models, Figure 4.10 is introduced. It shows an overview of the system, where all input parameters are shown in light blue. The power converter is not particularly modeled. As it is an important part of the system, an assumption of constant ef ciency is made. Referring back to Equation 3.7, the following assumption is made:

$$_{¡} = 95 \quad 98\% \tag{4.11}$$

Given that assumption all the system parameters can be calculated. In doing so, different operating ranges can be established, meaning different locations and water supply demands.

Figure 4.10: Overview of system

Chapter 5

Case Studies and Results

5.1 Example system 1, Azoia de Baixo, Portugal

After clarifying the framework for the methodology and establishing the parameters for the system, it is possible to design a sample system to evaluate the methodology. The system consists of a PV array, an inverter, a motor-pump set, and additional components such as wiring and piping. The example system is located in the area of Azoia de Baixo, Portugal, as it can be seen in Figure 5.1

Figure 5.1: Location of example system 1 [1]

5.1.1 Motor-pump unit

For choosing the ideal motor-pump unit, we need to consider the total dynamic head with the input H and amount of wanted out ow Q. Regarding the water source, we are considering a well system that results in the use of a submersible motor pump unit. For this case study, we validate the model with the following input parameters:

Table 5.1: Azoia de Baixo - Daily average water needs

Month	Water need (m^3=day)
Jan.	10
Feb.	15
Mar.	19
Apr.	21
May	33
Jun.	35
Jul.	40
Aug.	33
Sep.	24
Oct.	18
Nov.	10
Dec.	9

The parameter H describes the total dynamic head, TDH. This means that for this case study, we assume the total pressure of the system to be H = 100 m. Furthermore, the out ow Q must be determined. Table 5.1 gives us insight into the water consumption pattern of the selected location by showing the average daily out ows needed for each month. Given this information, we have the necessary input for the motor-pump model. The motor-pump model with the given input creates the following outputs, as seen in Table 5.2 and Table 5.3.

Table 5.2: Azoia de Baixo - Results of motor-pump model single phase

Pump Type	Motor Type	Load (%)	$_{Motor}$ (%)	Q (m^3h^{-1})	P_{Pump} (W)	P_{Motor} (W)	$_{Pump}$ (%)	$_{Subsystem}$ (%)
SP_17	MS 4000	70.11	71.83	3.10	1542.3	2147.3	54.03	38.81

Table 5.3: Azoia de Baixo - Results of motor-pump model three phase

Pump Type	Motor Type	Load (%)	$_{Motor}$ (%)	Q (m^3h^{-1})	P_{Pump} (W)	P_{Motor} (W)	$_{Pump}$ (%)	$_{Subsystem}$ (%)
SP7_17	MS 402	70.11	74.91	3.10	1542.3	2058.8	54.03	40.48
SP7_17	MS 4000	70.11	72.08	3.10	1542.3	2139.7	54.03	38.95
SP7_23	MS 4000	95.73	75.08	7.19	2871.8	3825.0	69.07	51.86
SP7_27	MS 4000	84.89	78.24	8.19	3395.7	4340.0	66.82	52.28
SP7_31	MS 4000	95.04	78.08	8.72	3801.8	4869.1	62.94	49.14

The result shows all possible combinations of motor-pump units satisfying the input of H = 100m. With this information, the operation ranges of the equipment are de ned. The selected location does not require a xed out ow per hour, which means that to select the best-suited pump, we consider the best subsystem ef ciency of the combined motor-pump unit. This means that the pump SP7_27 with the motor MS 4000 is selected showing a motor ef ciency of $_{Motor}$ = 78:24% and a pump ef ciency of $_{Pump}$ = 66:82% resulting in the highest subsystem ef ciency of $_{subsystem}$ = 52:28%. To ensure the supply of 8.19 m^3h^{-1}, the motor absorbs a power of 4340 W that must be supplied by the PV array.

5.1.2 Power Converter/Controller

The power converter ef ciency must be considered to calculate the power needed for the PV system. As stated in Equation 4.11, the ef ciency of the power converter is assumed to be between 95% and 98%, resulting in a power supply of:

$$P_{Needed} = \frac{P_{Motor}}{0:98} = 4428:6W \tag{5.1}$$

An AC converter needs to be selected for this representative system because the pumps are AC pumps. Within this context, it is important to note that although detailed modeling of the power inverter is not within the scope of this study, we assume constant ef ciency for the selected inverter. The power converter selection process involves a comprehensive validation procedure. The algorithm used in this study generates a spectrum of potential motor-pump combinations, each of which results in varying system ef ciencies. However, the choice and validation of a power converter transcends the scope of this research. But despite that, it underscores the importance of validating and selecting an appropriate power converter.

5.1.3 Photovoltaic array

Radiation data

After introducing the possible setup, de ning the available solar resources is necessary. Rural Azoia de Baixo (Latitude: 39.303, Longitude: -8.711) is the example location. The available solar radiation and the dry bulb temperature can be taken from the PVGIS website [2]. The average ambient temperature is presented in Figure 5.2a and the global horizontal irradiance in Figure 5.2b. In addition, to have more detailed data on the global horizontal irradiance received Table 5.4 is introduced. The table shows the average monthly global horizontal irradiance received for 2020.

(a) Dry bulb temperature (b) Global horizontal irradiance

Figure 5.2: Azoia de Baixo - Data retrieved from PVGIS

Table 5.4: Azoia de Baixo - Average monthly global horizontal irradiance

Month	Global horizontal irradiance (kW h=m ^{2}=month)
Jan.	66.19
Feb.	97.27
Mar.	142.22
Apr.	134.18
May	209.76
Jun.	218.08
Jul.	248.97
Aug.	210.18
Sep.	154.92
Oct.	114.87
Nov.	66.41
Dec.	60.55

Time of pump usage

The required time the power is demanded is determined by the water needed per day divided by the pump's out ow for the xed and given height. This means:

$$Time_{July} = \frac{40m^3=day^{-1}}{8:19m^3h^{-1}} = 4:88h \tag{5.2}$$

In July, the pump has to run 4.88 hours to satisfy the needed 40m^3=day. The results for each month of the year are summarized in Table 5.5.

