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Dedications

We dedicate the fruits of this endeavour to the people who are dearest to our hearts. Thanks to them

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Nomenclature of Equations

G : Global horizontal irradiance (GHI) [W/m^2]

G_{STG} : Reference irradiance at Standard Test Conditions [W/m^2]

H : Daily solar irradiation on the tilted PV array [$kWh/m^2/day$]

GHI : Annual global horizontal irradiation [$kWh/m^2/year$]

PSH : Peak sunshine hours [h/day]

T_{amb} : Ambient (dry-bulb) air temperature [$^{\circ}C$]

T_{cell} : PV cell junction temperature [$^{\circ}C$]

$NOCT$: Nominal Operating Cell Temperature [$^{\circ}C$]

γ : Temperature coefficient of maximum power [$^{\circ}C^{-1}$]

f_T : Thermal correction factor [*dimensionless*]

P_{MODULE} : Module peak power at Standard Test Conditions
[Wc]

N : Number of PV modules

P_{peak} : Total installed PV peak power [kWc]

V_{OC} : Open-circuit voltage per string [$V DC$]

V_{MPP} : Maximum power point voltage per string [$V DC$]

I_{MPP} : Total MPP current (3 strings in parallel) [$A DC$]

P_{DC} : Temperature-corrected DC power output of the PV array
[kW]

η_{MPPT} : MPPT controller efficiency [*dimensionless*]

η_{VFD} : VFD (inverter) efficiency [*dimensionless*]

η_{motor} : Motor efficiency [*dimensionless*]

η_{pump} : Hydraulic pump efficiency [*dimensionless*]

η : Combined pump-unit efficiency ($\eta_{pump} \times \eta_{motor}$)
[*dimensionless*]

η_{sys} : Overall system efficiency coefficient [*dimensionless*]

HMT : Total manometric head [*m*]

ρ : Water density [*kg/m³*]

g : Gravitational acceleration [*m/s²*]

V_d : Daily water volume requirement [*m³/day*]

Q : Instantaneous pump flow rate [*m³/h*]

$Q_{nominal}$: Nominal pump flow rate at rated power and design
HMT [*m³/h*]

P_{min} : Minimum shaft power required to start the pump [*kW*]

$P_{nominal}$: Nominal rated power of the motor–pump unit [*kW*]

p_{shaft} : Mechanical power available at the pump shaft [*kW*]

I : Flow index variable (empirical regression input)

a : Polynomial coefficient — quadratic term

b : Polynomial coefficient — linear term

c : Polynomial constant term

E_{hyd} : Required daily hydraulic energy [*kWh/day*]

E_{ele} : Required daily electrical energy at pump motor input
[*kWh/day*]

E_{PV} : PV energy produced per time step [*kWh*]

E_{pump} : Electrical energy consumed by the pump per time step

$[kWh]$

ΔV : Incremental water volume per time step $[m^3]$

V_a : Annual volume of water effectively delivered $[m^3/year]$

Δt : Simulation time step $[h]$

SF : Sizing / safety factor $[dimensionless]$

PR : Performance Ratio $[dimensionless]$

i : Discount rate $[year^{-1}]$

n : Economic life of the project $[years]$

CRF : Capital Recovery Factor $[dimensionless]$

$CAPEX$: Total capital expenditure $[DZD]$

C_a : Annualised capital cost $[DZD/year]$

$OPEX$: Annual operational expenditure $[DZD/year]$

C_w : Levelised cost of water per cubic metre $[DZD/m^3]$

f_{av} : System availability factor $[dimensionless]$

General Introduction:

The association between solar energy and water pumping is not a product of recent decades; its roots extend back to the earliest practical applications of the photovoltaic effect. Since Alexandre Edmond Becquerel first observed the photovoltaic effect in 1839 [1] many decades passed before this physical phenomenon was transformed into an industrially viable technology. In 1954, the first practical silicon solar cell with an efficiency of 6% was manufactured at Bell Laboratories by Chapin, Fuller, and Pearson, [1] and space applications began demonstrating the feasibility of this technology on a broader scale.

In the specific field of water pumping, the 1970s marked the real starting point. In 1975, the United Nations Development Programme (UNDP), in collaboration with the Food and Agriculture Organization (FAO), launched the first documented field trials of solar-powered water pumping in Mali, Mexico, and India, under the "*Solar Pump Pilot Project*", funded by the United States and a group of donor countries.[2] These early experiments demonstrated that direct solar pumping was technically feasible in remote areas, even though the cost of photovoltaic modules remained prohibitively high at the time, exceeding 76 USD per watt in 1977. [2]

During the 1980s and 1990s, solar pumping technology underwent fundamental transformations. The cost of photovoltaic modules fell rapidly, and the concept of Direct Coupled PV Pumping was formalised by Royer *et al.* in their

landmark reference work published in 1998, which established the mathematical and methodological foundations for designing such systems based on the energy-balance approach. By 2011, the cost of a photovoltaic module fell below one US dollar per watt for the first time in history,[2] opening unprecedented economic prospects for solar pumping applications and contributing to the widespread deployment of these systems worldwide.

Algeria possesses exceptional solar potential that places it among the world's leading countries in terms of solar resources, with annual Global Horizontal Irradiance (GHI) in its southern regions ranging between 2,000 and 2,600 kWh/m²/year more than twice the European average.[3] The first practical experiments with solar pumping in Algeria date back to the 1980s and 1990s, within the framework of rural development projects in remote southern regions, where the Algerian Space Agency (ASAL) and the Centre for the Development of Renewable Energies (CDER) contributed to advancing scientific research in this field. At the policy level, Algeria launched in 2011 its ambitious renewable energy programme targeting 22 GW of installed capacity by 2030,[4] and the Algerian Water Company (ADE) has been exploring the potential of solar energy to power pumping stations a goal that the present study seeks to evaluate and deepen.

The central research question of this thesis is whether a complete transition to battery-free solar pumping for drinking-water supply in Algeria's arid regions can be achieved while maintaining strict technical and economic viability.

To address this question, the present study pursues the following specific objectives:

Hydraulic Diagnosis: To analyze the hydraulic infrastructure of the Ouargla province's water supply networks, with a specific focus on evaluating the energy consumption profile of the Lassilis pumping station (LA SCILES S5) as a reference case.

Solar Resource Assessment: To accurately map the solar potential across three targeted sites (Ouargla, El Oued, and Mécheria) using the 2023 Algerian Renewable Energy Atlas (Atlas GEE).

Energy System Sizing: To design and optimize the photovoltaic architecture including the solar array configuration and pumping equipment applying the established methodology of Royer *et al.*

Hourly Simulation Modeling: To develop a deterministic simulation model in Python capable of processing the complete energy conversion chain, from solar irradiance to pumped water volume, across an 8,760-hour annual dataset.

Economic Evaluation: To calculate the Levelized Cost of Water (LCOW) and assess the financial competitiveness of the proposed battery-free system against conventional grid-connected and diesel-powered alternatives.

Multi-Criteria Comparative Analysis: To conduct a comprehensive evaluation of the three sites across technical, economic, social, and operational dimensions, ultimately identifying the most viable location for initial deployment.

This thesis is organised into four complementary chapters. Chapter I reviews the theoretical foundations of photovoltaic

energy and solar water pumping systems. Chapter II establishes the hydraulic and energetic reference framework through a detailed study of the Lassilis station in Ouargla, a solar resource assessment at the three sites, and a complete sizing methodology. Chapter III constructs the deterministic mathematical model and the hourly simulation programme. The thesis concludes with Chapter IV, which presents and discusses the simulation results for all three sites, followed by a techno-economic analysis and a multi-criteria comparison to identify the most suitable site for first implementation.

I.1 Introduction

Solar photovoltaic water pumping systems (SPVWPS) represent a promising solution for sustainable water supply, particularly in remote areas without access to grid electricity. These systems have been the subject of extensive research for over 50 years, evolving from experimental concepts in the early 1970s to viable, economical means of water pumping today.[5] The integration of photovoltaic technology with water pumping mechanisms offers an environmentally friendly alternative to conventional diesel-powered or grid-connected pumps, with applications ranging from irrigation and livestock watering to domestic water supply.

This chapter provides comprehensive information about photovoltaic energy fundamentals, solar water pumping technologies, different operating modes, and energy sources used in these systems. The interdisciplinary nature of SPVWPS encompasses mechanical, electrical, electronics, computer, control, and civil engineering fields, making it essential to understand each component and their interactions.

I.2 Fundamentals of Photovoltaic Energy

I.2.1 Photovoltaic Effect and Solar Cell Operation

Photovoltaic (PV) devices generate electricity directly from sunlight through an electronic process that occurs naturally in semiconductor materials. When photons strike and ionize semiconductor material on a solar panel, outer electrons break free from their atomic bonds. Due to the semiconductor structure, these electrons are forced in one direction, creating a flow of electrical current .[6] The photovoltaic effect was first observed in 1839 by Alexandre Edmund Becquerel and has since become the foundation for modern solar energy

conversion.

Solar cells are not 100% efficient in crystalline silicon technology, partly because only certain wavelengths within the spectrum can be absorbed. As of 2024, the world record for solar cell efficiency stands at 47.6%, achieved in May 2022 by Fraunhofer ISE using a III-V four-junction concentrating photovoltaic cell. However, in real-world conditions, triple junction cells developed by NREL have demonstrated tested efficiencies of 39.5%. Module performance is generally rated under standard test conditions (STC): irradiance of 1,000 W/m², solar spectrum of AM 1.5, and module temperature at 25°C.

I.2.2 Types of Photovoltaic Technologies

Several types of photovoltaic technologies are available, each with distinct characteristics and applications:

- **Crystalline Silicon (c-Si):** This is the most common and mature PV technology. Solar panels are created by connecting crystalline silicon solar cells in series. These panels have proven reliability with most manufacturers offering 25-year warranties and life expectancies exceeding 30 years. They perform well in both cold and hot weather conditions.
- **Thin-Film Photovoltaics:** Thin-film solar cells are manufactured by depositing one or more thin layers of PV material on supporting materials such as glass, plastic, or metal. The two main types are Cadmium Telluride (CdTe) and Copper Indium Gallium Diselenide (CIGS). CdTe is the second-most common PV material after silicon and can be produced using low-cost manufacturing processes. While these materials offer cost-effective alternatives, their efficiencies remain lower than crystalline silicon .[7]
- **Concentrating Photovoltaics (CPV):** These systems use lenses

and mirrors to reflect concentrated solar energy onto high-efficiency cells. CPV arrays are primarily found in the desert Southwest of the United States and require direct sunlight and tracking systems to be most effective .[6]

- **Organic and Quantum Dot PV:** Organic PV cells are composed of carbon-rich compounds that can be tailored to enhance specific functions such as bandgap, transparency, or color. While currently only about half as efficient as crystalline silicon cells with shorter operating lifetimes, they could be less expensive to manufacture in high volumes and can be applied to flexible substrates .[7]

I.2.3 Factors Affecting Photovoltaic Performance

The output power of photovoltaic systems is influenced by numerous environmental and technical factors. Research has demonstrated that solar irradiance, PV surface temperature, tilt angle, shadow, and dust accumulation significantly impact system performance. Temperature effects are particularly notable: when solar panel surface temperature increases by 1°C in summer and winter, efficiency decreases by approximately 0.48% and 0.42% respectively .[8]

Irradiance levels have a direct impact on pump flow rates and daily water production. For example, studies conducted in Egypt from December 2020 to June 2021 showed that irradiance values reached 755.7, 792.7, and 805.7 W/m² at 12:00 PM in December, March, and June respectively, resulting in daily pumped water volumes of 129, 164.1, and 181.8 m³/day .[8]

I.3 Photovoltaic System Operating Modes

I.3.1 Grid-Connected Systems

Grid-connected photovoltaic systems are connected to the utility grid and receive grid dispatch. These systems

typically operate in a "spontaneous self-use and surplus electricity connected to the grid" mode. The electricity generated by solar cells is given priority to the load, and when the load is not exhausted, excess electricity is sent to the grid. This configuration allows the PV system to supply power to the load while simultaneously feeding surplus energy back to the utility network .[9]

Grid-connected systems offer the advantage of not requiring energy storage devices, as the grid acts as an infinite energy sink and source. Many jurisdictions implement feed-in-tariff schemes that compensate energy producers based on the amount of renewable energy they contribute to the grid. These schemes typically require that energy producers have access to the grid, commit to long-term contracts (15-25 years), and accept cost-based compensation .[10]

I.3.2 Off-Grid (Standalone) Systems

Off-grid photovoltaic systems operate independently without relying on the electrical grid. These systems are commonly deployed in remote mountainous areas, regions without electricity access, islands, communication base stations, and for street lighting applications. The system typically consists of photovoltaic modules, solar controllers, inverters, batteries, and loads .[10]

In off-grid configurations, the system converts solar energy into electrical energy when sunlight is available. The solar controller manages the inverter to supply power to the load while simultaneously charging the battery bank. During periods without sunlight, the battery supplies power to maintain system operation. The charge controller, often called the "brain" of the off-grid system, regulates power flow from the solar panel to the battery or from the battery to the load, and controls battery

charging when excess power is available .[10]

I.3.3 Hybrid Systems

Hybrid systems combine characteristics of both grid-connected and off-grid configurations. These systems incorporate an islanding switch that connects and disconnects from the grid as required. The architecture provides added advantages by allowing the utility grid to be used according to load requirements while maintaining energy storage capability for backup power. Hybrid systems may also integrate additional energy sources such as diesel generators, small hydro, or biomass generators to ensure continuous power availability .[10]

I.3.4 Micro-Grid Systems

Micro-grids represent a new network structure comprising distributed power sources, loads, energy storage systems, and control devices. These autonomous systems are capable of self-control, protection, and management, and can be connected to the external grid or operate in isolation. Micro-grids facilitate the large-scale integration of distributed power and renewable energy sources, achieving complementary energy utilization and improving overall energy efficiency. They provide highly reliable supply of various energy forms for loads and represent an effective transition from traditional grids to smart grids .[9]

I.4.Solar Water Pumping System Components

I.4.1 System Architecture

A solar-powered water pumping system comprises several key components: a PV energy generator (solar panels), power converters (controllers and inverters), an electric motor, and a pump. The integration of these components determines the

overall system efficiency and performance .[8] The size of the PV system is directly dependent on the pump size, the amount of water required, and available solar irradiance.

The purpose of the controller is twofold: firstly, it matches the output power that the pump receives with the input power available from the solar panels; secondly, it provides low-voltage or high-voltage protection by switching off the system if voltage falls outside the pump's operating range. This protection increases the pump's service life and reduces maintenance requirements [11].

I.4.2 Operating Modes for Water Pumping

Two primary methods exist for pumping water with photovoltaic systems:

- **Real-time consumption ("Pumping in the Sun"):** In this method, solar energy is consumed in real-time without battery storage. This solution necessitates water storage in a tank, where water pumped during daylight hours is stored for later use. The solar-generated electricity directly powers the water pump, or water is pumped into an elevated tank during the day and distributed by gravity after dark .[8]
- **Battery-based storage:** The second technique uses batteries to store energy generated during the day, which can then be used to pump water at any time, including nighttime hours. While this approach provides greater flexibility in pumping schedules, it increases system cost due to battery expenses and maintenance requirements .[8]

For water pumping applications, energy storage in the form of water storage is generally preferable to battery storage, as no intermediary transformation between energy forms is required, improving overall system efficiency and reducing costs

. [11]

I.5. Motor Technologies for Solar Water Pumping

I.5.1 DC Motors

Direct Current (DC) motors are commonly used in solar water pumping systems, particularly for small to medium applications up to approximately 4 kW rating. DC motors offer several advantages: they can be directly coupled to PV arrays without requiring inverters, they have simpler speed control mechanisms, and they tend to be less expensive than AC alternatives. DC systems demonstrate overall higher efficiency levels (up to 90%) compared to AC pumps of similar size (50-70% efficiency), allowing for the use of smaller solar panel arrays and reducing overall system costs. [12]

DC motors are typically available in two configurations:

- **Brushed DC motors:** These motors use brushes to deliver current to motor windings through commutator contacts. While cost-effective and affordable, they have shorter lifespans due to brush wear, produce more noise over time, generate electromagnetic interference, and have poor air-tightness, making them unsuitable for submersible applications. [13]
- **Brushless DC motors:** These motors eliminate commutator brushes, resulting in longer lifespans, lower noise (15-20 dB quieter than equivalent AC pumps), reduced maintenance requirements, and improved reliability. Brushless motors feature integral rotors with complete isolation between stator and rotor, providing 100% waterproof operation suitable for submersible applications. [14]

I.5.2 AC Motors

Alternating Current (AC) motors are preferred for larger

solar pumping applications, particularly those exceeding 3 HP or operating in commercial and agricultural settings. AC motors require a variable frequency inverter to convert the DC electricity from solar panels to AC power. The supported power range of inverters extends from 0.15 to 55 kW, making them suitable for larger irrigation systems .[11]