Table 5.5: Azoia de Baixo - Time of pump usage

Month	Water demand	Hours of operation
Jan.	10	1.22
Feb.	15	1.83
Mar.	19	2.32
Apr.	21	2.56
May	33	4.03
Jun.	35	4.27
Jul.	40	4.88
Aug.	33	4.03
Sep.	24	2.93
Oct.	18	2.20
Nov.	10	1.22
Dec.	9	1.10

Analysis

To validate the desired system, we calculate a factor that indicates the month with the highest relation between the needed energy and the available energy. This step is the rst estimation to identify the design's worst case, the relevant case. Table 5.6 shows the pattern of water demand paired with the amount of irrigation time, resulting in a daily energy value needed when multiplying the number of hours with the power needed by the pump of 4428.6 W. This energy is then compared to the peak sun hours obtained per day. Peak sun hours describe the number of hours during one day when the insolation averages an equivalent solar irradiance of 1000 W=m^2 [53]. Given this information, it is possible to calculate a factor by dividing the needed energy by the equivalent sun hours, indicating the relevant month for the design. In this case, July shows the highest value, meaning that it is the relevant month.

Table 5.6: Azoia de Baixo - Equivalent hours per month

Month	Q=day(m^3=day)	Hours of operation (h)	E_{Needed}(kWh)	Equivalent sun hours (h)	Factor
Jan.	10	1.22	5.40	2.14	2.52
Feb.	15	1.83	8.10	3.47	2.34
Mar.	19	2.32	10.27	4.59	2.24
Apr.	21	2.56	11.34	4.47	2.54
May	33	4.03	17.85	6.77	2.64
Jun.	35	4.27	18,91	7.27	2.60
Jul.	40	4.88	21.61	8.03	2.69
Aug.	33	4.03	17.85	6.78	2.63
Sep.	24	2.93	12,98	5.16	2.51
Oct.	18	2.20	9.74	3.71	2.63
Nov.	10	1.22	5.40	2.21	2.44
Dec.	9	1.10	4.87	1.95	2.50

As a consequence, a typical day in July is analyzed to obtain the correct design of the PV system. For comparison, a typical day of December is also analyzed to highlight the difference and the consequences on the design when the system is not designed for the worst case. The month of December is chosen as a comparison, because it shows the lowest energy needed per day with 4.87 kWh and also has with 60.55 kW h=m^2=month the lowest received global horizontal irradiance.
Characteristic parameters for a typical July day are shown in Figure 5.3a and Figure 5.3b. With this input into the PV model, it is possible to obtain the exact generated DC output power for each panel, as seen representative for the panel LC-50-12M in Figure 5.3c. Given the information on the size of the active area of the PV panel, it is possible to calculate its ef ciency using Equation 3.13. The output is shown in Figure 5.3d. The graph indicates that the ef ciency of the panel varies over the day due to changing irradiance and cell temperature. Maximum ef ciency is reached around 10.5%. Furthermore, the panel's output power almost reaches the peak power given by the manufacturer of 50 W, reaching values of up to 49 W.

(a) Irradiance on typical summer day

(b) Average Temperature on typical summer day

(c) Power per Panel on typical summer day

(d) Ef ciency Panel on typical summer day

The same approach is used for a typical day in December. The following gures show a representative day in December. Figure 5.4a and Figure 5.4b show the characteristic global horizontal irradiance and the average temperature over the day. As a result of the data, the power of the panel is calculated using the PV model, followed by the ef ciency calculation using Equation 3.13. Several things are noticed. Temperatures reach only 11.5 ° C, while irradiance peaks at around 870 W=m^2. This means that the irradiance received by the panels is signi cantly lower than on a typical summer day. Consequently, the power generated by the PV panel peaks at a lower value of around 45 W. An interesting observation

is that the ef ciency is higher than on a typical summer day, reaching values of up to 11.5%. This is explained by the lower dry bulb temperatures that result in a lower cell temperature, which ultimately results in a higher ef ciency, although the received irradiance is lower than STC.

(a) Irradiance on typical winter day

(b) Average Temperature on typical winter day

(c) Power per Panel on typical winter day

(d) Ef ciency Panel on typical winter day

Determination of numbers of panels

Determining the number of panels involves analyzing the demand for December and July, which demand the lowest and highest water supply. After that, it is possible to calculate the number of needed panels by the following equation:

$$N_{panel} = \frac{P_{Load}}{P_{DC}} \tag{5.3}$$

where P_{Load} = 4428:6W

Performing so for the typical days in December and July, we obtain the results shown in Table 5.7 and Table 5.8. Given the uctuating power supply of the PV panel, the number of panels needed varies for each irradiance value. The approach divides the needed load P_{Load} by the power that one panel generates throughout the day. As a result, we obtain the number of panels needed for the speci c irradiance to achieve the power needed for the required time. To conclude the number of panels needed, we are considering the time when we can satisfy the water supply. Therefore, it is investigated for how long the PV array con guration can provide the required input power for the required time. In December, we need the minimum number of panels of 98 to satisfy the out ow of 8:19m^3h^{-1} for 1.10h. Applying

the same approach for a typical day in July, we need to satisfy the same out ow for 4.88h, resulting in a minimum number of panels of 114. The usage time has been calculated in Table 5.5 before. To enable usage throughout the year, the setup for the highest number of the worst-case scenario is chosen, resulting in

$$P_{peak} = N_{Panel} \quad P_{PeakPanel} = 114 \quad 50Wp = 5700Wp \tag{5.4}$$

for the PV array. Comparison between December and July showed that considering December would lead to an undersized PV array. As a result, the needed power supply and therefore the needed water demand could not be satis ed.

Table 5.7: Number of panels summer

Time	Power per Panel	Number of panels
0	0	-
1	0	-
2	0	-
3	0	-
4	0	-
5	0	-
6	0.37	-
7	5.46	812
8	17.08	260
9	28.79	154
10	38.95	114
11	45.50	98
12	49.12	91
13	49.21	90
14	45.54	98
15	38.94	114
16	29.71	150
17	18.16	244
18	6.54	677
19	0.4702	-
20	0	-
21	0	-
22	0	-
23	0	-

Table 5.8: Number of panels winter

Time	Power per Panel	Number of panels
0	0	-
1	0	-
2	0	-
3	0	-
4	0	-
5	0	-
6	0	-
7	0	-
8	19.71	225
9	31.96	139
10	42.16	106
11	45.81	97
12	45.84	97
13	42.17	106
14	31.37	142
15	17.99	247
16	0	-
17	0	-
18	0	-
19	0	-
20	0	-
21	0	-
22	0	-
23	0	-

Ef ciency

The total ef ciency of the system is calculated by Equation 3.15. Using the average ef ciency of the PV panel on the hours of operation with 10:68%, the total ef ciency of the system using panel LC-50-12M is:

$$_{total} = \quad _{pv} \quad _{EM} \quad _{pump} \quad _{inv} = 10:68\% \quad 78:24\% \quad 66:82\% \quad 98:00\% = 5:47\% \tag{5.5}$$

The total ef ciency displays the conversion of the solar energy received to the hydraulic output power by the pump.

Results

The results for all panels of the database are shown in Table 5.9 after showcasing the methodology on the panel LC50-12M. The table gives information about the systems and their total ef ciency. The Solar

Panel A-270P shows the highest overall system ef ciency of 8:38%, according to the calculation:

$$_{total} = {}_{pv} \quad {}_{EM} \quad {}_{pump} \quad {}_{inv} = 16:36\% \;\; 78:24\% \;\; 66:82\% \;\; 98:00\% = 8:38\% \tag{5.6}$$

The selection of this system with the highest ef ciency necessitates using 22 panels, yielding a system's peak power output of 5940 W and requiring an area of 35.72 square meters (m^2). Introducing the total system area in this context is signi cant, as it may impose spatial constraints on other system con gurations within the results. Hence, considering the available space for the PV array is imperative when selecting the system's components.

Table 5.9: Azoia de Baixo - Results for all panels of database

Panel Name	$_{pv}$ (%)	$_{inv}$ (%)	$_{EM}$ (%)	$_{pump}$ (%)	$_{total}$ (%)	N_{Panel}	P_{Peak} (W)	A_{Panel} (m^2)	A_{Total} (m^2)
LC50-12M	10.68	98.00	78.24	66.82	5.47	114	5700	0.46	52.50
NU-180	13.54	98.00	78.24	66.82	6.94	32	5760	1.31	41.92
KC200GT	14.03	98.00	78.24	66.82	7.19	29	5800	1.41	40.91
A-255P	15.45	98.00	78.24	66.82	7.92	23	5865	1.62	37.34
A-260P	15.73	98.00	78.24	66.82	8.06	23	5980	1.62	37.34
A-265P	16.05	98.00	78.24	66.82	8.22	22	5830	1.62	35.72
A-270P	16.36	98.00	78.24	66.82	8.38	22	5940	1.62	35.72

5.2 Example system 2, Marzling, Germany

As a second sample location, the suburban village of Marzling is chosen. Marzling is a small village close to the metropolitan region of Munich and is suitable for the case study because of its agricultural activities. Again, the design implementation consists of the PV array, an inverter, a motor-pump set, and the necessary additional components. The location of the researched area is shown in Figure 5.5.

Figure 5.5: Location of example system 2 [1]

5.2.1 Motor-pump unit

We use the same input parameters for the system to compare the in uence of the location on the design and the sizing of the SPWPS. Therefore, we are considering the following water needs presented in Table 5.10.

Table 5.10: Marzling- Daily average water needs

Month	Water need (m^3=day)
Jan.	10
Feb.	15
Mar.	19
Apr.	21
May	33
Jun.	35
Jul.	40
Aug.	33
Sep.	24
Oct.	18
Nov.	10
Dec.	9

In addition, the TDH of H = 100m is considered an input for the motor-pump model. Due to the same input parameters, the output does not change. A summary of the potential motor-pump combinations is given again in Table 5.11 and Table 5.12 for Marzling.

Table 5.11: Marzling - Results of motor-pump model single phase

Pump Type	Motor Type	Load (%)	$_{Motor}$ (%)	Q (m^3h^{-1})	P_{Pump} (W)	P_{Motor} (W)	$_{Pump}$ (%)	$_{Subsystem}$ (%)
SP_17	MS 4000	70.11	71.83	3.10	1542.3	2147.3	54.03	38.81

Table 5.12: Marzling - Results of motor-pump model three phase

Pump Type	Motor Type	Load (%)	$_{Motor}$ (%)	Q (m^3h^{-1})	P_{Pump} (W)	P_{Motor} (W)	$_{Pump}$ (%)	$_{Subsystem}$ (%)
SP7_17	MS 402	70.11	74.91	3.10	1542.3	2058.8	54.03	40.48
SP7_17	MS 4000	70.11	72.08	3.10	1542.3	2139.7	54.03	38.95
SP7_23	MS 4000	95.73	75.08	7.19	2871.8	3825.0	69.07	51.86
SP7_27	MS 4000	84.89	78.24	8.19	3395.7	4340.0	66.82	52.28
SP7_31	MS 4000	95.04	78.08	8.72	3801.8	4869.1	62.94	49.14

The chosen motor-pump unit is the highest ef ciency combination, the pump SP7 _27 paired with the submersible motor MS 4000. The parameters resulting are an absorbed power by the motor of $P_{Motor} = 4340W$ and an out ow $Q = 8:19m^3h^{-1}$, which must be supplied by the PV array.

5.2.2 Power Converter/Controller

Again, the power ef ciency of the converter must be considered to calculate the power needed for the PV system. As stated above, the ef ciency of the power converter is assumed to be between 95% and 98%, resulting in a power supply of the PV array:

$$P_{Needed} = \frac{P_{Motor}}{0:98} = 4428:6W \tag{5.7}$$

5.2.3 Photovoltaic array

Information on the temperature and irradiance of the investigated location is necessary to obtain the power provided by the PV array. Again, the data is retrieved from the PVGIS website [2]. The location is at latitude: 48.413, longitude: 11.797 and elevation: 452 m. The characteristic dry bulb temperature

can be found in Figure 5.6a and the global horizontal irradiance in Figure 5.6b. Furthermore, Table 5.13 provides detailed information on the average global horizontal irradiance of 2020. The year 2020 again serves as the reference data for this study.

(a) Dry bulb temperature (b) Global horizontal irradiance

Figure 5.6: Marzling - Data retrieved from PVGIS

Table 5.13: Marzling - Average monthly global horizontal irradiance

Month	Global horizontal irradiance (kWh=m^2=month)
Jan.	33.52
Feb.	56.60
Mar.	111.09
Apr.	178.81
May	162.93
Jun.	154.86
Jul.	192.68
Aug.	152.69
Sep.	116.94
Oct.	59.34
Nov.	35.81
Dec.	23.96

Time of pump usage

The time of pump usage does not change with the same input parameters and, therefore, is summarized in Table 5.14.