AC motors provide higher torque and can handle heavier loads, making them ideal for deep-well submersible pumps, industrial irrigation, and high-flow applications. They support various pump types including submersible, centrifugal, and deep well pumps, and can be integrated into hybrid systems or connected with backup generators. The use of variable frequency drives (VFDs) in AC systems allows for precise motor control, automatic start/stop functions, and fault detection, enhancing system intelligence and adaptability .[15]

While AC motors typically have longer working lifespans than DC motors and can provide larger bursts of power at higher speeds, they require more complex control systems and generally have lower efficiency than DC motors for small-scale applications .[16]

I.6 Pump Types and Mechanisms

I.6.1 Centrifugal Pumps

Centrifugal pumps are among the most widely used pump types in solar water pumping systems. These pumps feature one or more impellers inside a chamber (referred to as a pump stage). Water enters the eye of the impeller, and as it spins, centrifugal force pressurizes the water from one stage to another. To achieve high lift, multiple stages are stacked together in multi-stage configurations, with water pressure increasing as it moves from stage to stage. High-pressure centrifugal pumps can

contain up to 100 stages with heights reaching 6 meters .[12]

Centrifugal pumps require a minimum speed to start and deliver water. They can achieve flow rates up to 250 m³/hr, though efficiency reduces at high heads and low flows. The efficiency of centrifugal pumps deteriorates as speed varies, which must be considered in solar applications where power availability fluctuates with sunlight intensity .[12]

I.6.2 Positive Displacement Pumps

Positive displacement pumps are utilized for systems requiring high lift at low volumes. Unlike centrifugal pumps, positive displacement pumps can operate efficiently over a wide speed range and maintain fairly constant flow over a wide pressure range. These characteristics make them particularly suitable for solar applications where available power varies throughout the day. Positive displacement pumps are available in various designs including helical, diaphragm, and piston configurations. They can achieve heads up to 450 meters while maintaining high efficiency .[12.11]

I.6.3 Surface vs. Submersible Pumps

- **Surface Pumps:** Surface pumps are mounted at ground level with air-cooled motors that must be installed in well-ventilated locations protected from weather. They are designed to draw water from depths of 3-7 meters above the water surface through suction. If this vertical height (suction lift) is exceeded, the pump experiences cavitation, which can lead to impeller erosion and eventual pump failure. Surface pumps can be either centrifugal or positive displacement (diaphragm or piston) designs. They tend to be more efficient at high-flow pumping and less expensive than submersible pumps but are more complex to install and operate .[12]
- **Submersible Pumps:** Submersible pumps are installed

completely submerged in water and are predominantly used for deep-well pumping. They feature water-cooled or oil-cooled motors and must never be operated dry, as this will cause motor burnout. Submersible pumps are available in both centrifugal and positive displacement designs. Their underwater operation makes them quiet and efficient, with reduced maintenance requirements compared to surface pumps .[12.17]

I.7 Energy Storage and System Optimization

I.7.1 Storage Strategies

For solar water pumping applications, two main storage strategies exist: electrical energy storage in batteries and hydraulic storage in water tanks. Research and practical experience have demonstrated that water storage is generally superior to battery storage for pumping applications, as it eliminates the need for intermediary energy transformation, resulting in higher overall system efficiency and lower costs .[11]

When battery storage is employed in off-grid systems, the charge controller plays a critical role in managing energy flow. During peak photovoltaic power generation hours, the battery storage system is charged while maintaining power supply to loads. The discharge control strategy helps smooth the volatility of PV power output and assists with system peak regulation. Various operating modes can be implemented, including peak shaving, peak shaving with suppression, and peak shaving with transfer, each optimized for specific application requirements .[18]

I.7.2 Maximum Power Point Tracking (MPPT)

Maximum Power Point Tracking (MPPT) systems optimize the energy harvested from photovoltaic panels by

continuously adjusting the electrical operating point of the modules. The most common MPPT algorithm is the Perturb and Observe (P&O) method, which has proven effective in PV-based pumping systems. MPPT controllers are particularly important in systems without battery storage, where they enable cost-effective use of solar energy while improving overall system efficiency .[19]

In induction motor-based pumping systems, MPPT techniques differ from those used with DC-DC converters. Field-oriented control and MPPT strategies have been successfully introduced for global efficiency improvement. The implementation of optimal flux control through appropriate inverter firing patterns can maximize pump flow rate while achieving MPPT for the PV system and maximum motor efficiency at any irradiance and temperature condition .[20]

I.7.3 System Efficiency Considerations

The overall efficiency of a solar water pumping system depends on multiple factors including PV module efficiency, controller efficiency, motor efficiency, and pump efficiency. Studies have shown that optimizing tilt angle can significantly improve system performance. For instance, research conducted using PVSyst and SoSiT simulation tools demonstrated that systems installed at a 15° tilt angle exhibited higher efficiency compared to other angles for specific geographic locations .[21]

The relationship between power available from PV modules and pump flow rate is nonlinear and depends on solar irradiance levels. Daily water production correlates directly with effective global irradiation, emphasizing the importance of accurate solar resource assessment during system design. Additionally, proper sizing of all components from PV array capacity to pump selection is critical for achieving optimal

system performance and economic viability.

I.8 Economic and Environmental Considerations

I.8.1 Cost Analysis

The economics of solar water pumping systems have improved dramatically over recent decades. The cost of crystalline silicon PV modules, which stood at \$76.67/W in 1977, dropped below \$1.00/W by late 2011. As of 2017, power-purchase agreement prices for solar farms in the United States commonly fell below \$0.05/kWh, with the lowest bids in some Persian Gulf countries around \$0.03/kWh .[11]

For small systems below 3 HP, DC motors offer more affordable upfront costs due to their simpler design and fewer components, with no need for inverters. However, for larger applications exceeding 3 HP, while AC systems require additional investment in variable frequency inverters, the performance advantages and scalability often justify the higher initial cost. The key to minimizing solar pumping costs is reducing water demand through conservation measures such as drip irrigation, which can reduce consumption to less than half of traditional irrigation methods .[22]

I.8.2 Environmental Benefits

Solar photovoltaic water pumping systems offer significant environmental advantages over conventional diesel-powered or grid-connected alternatives. Once installed, PV systems generate no pollution or greenhouse gas emissions during operation. They show excellent scalability in respect to power needs, and silicon—the primary material in most solar cells—is abundant in Earth's crust. The systems are particularly valuable in developing countries where they eliminate reliance on toxic fuels that harm both the environment and community

members [23]

Diesel-powered pumps, while widely used for irrigation, face increasing challenges due to rising oil prices in international markets, harmful emissions from fuel combustion, high maintenance costs, and short lifespans. In contrast, solar PV water pumping systems are more economical, eco-friendly, reliable, require less maintenance, and have longer operational lifespans .[10] Additionally, rooftop PV systems typically recoup the energy invested in their manufacturing and installation within 2 years while generating up to 95% clean energy thereafter.

I.9 Applications and Global Deployment

Solar-powered water pumps serve diverse applications including domestic water supply, livestock watering, and irrigation. They prove especially useful in small-scale or community-based irrigation projects, though large-scale irrigation requiring high water volumes may face efficiency challenges due to the large PV arrays needed and potential excess energy generation during non-irrigation seasons .[11]

India has emerged as a major adopter of solar PV water pumping technology. Most systems installed in India feature 2.0-3.7 kW motors receiving energy from 4.8 kWp PV arrays. These 3.7 kW systems can deliver approximately 124,000 liters of water per day from combined static and dynamic heads totaling 120 meters. By August 30, 2016, approximately 120,000 solar PV water pumping systems had been installed worldwide, demonstrating the technology's growing acceptance and viability .[1]

Without reliable water sources, many communities in developing countries must depend on rainfall and inaccessible water sources, limiting harvests to perhaps twice yearly. Solar-

powered water pumps enable agricultural communities to improve food security, increase community wellness, and reduce poverty by providing reliable irrigation independent of rainfall patterns or grid electricity availability [23]

I.10 Conclusion

Solar photovoltaic water pumping systems represent a mature, viable technology for sustainable water supply across diverse applications and geographic contexts. The integration of photovoltaic energy generation with water pumping mechanisms offers environmental, economic, and social benefits, particularly for remote and off-grid locations. Through careful selection of operating modes, motor technologies, pump types, and system configurations, SPVWPS can be optimized to meet specific application requirements while maximizing efficiency and minimizing lifecycle costs.

The continued reduction in photovoltaic module costs, combined with advances in motor technology, control systems, and energy storage solutions, positions solar water pumping as an increasingly competitive alternative to conventional pumping methods. As global awareness of environmental sustainability grows and access to reliable electricity remains challenging in many regions, the adoption of solar water pumping systems is expected to expand significantly in the coming decades.