Table 5.14: Marzling - Time of pump usage

Month	Water demand	Hours of operation
Jan.	10	1.22
Feb.	15	1.83
Mar.	19	2.32
Apr.	21	2.56
May	33	4.03
Jun.	35	4.27
Jul.	40	4.88
Aug.	33	4.03
Sep.	24	2.93
Oct.	18	2.20
Nov.	10	1.22
Dec.	9	1.10

Analysis

Again, to validate the desired system, we calculate a factor that indicates the month with the highest relationship between the energy needed and the energy available. Table 5.15 shows the pattern of water demand paired with the amount of irrigation time, resulting in a daily energy value when multiplying the hours by the power needed by the pump of 4428.6 W. This energy is then compared to the peak sun hours obtained per day. In this case, December shows the highest factor with 6.33, the month to consider for designing and sizing the PV array. The factor is proportionally high due to the low equivalent sun hours in December for this location, with only 0.77h.

Table 5.15: Marzling - Equivalent hours per month

Month	Q=day(m^3=day)	Hours of operation (h)	E_{Needed}(kWh)	Equivalent sun hours (h)	Factor
Jan.	10	1.22	5.40	1.24	4.36
Feb.	15	1.83	8.10	2.02	4.01
Mar.	19	2.32	10.27	3.58	2.87
Apr.	21	2.56	11.34	5.96	1.90
May	33	4.03	17.85	5.26	3.39
Jun.	35	4.27	18.91	5.16	3.66
Jul.	40	4.88	21.61	6.22	3.47
Aug.	33	4.03	17.85	4.93	3.63
Sep.	24	2.93	12.98	3.90	3.33
Oct.	18	2.20	9.74	1.91	5.10
Nov.	10	1.22	5.40	1.19	4.54
Dec.	9	1.10	4.87	0.77	6.33

Furthermore, it is necessary to clarify the framework for the analysis. The irradiance, ambient temperature, representative power output, and representative ef ciency of the LC-50-12M panel are presented below. The temperatures and received irradiance are signi cantly lower than in the location previously investigated, as it can be seen in Figure 5.7a and Figure 5.7b. Furthermore, the power generated by the representative panel LC-50-12M and the corresponding ef ciency are shown in Figure 5.7c and Figure 5.7d. The observations that can be made are that the generated power is signi cantly lower than the peak power of the representative panel with 50 W_p. In addition a signi cant ef ciency drop can be observed when analyzing the ef ciency during the day.

(a) Irradiance on typical December day

(b) Average Temperature on typical December day

(c) Power per Panel on typical December day

(d) Ef ciency Panel on typical December day

Results

When analyzing the month of December with the panels available from the database, it becomes clear that the number of panels needed increases signi cantly for all types of individual panels. The results of the modeling with the tool are summarized in Table 5.16. Several key facts can be seen when analyzing the results. The ef ciency of the panel is mostly lower than the STC ef ciency and the ef ciency of the previously researched location. This is because of the non-ideal conditions in operation where the ambient temperature is very low, signi cantly lower than in STC. Correction of electrical performance due to the low cell temperature bene ts the overall ef ciency of the panel during operation, but because the irradiance is noticeably lower than in STC the overall ef ciency of the panel in operation decreases.

Table 5.16: Marzling - Results for all panels of database

Panel Name	$_{pv}$ (%)	$_{inv}$ (%)	$_{EM}$ (%)	$_{pump}$ (%)	$_{total}$ (%)	N_{Panel}	P_{Peak} (W)	A_{Panel} (m^2)	A_{Total} (m^2)
LC50-12M	9.31	98.00	78.24	66.82	4.77	677	33850	0.46	311.42
NU-180	11.80	98.00	78.24	66.82	6.05	187	33660	1.31	244.97
KC200GT	13.52	98.00	78.24	66.82	6.93	149	29800	1.41	210.09
A-255P	12.99	98.00	78.24	66.82	6.66	138	33190	1.62	223.56
A-260P	13.11	98.00	78.24	66.82	6.72	137	35620	1.62	221.94
A-265P	13.46	98.00	78.24	66.82	6.90	133	35245	1.62	215.46
A-270P	13.79	98.00	78.24	66.82	7.07	130	35100	1.62	210.6

The system with the highest ef ciency can be observed with the Panel A-270P and is calculated as:

$$_{total} = {}_{pv} \quad {}_{EM} \quad {}_{pump} \quad {}_{inv} = 13{:}79\% \;\; 78{:}24\% \;\; 66{:}82\% \;\; 98{:}00\% = 7{:}07\% \tag{5.8}$$

This system needs N = 130 panels to satisfy the needed power for the demanded time of operation, resulting in a peak power P_{Peak} of 35100W and an area of 210.6 square meters (m^2) of the system.

5.3 Example system 3, Marzling, Germany - Different input

5.3.1 Motor-pump unit

We consider that the total dynamic head H = 200m to have an adequate comparison with the previous location. Furthermore, information is available about the average monthly water needs, shown in Table 5.17. Given this information, we assume an initial guess of needed out ow Q of 5 m^3h^{-1}, which we use as input for the motor-pump model.

Table 5.17: Marzling (Different Input) - Daily average water needs

Month	Water need (m^3=day)
Jan.	10
Feb.	15
Mar.	28
Apr.	36
May	40
Jun.	44
Jul.	50
Aug.	43
Sep.	32
Oct.	15
Nov.	10
Dec.	6

As a result, we obtain the following outputs shown in Table 5.18. The table summarizes the possible combinations of the motor-pump set for the input of H = 200 m for three-phase solutions. There are no possible one-phase solutions for the required TDH. The best ef ciency shows the combination of the pump SP7_42 connected to the submersible MS 6000 motor with a pump ef ciency $_{Pump}$ of 69.15% and a motor ef ciency $_{Motor}$ of 80.41% given the load on the motor of 95.24%. This results in a total subsystem ef ciency $_{subsystem}$ of 55.60%. The resulting parameters to consider are the out ow Q = 6.61 m^3h^{-1} and the absorbed power of the motor P_{Motor} = 6514.9 W. This power is then considered for sizing of the the PV array and is used for further calculations.

Table 5.18: Marzling (Different Input) - Results of motor-pump model three phase

Pump Type	Motor Type	Load (%)	$_{Motor}$ (%)	Q (m^3h^{-1})	P_{Pump} (W)	P_{Motor} (W)	$_{Pump}$ (%)	$_{Subsystem}$ (%)
SP7_37	MS 4000	80.03	80.04	5.31	4401.8	5499.5	66.05	52.87
SP7_42	MS 4000	95.24	79.86	6.61	5238.3	6559.6	69.15	55.22
SP7_51	MS 4000	86.21	78.20	7.96	6466.00	8268.5	67.02	52.41
SP7_59	MS 4000	96.89	78.20	8.52	7266.7	9292.4	64.68	50.58
SP7_37	MS 6000	80.03	80.10	5.31	4401.8	5495.3	66.05	52.91
SP7_42	MS 6000	95.24	80.41	6.61	5238.3	6514.9	69.15	55.60
SP7_51	MS 6000	86.21	82.00	7.96	6466.00	7885.3	67.02	54.96
SP7_59	MS 6000	96.89	82.00	8.52	7266.7	8861.8	64.68	53.04

5.3.2 Power Converter/Controller

Again, the ef ciency of the power converter must be considered to calculate the power needed for the PV system. The ef ciency of the power converter is assumed to be between 95% and 98%. Using P_{inv} = 98% the power supply of the PV array results in:

$$P_{Needed} = \frac{P_{Motor}}{0:98} = 6647:86W \tag{5.9}$$

This means a power of P_{Needed} = 6647.86 W is considered for the sizing of the PV array.

5.3.3 Photovoltaic array

As before, we need insight into the temperature and irradiance of the researched location to obtain the power provided by the PV array. Again, the data is retrieved from the PVGIS website [2]. The location is at Latitude: 48.413, Longitude: 11.797, and an elevation of 452 m. Furthermore, according to the website, the ideal slope is = 41 ° and the optimal azimuth angle is = 2°. The year 2020 again serves as the reference data for this study.

Time of pump usage

Again, the time it takes to ensure the power supply is determined by the total water needed per day divided by the selected out ow Q of the pump for the total dynamic head of the input. Based on the formula:

$$Time_{July} = \frac{50m^3=day^1}{6:61m^3h^{-1}} = 7:56h \tag{5.10}$$

The calculations are summarized in Table 5.19. The results show the different hours of operation of the motor-pump unit in different months of the year according to the water demand. The most time of operation is in July with 7.56 hours whereas the lowest time of operation is in December with 0.91 hours.

Table 5.19: Marzling (Different Input) - Time of pump usage

Month	Water demand	Hours of operation
Jan.	10	1.51
Feb.	15	2.27
Mar.	28	4.24
Apr.	36	5.45
May	40	6.05
Jun.	44	6.66
Jul.	50	7.56
Aug.	43	6.51
Sep.	32	4.84
Oct.	15	2.27
Nov.	10	1.51
Dec.	6	0.91

Analysis

To obtain the month to consider for sizing the equivalent sun hours per month compared to the energy needed per day. This factor identi es June as the month with the highest factor of 8.57. This means that the month of June is further analyzed.

Table 5.20: Marzling (Different Input) - Equivalent hours per month

Month	Q=day(m^3=day)	Hours of operation (h)	E_{Needed}(kWh)	Equivalent sun hours (h)	Factor
Jan.	10	1.51	10.06	1.24	8.09
Feb.	15	2.27	15.09	2.02	7.46
Mar.	28	4.24	28.16	3.58	7.86
Apr.	36	5.45	36.21	5.96	6.07
May	40	6.05	40.23	5.26	7.65
Jun.	44	6.66	44.25	5.16	8.57
Jul.	50	7.59	50.29	6.22	8.09
Aug.	43	6.51	43.25	4.93	8.78
Sep.	32	4.84	32.18	3.90	8.26
Oct.	15	2.27	15.09	1.91	7.88
Nov.	10	1.51	10.06	1.19	8.43
Dec.	6	0.91	6.03	0.77	7.81

Results

The results for all panels of the database are summarized for a typical day in June in Table 5.21.

Table 5.21: Marzling (Different Input) - Results for all panels of database

Panel Name	$_{pv}$(%)	$_{inv}$(%)	$_{EM}$(%)	$_{pump}$(%)	$_{total}$(%)	N_{Panel}	P_{Peak} (W)	A_{Panel}(m^2)	A_{Total}(m^2)
LC50-12M	10.96	98.00	80.41	69.15	5.97	261	13050	0.46	120.06
NU-180	13.83	98.00	80.41	69.15	7.54	74	13320	1.31	96.94
KC200GT	14.43	98.00	80.41	69.15	7.86	65	13000	1.41	91.65
A-255P	15.69	98.00	80.41	69.15	8.55	53	13515	1.62	85.86
A-260P	15.97	98.00	80.41	69.15	8.70	52	13520	1.62	84.24
A-265P	16.29	98.00	80.41	69.15	8.88	51	13515	1.62	82.62
A-270P	16.62	98.00	80.41	69.15	9.06	50	13500	1.62	81.00

The results show the best overall system ef ciency with the PV panel A-270P of:

$$_{total} = \quad _{pv} \quad _{EM} \quad _{pump} \quad _{inv} = 16:62\% \;\; 80:41\% \;\; 69:15\% \;\; 98:00\% = 9:06\% \tag{5.11}$$

The system consists of 50 panels resulting in a peak power of P_{Peak} = 13500W and an area of 81.00 square meters (m^2) of the system.

5.4 Comparison of results

After researching three different setups, it is possible to compare the results. Three setups have been tested:

- System 1 - Azoia de Baixo with Input 1
- System 2 - Marzling with Input 1
- System 3 - Marzling with Input 2

The comparison between the results of system 1 and system 2 serves to highlight the difference in external parameters such as location. System 3 instead shows the change in output with different input parameters, such as the change in the required TDH. To compare the nal results and observations, the best system ef ciencies of all three systems are presented in the following Table 5.22:

Table 5.22: Comparison of results of best system ef ciency

System	Panel Name	$_{pv}$ (%)	$_{inv}$ (%)	$_{EM}$ (%)	$_{pump}$ (%)	$_{total}$ (%)	N_{Panel}	P_{Peak} (W)	A_{Panel} (m^2)	A_{Total} (m^2)
1	A-270P	16.36	98.00	78.24	66.82	8.38	22	5940	1.62	35.72
2	A-270P	13.79	98.00	78.24	66.82	7.07	130	35100	1.62	210.6
3	A-270P	16.62	98.00	80.41	69.15	9.06	50	13500	1.62	81.00

When comparing the results for system 1 and system 2 it becomes noticeable that the size of the PV array is strongly linked to the location. For the same water output and required TDH system 2 in Marzling has to be sized almost 6 times bigger in peak power than in Azioa de Baixo. This results in a much larger space utilization of up to 210 square meters (m^2). Additionally, the ef ciency of the PV array during pump operation is an issue. There is a signi cant drop in ef ciency when comparing the two locations. The ef ciency of the PV array in Azoia de Baixo is of 16.36% compared to 13.79% in Marzling, resulting in a total system ef ciency of 8.38% versus 7.07%. There are several probable reasons for this observation. The irradiance received in Azoia de Baixo is signi cantly higher than the irradiance received in Marzling over a year, as we can observe from Table 5.4 and Table 5.13. As a consequence, the PV array has to be extremely oversized, making it a non-viable option for a standalone system in the area of Marzling. In this scenario, a complementary power source, such as a grid supply, would be needed. In contrast, the combination of components found for Azoia de Baixo appears to be a viable option for the required water demand and TDH, resulting in a peak power of the system of only 5940 W and utilizing only a space of 35.72 square meters. The peak power in comparison does not exceed the power supply of 4428.6 W needed by a large margin.