CHAPTER II

Sizing of Photovoltaic Pumping Systems

Water Networks, Sizing, Applied to Arid Regions of Algeri

II.1 Introduction

The techno-economic performance of solar photovoltaic water pumping systems is governed by three interdependent dimensions: hydraulic (water depth, flow rate, and storage), energetic (matching the pump's power curve to the solar irradiance profile), and economic (levelized cost of water compared to diesel or grid extension). The southern wilayas of Algeria Ouargla, El Oued, and Naâma (Mécheria) exemplify this combination of exceptional solar irradiance, deep aquifer dependence, and dispersed settlement patterns, making them an ideal integrated case study.

This chapter develops a comprehensive treatment of solar pumping across the following sections: Section II.2 analyzes the reference pumping station at Lassilis (Ouargla) and its electrical consumption patterns; Section II.3 assesses the solar resource at each site; Section II.4 establishes the complete sizing methodology; Section II.5 presents the mathematical models for each subsystem; and Section II.6 delivers the techno-economic analysis (CAPEX, OPEX, and levelized cost of water).

Throughout, battery storage is deliberately excluded in favor of hydraulic storage in elevated reservoirs, in accordance with best practice for solar pumping where adequate storage infrastructure already exists.

II.2 Water Networks of the Wilaya of Ouargla

II.2.1 Hydrogeological Context

The Wilaya of Ouargla, located in south-eastern Algeria at approximately 31.95°N, 5.32°E and an altitude of 141 m above sea level, draws on two major Saharan aquifer systems that underpin all municipal and agricultural water supply in the region. The wilaya covers approximately 163,233 km² one of the largest administrative divisions in Algeria and hosts a population of approximately 650,000 inhabitants [22] distributed across a landscape dominated by *ergs* (sand seas), *hamadas* (rocky plateaux), and the vast depression of the Oued Mya basin [23].

The Continental Intercalaire (CI) is a deep, confined, high-yield formation that extends across the entire northern Sahara at depths of 800–2,000 m [24.25] . In practice, exploitation of the CI requires boreholes of several hundred metres and involves artesian pressures that have historically reduced significantly due to widespread extraction across the transboundary aquifer system shared by Algeria, Tunisia, and Libya [26] .

The Complexe Terminal (CT), shallower but more directly accessible, comprises several superimposed sandy and calcareous formations at depths of 50–600 m [27.25] . Municipal and agricultural supply in the Ouargla basin relies primarily on the CT, whose piezometric surface has declined noticeably over recent decades due to overexploitation [27] . Wells drilled into the CT generally encounter artesian conditions that have diminished substantially; pumping is therefore

necessary to lift water from dynamic levels that now commonly lie 40–80 m below the wellhead [27] These aquifers are the sole water resource in this desert region and supply all 21 communes managed by the Algerian Water Company (ADE) [22] .

The resulting hydraulic head (HMT) for distribution systems must incorporate the dynamic water level, the discharge head to the storage reservoir, and the friction losses in the rising main. A design HMT value of 75 m is adopted consistently for all sites in this study.

Parameter	Indicative value
Communes supplied	21
Aquifers exploited	Complexe Terminal (CT)
Borehole depth	50–300 m depending on the aquifer
Treatment methods	Chlorination, de-ironing, pH correction
Storage	reservoirs + elevated water towers
Distribution	Gravity-fed from water towers

Table II.1 – General characteristics of the AEP network, Wilaya of Ouargla

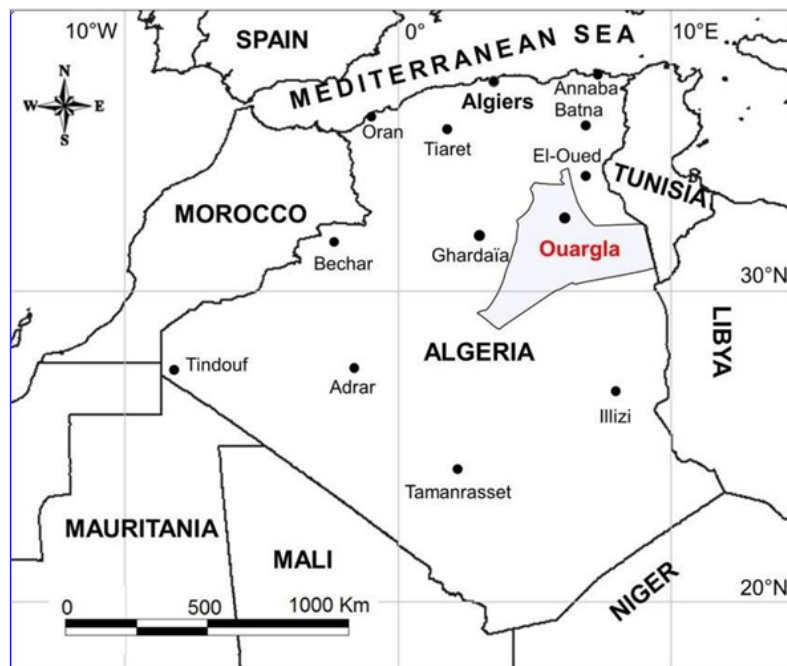


Figure II.1 – Geographic location of the Wilaya of Ouargla (south-eastern Algeria)

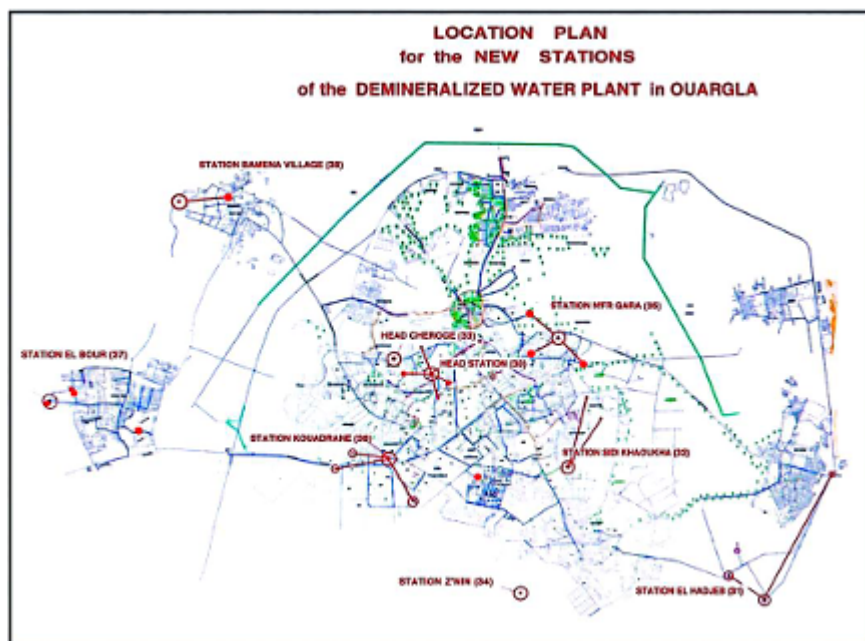


Figure II 2 – Location of the nine demineralisation stations in the Wilaya of Ouargla

II.2.2 General AEP Network Organisation

The drinking water supply (AEP) network of the Wilaya of Ouargla comprises deep-well submersible pumps, intermediate storage reservoirs, treatment stations (chlorination, de-ironing, pH correction), elevated water towers, and gravity-fed distribution pipelines. Because the region relies exclusively on groundwater, every cubic metre delivered to consumers passes through at least one pumping stage, making energy consumption a key operational parameter and justifying the strategic importance of introducing renewable energy into the pumping chain.

II.2.3 Lassilis Pumping Station

II.2.3.1 Station Overview

The Lassilis station, designated LA SCILES S5, is the principal hydraulic facility serving the central urban area and industrial zone of the Wilaya of Ouargla. It extracts raw water from a borehole field equipped with multiple submersible pumps up to six of which operate simultaneously depending on demand treats it through a demineralisation complex, and delivers it to the urban distribution network. The station also includes a 110 kW delivery pump that refills the elevated water tower.

The complete hydraulic chain comprises: (1) a borehole field with several wells, each fitted with a 37 kW submersible pump, with a maximum of six pumps running concurrently; (2) a raw water reservoir (Reservoir 1) receiving the combined flow from the active borehole pumps; (3) a treatment facility performing demineralisation, chlorination and pH correction; (4) a treated water reservoir (Reservoir 2); and (5) delivery to the urban network via the 110 kW pump, supplemented by a water tower for pressure regulation.



Figure II.3 – Treatment building at the LA SCILES S5 station

Each well pump is driven by a 37 kW three-phase motor. For sizing purposes, a hydraulic head (HMT) of 75 metres was adopted in this study, a conservative design value that takes into account the dynamic water level, the discharge head to Reservoir 1, and the energy loss due to friction in the main riser pipe.