System 3 instead is operating under different conditions. In the case study, the TDH changed from 100m to 200m compared to systems 1 and 2. The result shows a change in ef ciency for all subsystems. As a result of the input change, the electrical machine and the pump itself operate with higher ef ciency. In addition, the PV array reaches the highest observed ef ciency of 16.62%. Both of these observations lead to the best system ef ciency of 9.06% of all three investigated systems.

These observations can be explained by a combination of factors that in uence each other. June is one of the months with the highest global horizontal irradiance received during an average year in Marzling. As a consequence, Marzling has a high amount of equivalent sun hours during the investigated period. These two key observations, paired with the individual water demand of the place, ultimately lead to the design of the PV array showing the best operation ef ciency of the investigated scenarios.

Since this research focuses on ef ciency, the general observation can be made that the PV panels with the best individual ef ciency also show the best ef ciency during operation. This does not necessarily mean that the panel with the highest ef ciency will be the solution with the least space utilization or the solution that is the most economical. This issue will be discussed later as it comes to the limitations and future work of this research.

Chapter 6

Conclusions and Future Work

6.1 Conclusion

Ultimately, the research on the optimization of solar-powered water pumping systems has shown an interesting approach to optimize the usage of such systems. With the introduction of a motor-pump model, it was possible to identify the best combination of components between the electrical machine and the pump given external limitations such as the needed TDH. Possible matches offer valuable information on possible out ows Q from the pumps and the ef ciencies of both, motors and pumps. The difference in performance is mainly caused by the component itself, as well as its subject to external parameters and limitations. With the model offering a list of all motor-pump combinations, it is possible to identify the operation range and the ef ciency of each motor-pump set. The selection of the suitable motor-pump unit for this research has been made by focusing on the best subsystem ef ciency. However, other criteria such as availability, price, etc. can be used to identify the selected components. The proposed model for the motor-pump unit showed that, depending on the combination of components used together, we can observe a signi cant difference in the operation ef ciency. It also showed that depending on the motor-pump unit, different out ows Q can be satis ed.

To obtain the power supply needed for the motor pump system, a model for the photovoltaic array was introduced. By creating a sample database of different PV panels with different electrical characteristics, it was possible to investigate the behavior of different PV panels from different manufacturers when used in SPWPS. The behavior of the PV subsystem is strongly connected to external in uences, such as location. The results showed that, on the one hand, it is possible to implement a reasonable-sized solar-powered water pumping system for Azoia de Baixo in Portugal for the required water demand and pressure height. On the other hand, implementing the same system with the same framework in Marzling is not feasible and requires a massive oversizing of the PV array. The factor of which the PV array has to be larger reaches almost reaches 6. This is mainly connected to the difference in irradiance that the locations receive, meaning that the irradiance received per year per square meter is signi cantly higher in the research location in Portugal than in Germany.

However, this study clearly shows that this technology can be a viable option to satisfy the water demand in many locations around the world. Therefore, the usage and optimization of solar-powered water pumps remain a priority to ensure access to fresh water to reduce greenhouse emissions. The technology offers a reliable and sustainable option for agriculture as well as for many people in the world who depend on these standalone systems.

In general, the results highlighted that the use of solar-powered water pumping systems can never be addressed in a general approach but rather has to be adapted and optimized for each location, in uence

and limitations. Standalone systems may be a viable solution in some areas but need a complementary power supply elsewhere. Consequently, it is of great importance to consider the environmental framework for the design of a power system.

In conclusion, this study successfully addressed the research question of developing a strategy to optimize the overall performance of solar-powered water pumping systems under diverse environmental conditions by introducing accurate models for the subsystems of the technology to identify the most ef cient components during operation. As a result, the study aimed to tailor this approach to speci c geographic locations, where it is to emphasize that location and external parameters play a crucial role in the feasibility of power systems.

Although this work introduced possible component selection based on the best overall system ef ciency, it is still possible to consider different selection criteria. Linking the models showcased optimal systems for the highest ef ciency operation. However, an ef ciency consideration may not always be the preferred selection criterion, which is why it is of great importance to consider various effects when designing a power system. Therefore, the following paragraph serves to give ideas on future work that builds on this research.

6.2 Future work

This part aims to give ideas and suggestions that can be used to build on this research. The thesis focuses primarily on the ef ciency of individual subsystems and the overall performance of the solar-powered water pumping system. Nevertheless, it may not be of primary interest to the user of the technology to focus on such. As a consequence, the constraints of this work automatically become suggestions for future work.

A very important suggestion for future work is to incorporate a detailed and comprehensive economic evaluation of the different components of the system. This would allow the potential user to select the most economical option for selecting the components.

Another suggestion involves the constraint of the available space. The results of the research were usually automatically those where the least space was occupied. However, in practice space can be a limiting factor. When there is limited space, the sizing of the PV array becomes the major concern outside of any ef ciency and economic observations.

Overall, to create a multidimensional approach, it is necessary to weigh the different constraints against each other.

In doing so, formulating the initial design variables, as introduced in the thesis, helps to create a system. The thesis focuses on the primary objective of maximizing the ef ciency of the technology. However, if the prioritized objectives, including economic and space constraints, are not met, the design variables undergo modi cation until an optimal design is reached. This approach helps to idealize the proposed system in terms of cost-effectiveness, space constraints, and, therefore, overall performance.

Bibliography

[1] Google Maps. URL https://www.google.pt/maps/@38.7448832,-9.1357184,14z?entry=ttu .