II.2.3.2 Hydraulic Flow Diagram

The flow diagram of the Lassilis station illustrates the complete

water path from the six boreholes to the external distribution network. The following table summarises the six successive hydraulic stages:

	Description	Main Equipment
1 – Extraction	Pumping from the active boreholes (up to 6 simultaneously) into storage reservoir (1)	Submersible pumps 37 kW each · HMT = 75 m
2 – Storage (1)		Reservoir (1)
3 – Treatment	Chlorination, de-ironing, pH correction	Treatment station
4 – Storage (2)	Storage of treated water before delivery	Reservoir (2)
5 – Delivery	Pumping treated water to the water	Delivery pump 110 kW

	tower	
6 – Distribution	Gravity-fed supply of the external network	Water tower + network

Table II.2 – Hydraulic circuit steps at the Lassilis station

Figure II.1 below shows the hydraulic flow diagram of the Lassilis station, from the borehole field to the urban distribution network.



II.3 Electricity Consumption and Correlation with Water Demand

II.3.1 Installed Power

The installed electrical power at the Lassilis station is summarised in Table II.3. When all available borehole pumps are active simultaneously (maximum six units), the extraction stage alone draws up to 222 kW. Combined with the 110 kW delivery pump and auxiliary loads, the total installed power reaches approximately 337 kW. This substantial energy demand makes the station a high-priority candidate for solar integration.

Equipment	Power (kW)	Role
Extraction pumps (37 kW × up to 6 active)	up to 222 kW	Boreholes → Reservoir (1)
Delivery pump	110 kW	Reservoir (2) → Water tower
Auxiliaries (lighting, automation)	~5 kW	General operation

Estimated total installed (all active)	~337 kW	—
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Table II.3 – Installed power at the Lassilis station

II.3.2 Estimated Daily Consumption

Based on the average operating hours of each piece of equipment, the estimated daily electricity consumption is approximately 4,108 kWh/day, as detailed in Table II.4. This translates to an annual energy consumption of approximately 1.5 GWh/year for the station as a whole, representing a significant operational cost burden at conventional grid tariffs.

Equipm ent	Pow er (kW)	Hours/d ay (avg.)	Energy/ day (kWh)
Extracti on pumps (6 × 37 kW)	222	14 h	3,108
Delivery pump	110	8 h	880

(110 kW)			
Auxiliaries	5	24 h	120
Estimated daily total	—	—	~4,108 kWh/day

Table II.3 – Estimated daily electricity consumption at the Lassilis station

II.3.3 Temporal Alignment Between Pumping Schedules and Daily Water Demand

Water demand follows a typical diurnal profile characterised by two distinct peaks: a morning peak (06:00–09:00) when household activity begins, and an evening peak (17:00–21:00) when the population returns home. The significant hydraulic storage capacity of the station comprising the two reservoirs and the elevated water tower allows pumping to be temporally decoupled from consumption. This characteristic is essential for the viability of solar integration: peak solar hours (09:00–16:00) coincide with periods of relatively low consumption, and the energy produced during this window can be accumulated hydraulically in the storage reservoirs for later use during the evening demand peak.

Time Slot	Consumer Demand	Current Pumping	Remark
06:00–09:00	High	Yes	Morning peak
09:00–16:00	Low to moderate	Yes	Optimal solar window → PV pumping
16:00–21:00	High	Yes	Evening peak – limited solar
21:00–06:00	Very low	Occasionally	Night storage

0			
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Table II.4 – Temporal Alignment Between Daily Water Demand Patterns and Pumping Schedules

$$.4 \text{ kWh/day (II.2)}$$

$$E_{elec} = \frac{77.4}{0.648} = 119.4 \text{ kWh/day (II.3)}$$

The required PV peak power is then computed for each site using its site-specific PSH value, with a 20 % sizing margin applied:

II.4 Solar Resource Assessment

II.4.1 Solar Resource at Ouargla

Ouargla is located in one of the highest solar irradiance zones of North Africa, at approximately 31.9°N, 5.3°E. The region receives a Global Horizontal Irradiance (GHI) exceeding 2,400 kWh/m²/year, with more than 3,000 sunshine hours per year [3] , with more than 3,000 sunshine hours per year. The *Atlas GEE* 2023[3] reports 2,150–2,200 kWh m⁻² yr⁻¹ at the site coordinates, with a mean daily peak sunshine hour (PSH) value of 5.9–6.0 h d⁻¹ at optimal tilt. This places Ouargla among the most favourable sites in the world for photovoltaic applications.

Monthly irradiance analysis shows a pronounced

summer maximum (June–July mean daily GHI exceeding 7.5 kWh m⁻² d⁻¹) and a moderate winter minimum (December–January remaining above 3.8 kWh m⁻² d⁻¹) [3] . Peak cell temperatures above 65 °C occur in summer, causing a significant reduction in panel efficiency, as discussed in Section II.5. Effective pumping irradiance (> 400 W/m²) is available from approximately 09:00 to 17:00 on clear summer days — about 8 productive hours per day [29.3] .

II.4.2 Solar Resource at El Oued

The Wilaya of El Oued (33.37°N, 6.87°E), historically known as the "city of a thousand domes", records an annual GHI of 2,050–2,100 kWh m⁻² yr⁻¹ according to the *Atlas GEE* 2023 [3] , with a mean daily PSH of 5.6–5.8 h d⁻¹ at an optimal tilt angle of approximately 32° facing due south. The monthly distribution shows a characteristic summer plateau (June–August: 7.0–7.4 kWh m⁻² d⁻¹) and a moderate winter trough (December–January: 3.5–3.9 kWh m⁻² d⁻¹)[27]. The proximity to the Mediterranean depression creates additional dust-loading challenges for PV modules, which must be factored into the sizing margin [29.3] .

II.4.3 Solar Resource at Mécheria (Naâma)

Mécheria (33.55°N, 0.28°W), situated at 1,126 m altitude on the high steppic plains (*Hauts Plateaux*) of western Algeria, belongs to the semi-arid steppe climate zone (Köppen

BSk) rather than the fully arid desert zones of the two southern sites. The *Atlas GEE 2023* [3] records an annual GHI of 1,800–1,900 kWh m⁻² yr⁻¹ at Mécheria, with mean daily PSH values of 5.0–5.2 h d⁻¹ at an optimal tilt of approximately 33°. Although significantly lower than Ouargla and El Oued, this irradiance level substantially exceeds the economic viability threshold for PV pumping and is well above typical Central European values [3]. The cooler climate (summer maxima rarely exceeding 40 °C, winter temperatures below 0 °C) reduces the thermal penalty on PV output relative to the southern sites [29.3].

II.5 Sizing of the Solar Pumping System

II.5.1 Choice of Pumping Strategy

In direct solar pumping, the pump operates only when sufficient solar energy is available. No battery storage is used: the PV field powers the pump in real time through a variable frequency drive (VFD) incorporating MPPT control, and water is stored hydraulically in reservoirs or water towers for later use. This is unequivocally the most cost-effective approach for installations where adequate storage infrastructure already exists, as it eliminates the capital cost, maintenance burden, and efficiency losses associated with any form of electrical storage.

The GIZ/ANME technical guide (Fiche N°5, 2017) explicitly recommends this configuration as the preferred solution for agricultural and drinking-water supply systems in off-grid Saharan zones, noting that hydraulic storage is far more

economical than electrical storage for pumping applications.

- Advantages: lower capital cost, no battery replacement, simple maintenance, higher round-trip efficiency.
- Drawbacks: pumping restricted to daylight hours mitigated entirely by the existing hydraulic storage at all three sites.

Battery storage is excluded from this study at all stages of the analysis. The Lassilis station already has two large storage reservoirs (Reservoir 1 and Reservoir 2) and a water tower; the same hydraulic buffer infrastructure is supposed existing at the El Oued and Mécheria reference stations. Direct solar pumping is therefore the only strategy considered, and all sizing, modelling, and economic calculations are performed on this basis exclusively.

II.5.2 Sizing Methodology

The sizing of a solar pumping system is governed by the energy-balance method detailed in Royer et al. [29], which equates the hydraulic energy demand with the electrical energy produced by the PV field over the course of a reference day. The key input parameters are:

- Daily water requirement V_d (m³/day) determined by population served and per-capita demand.
- Hydraulic head HMT (m) comprising static head, drawdown, friction losses, and pressure head; adopted as 75 m for all three sites in this study.

- Available daily peak sunshine hours PSH (h/day) numerically equal to daily GHI in kWh m⁻².
- Component efficiencies:
- pump unit efficiency
- $\eta_{mp} = \eta_{pump} \times \eta_{motor}$ (II.1)
- inverter efficiency η_{inv} MPPT efficiency η_{MPPT} .

The required hydraulic energy per day is [29]:

$$E_{hydr} = \frac{(\rho \times g \times Vd \times HMT)}{3,600,000} \quad (II.2)$$

where $\rho = 1,000 \text{ kg m}^{-3}$ and $g = 9.81 \text{ m s}^{-2}$. The required electrical energy to be supplied to the pump motor is [29] :

$$E_{elec} = \frac{E_{hydr}}{\eta_{mp}} \quad (II.3)$$

The available solar energy at a given site is commonly expressed in terms of **Peak Sunshine Hours (PSH)**. The PSH is defined as the number of hours per day during which the solar irradiance would be at the reference level of $G_{STC}=1,000 \text{ W/m}^2$ (i.e., Standard Test Conditions) if the total daily solar energy incident on the PV array were concentrated at that reference level. It is calculated as:

$$PSH = \frac{H_{tilt}}{G_{STC}} \quad (II.3b)$$

where:

- H_{tilt} is the daily solar irradiation on the tilted PV array (kWh/m²/day),

- $G_{STC}=1 \text{ kW/m}^2$ is the reference irradiance at STC.

Thus, the numerical value of PSH (in hours) is exactly equal to the daily irradiation expressed in kWh/m². For example, a daily irradiation of 5.9 kWh/m² corresponds to 5.9 peak sunshine hours. This conversion is valid provided the same reference irradiance is used.

The required PV peak power, accounting for all system losses and a sizing margin SF [29.30.31] :

$$P_{pv} = \frac{E_{elec}}{PSH \times \eta_{sys}} \quad (\text{II.4})$$

where $\eta_{sys} \approx 0.87$ integrates wiring losses (~2 %), MPPT conversion losses (~2 %), and the mean annual thermal derating (~9 %). A sizing factor $SF \geq 1.20$ (typically 1.25–1.58 in practice) is added to account for dust soiling, wiring losses, and system degradation over the 15-year economic lifetime [32.30.33] .

II.5.3 Sizing Results by Site

Applying the methodology of Section II.5.2 with $V_d = 378 \text{ m}^3/\text{day}$, $HMT = 75 \text{ m}$, and $\eta_{mp} = 0.72 \times 0.90 \approx 0.648$:

$$E_{hydr} = \frac{(1,000 \times 9.81 \times 75 \times 378)}{3,600,000} \approx 77$$

Parameter	Ouargla	El Oued	Mécheria
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Mean annual PSH (h d⁻¹)	5.9	5.7	5.1
P_{PV} calculated (kWc)	23.3	24.1	26.9
P_{PV} with 20 % margin (kWc)	27.9	28.9	32.3
Number of modules adopted	75	75	75
Installed PV power (kWc)	42.375	42.375	42.375
Configuration	3 × 25 series	3 × 25 series	3 × 25 series

Table II.5 – PV field sizing results by site (Royer et al. [29];
Atlas GEE 2023 [3])

The deliberate standardisation of the PV field to 75 modules of 565 Wc (42.375 kWc) across all three sites despite differing irradiance levels reflects a procurement and maintenance optimisation strategy: a single module type, inverter specification, and structural design can be purchased, stocked, and serviced across multiple installations, reducing both unit costs and spare-part complexity. The lower-irradiance site (Mécheria) is covered by the same field because the required P_{PV} (32.3 kWc) remains below the installed capacity of 42.375 kWc.

Parameter	Value (all sites)
Module model	JinkoSolar Tiger NEO 565 Wc (mono-PERC)
Number of modules	75
String configuration	3 strings $\times$ 25 modules in series
Total installed PV power	42.375 kWc
Open-circuit voltage per string (STC)	1,265 V DC
MPP voltage per string (STC)	1,020 V DC
Total MPP current (3 strings)	24.9 A DC
VFD / MPPT controller	37 kW, output 3-phase 380/400 V AC
Energy storage	None – hydraulic storage only
Design HMT	75 m
Nominal pump flow at 75 m HMT	52.5 m ³ /h

Table II.6 – Standardised PV field and pump configuration for all three sites

II.6 Conclusions

This chapter has developed an integrated treatment of the three dimensions governing the techno-economic performance of solar PV water pumping in arid Algeria: hydraulic, energetic, and economic.

The Lassilis pumping station (Ouargla) was established as the hydraulic reference, consuming approximately 4,108 kWh/day (~1.5 GWh/year). The temporal alignment between the optimal solar window (09:00–16:00) and the lowest daily consumption periods provides clear justification for hydraulic storage over any form of electrical storage.

All three sites Ouargla, El Oued, and Mécheria comfortably exceed the economic viability threshold for PV pumping, with GHI values ranging from 1,800 to 2,400 kWh/m²/year. Applying the energy-balance methodology of Royer *et al.*, a standardised field configuration of 75 JinkoSolar Tiger NEO 565 Wc modules (42.375 kWc, 3 × 25 series) was adopted uniformly across all sites, balancing technical performance with logistical efficiency.

Together, these results establish the complete hydraulic, energetic, and photovoltaic reference framework upon which the modelling and simulation of the following chapter is built.

CHAPTER III

Modelling and Simulation of the Solar Pumping Sy

III.1 Introduction

Chapter II established the hydraulic, energetic, and photovoltaic reference framework for the three study sites. This chapter builds directly on that framework by constructing a deterministic, hourly time-step simulation model implemented in Python. The model ingests measured meteorological records global horizontal irradiance G and ambient air temperature T_{amb} and propagates them through a chain of sub-models to produce, at each time step, the temperature-corrected DC power of the PV field, the electrical power delivered to the pump after MPPT and VFD conversion, the instantaneous flow rate, and the cumulative water volume. The simulation architecture follows Royer et al. [29] for direct-coupled PV pumping, while the pump efficiency is modelled using the empirical regression published by Nesma et al. [32]. All key mathematical relationships are stated explicitly with symbols defined, and the complete Python source code is described section by section.

III.2 System Architecture and Modelling

Hypotheses

III.2.1 Physical Chain Considered

The system modelled in this chapter corresponds exactly to the installation described in Chapter II: a PV field of 42.375 kW_c (75 monocrystalline modules of 565 W_c each) feeds, without battery storage, a 37 kW solar-pump VFD that drives a three-phase submersible induction motor mechanically coupled to a centrifugal pump. The full signal (energy) chain is:

*Solar irradiance → PV field (DC) → MPPT / VFD → Motor →
Pump → Hydraulic output*

The following hypotheses bound the model:

- The simulation operates at a one-hour time step, matching the temporal resolution of the meteorological datasets from Ouargla, El Oued and Mécheria.
- No battery is present; the pump operates only when the available PV power exceeds the minimum start-up threshold.
- The total manometric head (HMT) is treated as a constant at 75 m throughout each simulation run, consistent with the design value adopted in Chapter II. Dynamic drawdown effects are not modelled explicitly.
- The MPPT controller is assumed to operate at its rated efficiency at every time step where it is active; no partial-load MPPT derating is applied.
- Module soiling is captured through an annual average derating factor embedded in the system efficiency coefficient η_{sys} , rather than as a time-varying variable.
- Electrical cabling losses between the PV field and the VFD are lumped into a fixed resistive loss coefficient.

III.2.2 Model Parameters

Table III.1 – Fixed parameters of the simulation model

Parameter	Symbol	Value
PV peak power	$P_{PV_{peak}}$	42.375 kWc
Number of modules	N_{mod}	75

Module peak power (STC)	P_{mod}	565 Wc
Temperature coefficient (P_max)	γ	$-0.0035\text{ }^{\circ}\text{C}^{-1}$
NOCT	NOCT	45 $^{\circ}\text{C}$
MPPT controller efficiency	η_{MPPT}	0.98
VFD (inverter) efficiency	η_{VFD}	0.95
Nominal motor–pump power	P_{nom}	37 kW
Minimum start power	P_{min}	14 kW
Nominal flow at 75 m HMT	Q_{nom}	52.5 m ³ /h
Total manometric head	HMT	75 m
Water density	ρ	1 000 kg/m ³
Gravitational acceleration	g	9.81 m/s ²

III.3 Mathematical Model

III.3.1 Photovoltaic Cell Operating Temperature

The electrical output of a crystalline silicon module depends on the temperature of its active junction, which differs from the ambient air temperature because the module absorbs a fraction of the incident radiation as heat. The NOCT (Nominal Operating Cell Temperature) model, widely used in engineering practice [29,3], estimates the cell temperature T_{cell} ($^{\circ}\text{C}$) as:

$$T_{cell} = T_{amb} + \frac{(NOCT - 20)}{800} \times G \quad (\text{III.1})$$

T_{cell} — cell junction temperature (°C)