[2] JRC Photovoltaic Geographical Information System (PVGIS) - European Commission. URL https://re.jrc.ec.europa.eu/pvg_tools/en/ .

[3] PlotDigitizer Online App. URL https://plotdigitizer.com/app .

[4] Abdulhamid Alshamani. Design and Modelling of a Large-Scale Solar Water Pumping System for Irrigation in Saudi Arabia. Technical report, 2018.

[5] Athil S. Al-Ezzi and Mohamed Nainar M. Ansari. Photovoltaic Solar Cells: A Review, 8 2022. ISSN 25715577.

[6] Ilja Bakman. High-Ef ciency Predictive Control of Centrifugal Multi-Pump Stations with Variable-Speed Drives. 2016. ISBN 9789949239610.

[7] Matthew T. Boyd, Sanford A. Klein, Douglas T. Reindl, and Brian P. Dougherty. Evaluation and validation of equivalent circuit photovoltaic solar cell performance models. Journal of Solar Energy Engineering, Transactions of the ASME, 133(2), 2011. ISSN 01996231. doi: 10.1115/1.4003584

[8] P. E. Campana, H. Li, J. Zhang, R. Zhang, J. Liu, and J. Yan. Economic optimization of photovoltaic water pumping systems for irrigation. Energy Conversion and Management, 95:32–41, 5 2015. ISSN 01968904. doi: 10.1016/j.enconman.2015.01.066

[9] Rui Castro. Electricity Production from Renewables. Springer International Publishing, 2022. doi: 10.1007/978-3-030-82416-7

[10] Steven C. Chapra and Raymond P. Canale. Numerical methods for engineers. McGraw-Hill Higher Education, 2010. ISBN 9780073401065.

[11] Rosa J. Chilundo, Urânio S. Mahanjane, and Diana Neves. Design and Performance of Photovoltaic Water Pumping Systems: Comprehensive Review towards a Renewable Strategy for Mozambique. Journal of Power and Energy Engineering, 06(07):32–63, 2018. ISSN 2327-588X. doi: 10.4236/jpee.2018.67003

[12] Alma D Cota Espericueta, Robert E Foster, Luis M Gómez Rocha, Michael P Ross, Charles J Hanley, Vipin P Gupta, Octavio Montúfar, Avilez Fideicomiso, Riesgo Compartido, San Luis Potos´, Col Roma Sur, Arturo Romero, and Paredes Rubio. TEN-YEAR RELIABILITY ASSESSMENT OF PHOTOVOLTAIC WATER PUMPING SYSTEMS IN MEXICO. Technical report, 2004.

[13] Abdel Karim Daud and Marwan M. Mahmoud. Solar powered induction motor-driven water pump operating on a desert well, simulation and eld tests. Renewable Energy, 30(5):701–714, 4 2005. ISSN 09601481. doi: 10.1016/j.renene.2004.02.016

[14] Dr. Herbert Wade and Global Sustainable Energy Solutions. SOLAR WATER PUMPING SYSTEMS SYSTEM DESIGN, SELECTION AND INSTALLATION GUIDELINES. Technical report, 2019.

[15] John A. Duf e and William A. Beckman. Solar engineering of thermal processes. Wiley, 2013. ISBN 9780470873663.

[16] Food and Agriculture Organization of the United Nations. The State of the World's Land and Water Resources for Food and Agriculture – Systems at breaking point (SOLAW 2021). FAO, 12 2021. doi: 10.4060/cb7654en

[17] Stuart Fox. Balance of Solar PV Systems (BOS), 2012. URL https://www.greentechrenewables.com/article/balance-solar-pv-systems-bos .

[18] Levon Gevorkov, José Luis Dom´nguez-Garc´a, and Lluis Trilla Romero. Review on Solar Photovoltaic-Powered Pumping Systems, 1 2023. ISSN 19961073.

[19] A. A. Ghoneim. Design optimization of photovoltaic powered water pumping systems. Energy Conversion and Management, 47(11-12):1449–1463, 7 2006. ISSN 01968904. doi: 10.1016/j.enconman.2005.08.015

[20] Misrak Girma, Abebayehu Assefa, and Marta Molinas. Feasibility study of a solar photovoltaic water pumping system for rural Ethiopia. AIMS Environmental Science, 2(3):697–717, 2015. ISSN 2372-0352. doi: 10.3934/environsci.2015.3.697 URL http://www.aimspress.com/article/10.3934/environsci.2015.3.697 .

[21] GRUNDFOS. SP A, SP Submersible pumps, motors and accessories 50 Hz. Technical report.

[22] Santiago Guerrero, Ben Henderson, Hugo Valin, Charlotte Janssens, Petr Havl´k, and Amanda Palazzo. THE IMPACTS OF AGRICULTURAL TRADE AND SUPPORT POLICY REFORM ON CLIMATE CHANGE ADAPTATION AND ENVIRONMENTAL PERFORMANCE A MODEL-BASED ANALYSIS OECD TRADE AND AGRICULTURE DIRECTORATE The Impacts of Agricultural Trade and Support Policy Reform on Climate Change Adaptation and Environmental Performance: A Model-Based Analysis. Technical report, 2022.

[23] A. Hamidat and B. Benyoucef. Mathematic models of photovoltaic motor-pump systems. Renewable Energy, 33(5):933–942, 5 2008. ISSN 09601481. doi: 10.1016/j.renene.2007.06.023

[24] HOMER. HOMER - Hybrid Renewable and Distributed Generation System Design Software, 2023. URL https://www.homerenergy.com/ .

[25] Carlo Ingrao, Rossana Strippoli, Giovanni Lagioia, and Donald Huisingh. Water scarcity in agriculture: An overview of causes, impacts and approaches for reducing the risks, 8 2023. ISSN 24058440.

[26] Intergovernmental Panel on Climate Change. Climate change 2014 : synthesis report : longer report. ISBN 9789291691432.

[27] IRENA. RENEWABLE POWER GENERATION COSTS IN 2018. Interbational Renewable Energy Agency, Abu Dhabi, 2019. ISBN 978-92-9260-126-3. URL www.irena.org .

[28] Q Kou, S A Klein, and W A Beckman. A METHOD FOR ESTIMATING THE LONG-TERM PERFORMANCE OF DIRECT-COUPLED PV PUMPING SYSTEMS. Technical report, 1998.