T_{amb} — ambient (dry-bulb) air temperature (°C)

$NOCT$ — nominal operating cell temperature, taken as 45 °C for the selected module

G — in-plane global irradiance ($W\ m^{-2}$); for a horizontal dataset, G is the measured GHI

III.3.2 Temperature-Corrected PV Array DC Power

At Standard Test Conditions (STC: $G_{STC} = 1\ 000\ W\ m^{-2}$, $T_{cell_{stc}} = 25\ ^\circ C$), the array produces its rated peak power $P_{PV_{peak}}$. Under operating conditions characterised by G and T_{cell} , the array DC power P_{DC} (kW) is:

$$P_{DC} = P_{PV_{peak}} \times \frac{G}{G_{STC}} \times [1 + \gamma(T_{cell} - 25)] \quad (III.2)$$

$P_{PV_{peak}}$ — rated peak power of the PV array at STC (kWc)

G_{STC} — reference irradiance at STC = $1\ 000\ W\ m^{-2}$

G — operating irradiance ($W\ m^{-2}$)

γ — temperature coefficient of maximum power = $-0.0035\ ^\circ C^{-1}$

T_{cell} — cell temperature from equation (III.1) (°C)

The bracket term $[1 + \gamma(T_{cell} - 25)]$ is the thermal correction factor f_T introduced in Chapter II. Its value is clipped to zero for physical consistency: a module cannot deliver negative power. Equally, P_{DC} is bounded above by $P_{PV_{peak}}$ to avoid numerical artefacts at irradiances slightly above $1\ 000\ W\ m^{-2}$ that can arise in desert environments due to ground reflection or transient cloud-edge enhancement.

III.3.3 Power at the Pump Shaft after MPPT

Tracking and VFD Conversion

The MPPT controller continuously adjusts the operating point of the PV array to extract the maximum available power. It then passes this power to the VFD, which converts the variable-voltage DC from the array into variable-frequency three-phase AC suitable for the induction motor. Each stage introduces a conversion loss represented by a constant efficiency coefficient. The mechanical power available at the pump shaft P_{shaft} (kW) is:

$$P_{shaft} = \min (P_{DC} \times \eta_{MPPT} \times \eta_{VFD} \cdot P_{nom}) \quad (III.3)$$

η_{MPPT} — MPPT controller efficiency = 0.98

η_{VFD} — VFD (inverter) efficiency = 0.95

P_{nom} — nominal rated power of the motor–pump unit = 37 kW

The min() operator in equation (III.3) caps the shaft power at the nominal motor rating. Any excess PV production beyond this ceiling is dissipated as heat in the VFD's brake resistor or simply not drawn from the field. This situation occurs during peak summer irradiance at Ouargla and El Oued, when the field delivers up to 42 kW DC while the motor can only absorb 37 kW at rated conditions.

III.3.4 Pump Start-Up Threshold

A centrifugal pump coupled to an induction motor requires a minimum power to overcome the static head and initiate rotation against the hydraulic resistance. Below this threshold the VFD cannot accelerate the motor to the minimum rotational speed at which the pump generates sufficient head to lift water 1,41,4. The minimum start power P_{min} is set at 14 kW (approximately 38 % of the 37 kW nominal), consistent with manufacturer data for a 6-inch multistage submersible operating at 75 m HMT and supported by the empirical guidelines of Karassik et al. [34] and by field observations reported in Nesma et al. [32] for a similar borehole pump. In the simulation:

$$Q = 0 \quad \text{if} \quad P_{Shaft} \leq P_{min} \quad (III.4)$$

Below this threshold, the electrical energy produced by the PV field is not utilised for pumping; it represents a morning and evening loss that is characteristic of direct-coupled PV pump systems without battery storage [29]. The threshold also marks the lower boundary of the flow–power characteristic described in the next section.

III.3.5 Pump Flow Rate as a Function of Available Shaft Power

Between the start-up threshold P_{min} and the nominal power P_{nom} , the flow rate Q ($\text{m}^3 \text{ h}^{-1}$) is determined by linear interpolation on the Q–P characteristic of the pump at the design HMT [1]:

$$Q = \eta_{Pump} \times Q_{nom} \times \frac{(P_{shaft} - P_{min})}{(P_{nom} - P_{min})} \quad \text{for } P_{min} < P_{shaft} < P_{nom} \quad (III.5a)$$

$$Q = \eta_{Pump} \times Q_{nom} \quad \text{for } P_{shaft} \geq P_{nom} \quad (III.5b)$$

Q_{nom} — nominal flow at rated power and design HMT = $52.5 \text{ m}^3 \text{ h}^{-1}$

P_{min} — minimum start power = 14 kW

P_{nom} — nominal motor power = 37 kW

The hydraulic efficiency $\eta_{pump}(Q)$ is given by the empirical polynomial derived from Nesma et al. [32]:

$$\eta_{pump}(Q) = -1 \times 10^{-6} I_R^2 + 0.0021 I_R - 0.2583 \quad (III.7)$$

III.3.7 Instantaneous Volume, PV Energy and Pump Energy

At each hourly time step of duration Δt (h), the incremental water volume ΔV (m^3), the PV energy produced E_{PV} (kWh), and the

electrical energy consumed by the pump E_{pump} (kWh) are:

$$\Delta V = Q \times \Delta t \quad (III.8)$$

$$E_{PV} = P_{DC} \times \Delta t \quad (III.9)$$

$$E_{pump} = P_{shaft} \times \Delta t \quad (III.10)$$

Cumulative annual values are obtained by summation over all 8 760 hourly records. The ratio E_{pump} / E_{PV} represents the electrical efficiency of the MPPT–VFD chain and serves as a consistency check: it should remain close to $\eta_{MPPT} \times \eta_{VFD} = 0.98 \times 0.95 = 0.931$ in the hours when the pump is operating at nominal power.