[29] Suman Kumar Laha, Pradip Kumar Sadhu, Rudra Sankar Dhar, Rajesh Dey, Sumanta Bhattacharya, Ankur Ganguly, and Ashok Kumar Naskar. Analysis of mechanical stress and structural deformation on a solar photovoltaic panel through various wind loads. Microsystem Technologies, 27(9):3465–3474, 9 2021. ISSN 14321858. doi: 10.1007/s00542-020-05142-8

[30] Lorentz. The Solar Water Pumping Company PS2. 2023.

[31] Matlab. Polynomial curve tting - MATLAB poly t. URL https://www.mathworks.com/help/matlab/ref/polyfit.html .

[32] A. Mérida Garc´a, J. Gallagher, A. McNabola, E. Camacho Poyato, P. Montesinos Barrios, and J. A. Rodr´guez D´az. Comparing the environmental and economic impacts of on- or off-grid solar photovoltaics with traditional energy sources for rural irrigation systems. Renewable Energy, 140: 895–904, 9 2019. ISSN 18790682. doi: 10.1016/j.renene.2019.03.122

[33] Krishnappa Muralidhar and Natarajan Rajasekar. A review of various components of solar water-pumping system: Con guration, characteristics, and performance, 9 2021. ISSN 20507038.

[34] M. Nabil, S. M. Allam, and E. M. Rashad. Performance improvement of a photovoltaic pumping system using a synchronous reluctance motor. Electric Power Components and Systems, 41(4): 447–464, 2 2013. ISSN 15325008. doi: 10.1080/15325008.2012.749554

[35] Aryana Y Nakhai. Techno-Economic Analysis of a PV-Battery Water Pumping Microgrid System for Off-Grid Rural Communities in the United States: Case Study of the Navajo Nation. Technical report, 2020.

[36] Cherie Orpia, Julius Orpia, and Milagros Liberato. Technical and Economic Analysis of Solar Photovoltaic Water Pumps against Conventional Systems in Common Crops in Ilocos Sur, Philippines. Technical Report 2, 2021. URL www.psychologyandeducation.net .

[37] Justyna Pastuszak and Pawe Węgierek. Photovoltaic Cell Generations and Current Research Directions for Their Development, 8 2022. ISSN 19961944.

[38] Gloria Puglia. Study and development of a web-based software for hybrid energy system design and solar prediction analysis. Technical report.

[39] PVsyst. Features – PVsyst, 2023. URL https://www.pvsyst.com/features/ .

[40] L. R.D. Reis, J. R. Camacho, and D. F. Novacki. The newton raphson method in the extraction of parameters of PV modules. Renewable Energy and Power Quality Journal, 1(15):634–639, 4 2017. ISSN 2172038X. doi: 10.24084/repqj15.416

[41] RETScreen. RETScreen, 2023. URL https://natural-resources.canada.ca/maps-tools-and-publications/tools/modelling-tools/retscreen/7465 .

[42] SAM. Home - System Advisor Model - SAM., 2023. URL https://sam.nrel.gov/ .

[43] Schletter. PV MAX S PRODUKTBLATT. 2023. URL www.schletter-group.com .

[44] Santosh Singh Raghuwanshi and Rajesh Arya. Reliability Evaluation of Stand-alone Solar PV Energy System for Irrigation. Technical report, 2018. URL http://ssrn.com .

[45] Daisuke Somekawa, Tetsuro Taniguchi, and Yoshihito Taniike. WIND LOADS ACTING ON PV PANELS AND SUPPORT STRUCTURES WITH VARIOUS LAYOUTS. The Eighth Asia-Paci c Conference on Wind Engineering, 2013. doi: 10.3850/978-981-07-8012-8

[46] Vincenzo Stornelli, Mirco Muttillo, Tullio de Rubeis, and Iole Nardi. A new simpli ed ve-parameter estimation method for single-diode model of photovoltaic panels. Energies, 12(22), 11 2019. ISSN 19961073. doi: 10.3390/en12224271

[47] Aya Tafech, Dia Milani, and Ali Abbas. Water storage instead of energy storage for desalination powered by renewable energy - King Island case study. Energies, 9(10), 10 2016. ISSN 19961073. doi: 10.3390/en9100839

[48] Tanguy Lunel. A Flexible, Genuine Software for the Simulation and Sizing of Photovoltaic Pumping Systems. Technical report, 2020.

[49] United Nations - Economic and Social Council. Progress towards the Sustainable Development Goals. Technical report, 2022. URL https://unstats.un.org/sdgs/.

[50] B Shinde V and S Wandre S. Solar photovoltaic water pumping system for irrigation: A review. African Journal of Agricultural Research, 10(22):2267–2273, 5 2015. doi: 10.5897/ajar2015.9879

[51] Juan F. Velasco-Muñoz, José A. Aznar-Sánchez, Ana Batlles-delaFuente, and Maria Dolores Fidelibus. Sustainable irrigation in agriculture: An analysis of global research, 2019. ISSN 20734441.

[52] Shrey Verma, Shubham Mishra, Subhankar Chowdhury, Ambar Gaur, Subhashree Mohapatra, Archana Soni, and Puneet Verma. Solar PV powered water pumping system - A review. In Materials Today: Proceedings, volume 46, pages 5601–5606. Elsevier Ltd, 2020. doi: 10.1016/j.matpr.2020.09.434

[53] Asenath W. Kiprono and Alberto Ibáñez Llario. Solar Pumping for Water Supply. Practical Action Publishing, 9 2020. doi: 10.3362/9781780447810

[54] Harry Wirth and Fraunhofer Ise. Recent Facts about Photovoltaics in Germany. Technical report, 2021. URL https://www.ise.fraunhofer.de/en/publications/studies/recent-facts- .

[55] World Bank Group. Solar Pumping: The basics. 2018.

[56] World Health Organization., UNICEF., Water Supply and Sanitation Collaborative Council., and WHO/UNICEF Joint Water Supply and Sanitation Monitoring Programme. Global water supply and sanitation assessment 2000 report. World Health Organization, 2000. ISBN 9241562021.

Appendix A

PV Panel Datasheets

atersa
grupo elecnor

Optimum
new range

Solar module (60 cells 6”)

A-xxxP GSE (255/260/265/270 W)

Optimize your instalations.

High module ef®ciency and stable power output based on leading process technology.

Outstanding electrical performance under high-temperature conditions or low-irradiance conditions.

Ease of installations due to the innovative engineering design.

Rigorous quality control meets the highest international standard.

Warranty, 10-year workmanship and 25-year performance.

A unique system in the market, patented by Atersa.

TES Veri®ed

Please check our website for more detailed information on the terms and conditions of the warranty