III.4 Simulation Program and Flowchart

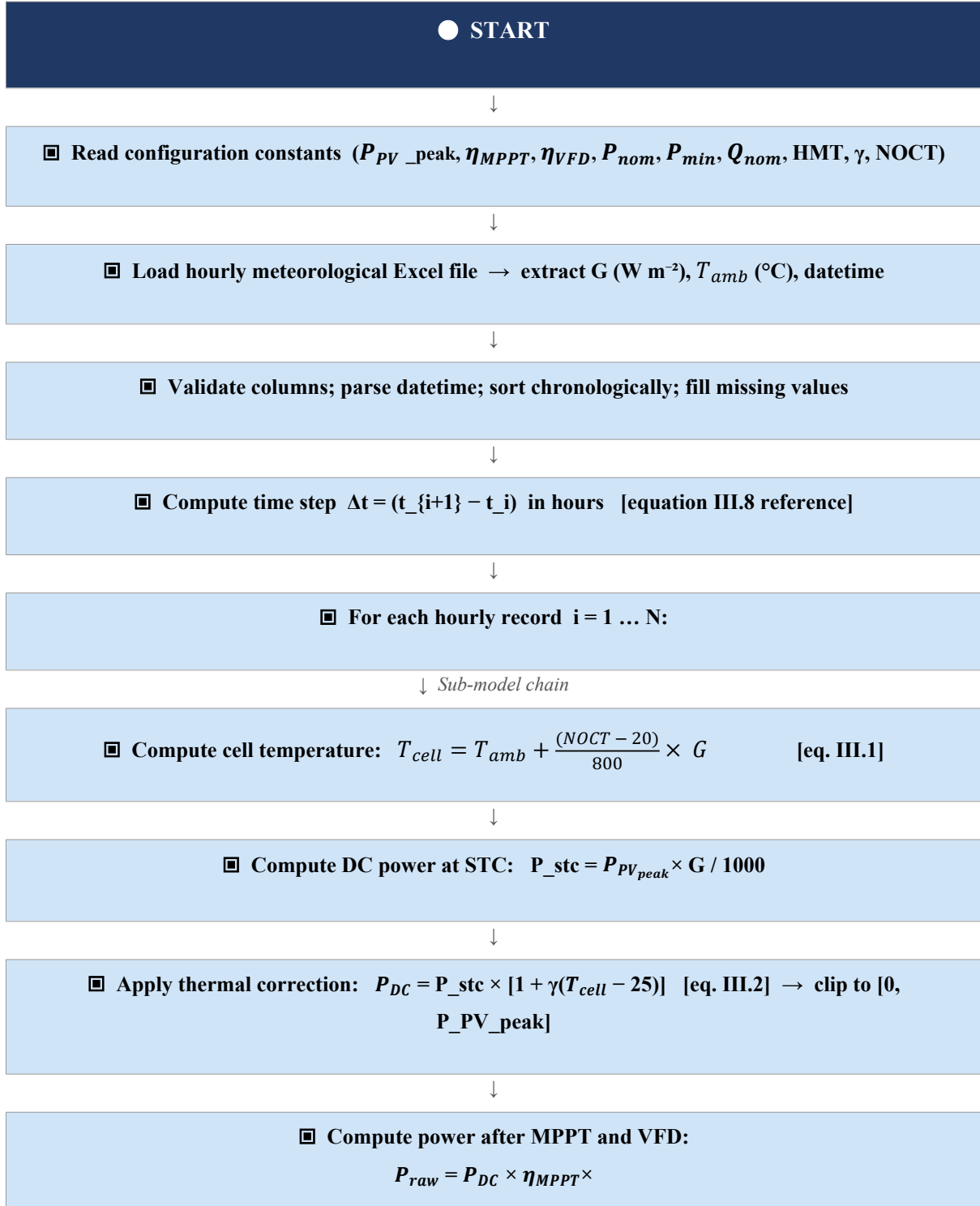
III.4.1 Program Structure

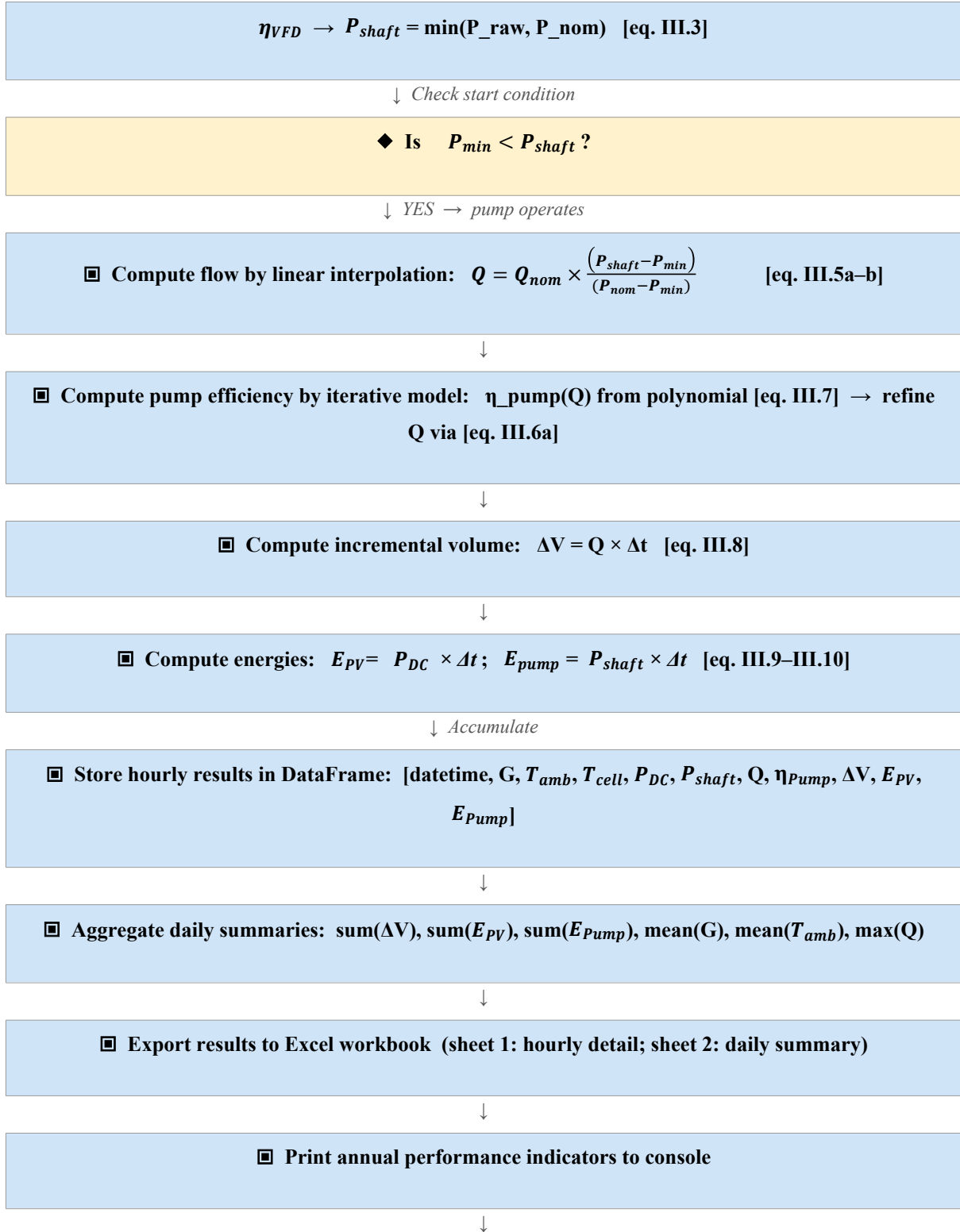
The simulation is implemented as a single Python module (`simulation_pompage.py`) organised around five functional blocks: (1) user-editable configuration constants; (2) sub-model functions (cell temperature, PV power, pump efficiency, flow rate, volume per step); (3) data ingestion and validation from the Excel meteorological file; (4) the main simulation loop applied as a vectorised Pandas operation over the full annual dataset; and (5) export of the hourly detail table and daily summary to a new Excel workbook.

III.4.2 Flowchart of the Simulation Algorithm

Figure III.1 presents the logical flowchart of the simulation. Rectangular blue boxes represent computational processes; yellow diamond boxes represent conditional branch points; and dark terminal boxes mark the start and end of the programme. The arrows indicate the direction of data flow through the algorithm.

Figure III.1 – Flowchart of the solar pumping simulation programme





● END

The branch labelled 'NO' at the start-condition diamond ($P_{shaft} \leq P_{min}$) sets $Q = 0$, $\Delta V = 0$, and $E_{pump} = 0$ for that time step, while $E_{PV} = P_{DC} \times \Delta t$ is still recorded to quantify the unutilised PV energy during off-pump hours.

III.5 Input Data and Preprocessing

III.5.1 Meteorological Datasets

Three hourly meteorological datasets are used, one for each study site. Each file is an Excel workbook containing a minimum of three columns: an hour index (integer 1 to 8 760, corresponding to the calendar hours of a representative year), the global horizontal irradiance G in W m^{-2} , and the ambient temperature T_{amb} in $^{\circ}\text{C}$. The datasets were obtained from the Meteonorm 8 software database [35], which generates hourly stochastic meteorological years from multi-year satellite and ground-station records.

III.5.2 Data Preprocessing

Each Excel file is loaded into a Pandas DataFrame. The hour index is converted to a datetime column starting from 1 January of a representative year. Missing or invalid values are filled with zero for irradiance and linearly interpolated for temperature. The data are sorted chronologically, and the time step Δt between consecutive records is computed in hours.

III.6 Conclusion

This chapter has presented the full mathematical model and the corresponding Python simulation programme for the battery-free solar pumping system. All parameters are explicitly defined and all

equations are numbered for cross-reference.

In the following chapter, the actual model will be applied to simulate the behavior of the system independently by using the three hourly meteorological datasets of Ouargla, El Oued, and Mécheria.

CHAPTER IV

Results and Discussi

IV.1 Introduction

This chapter presents the technical and economic performance of three solar pumping systems located in Ouargla, El Oued, and Mécheria. The simulation model from Chapter III was applied to hourly weather data. Each dataset contains 8,760 hourly values of global horizontal irradiance (W m^{-2}) and ambient temperature ($^{\circ}\text{C}$). The modelled system is identical at all three sites: a PV array of 42.375 kWc (75 monocrystalline modules of 565 Wc each) powers a 37 kW solar pump via a variable-frequency drive, connected to a submersible centrifugal pump at a total head of 75 m. The chapter is organised into sections covering monthly performance, cross-site comparison, economic analysis, multi-criteria decision analysis.

IV.2 Results for Ouargla

IV.2.1 Monthly Performance

Figure IV.1 shows the monthly histograms for Ouargla. The global horizontal irradiance (GHI) follows a bell-shaped seasonal pattern, peaking in June–July and reaching its minimum in December. PV energy generation tracks GHI closely, with the highest monthly output of 8 881 kWh recorded in August and the lowest of 3 835 kWh in December. The pumped water volume mirrors this pattern, rising from 1 831 m^3 in December to a maximum of 9 023 m^3 in August (a seasonal ratio of 4.9:1). Pump operating hours range from 112 h in December to 278 h in August, and the peak instantaneous flow rate of $52.5 \text{ m}^3 \text{ h}^{-1}$ is sustained from March to October, confirming that the motor operates at its nominal point for most of the pumping season.

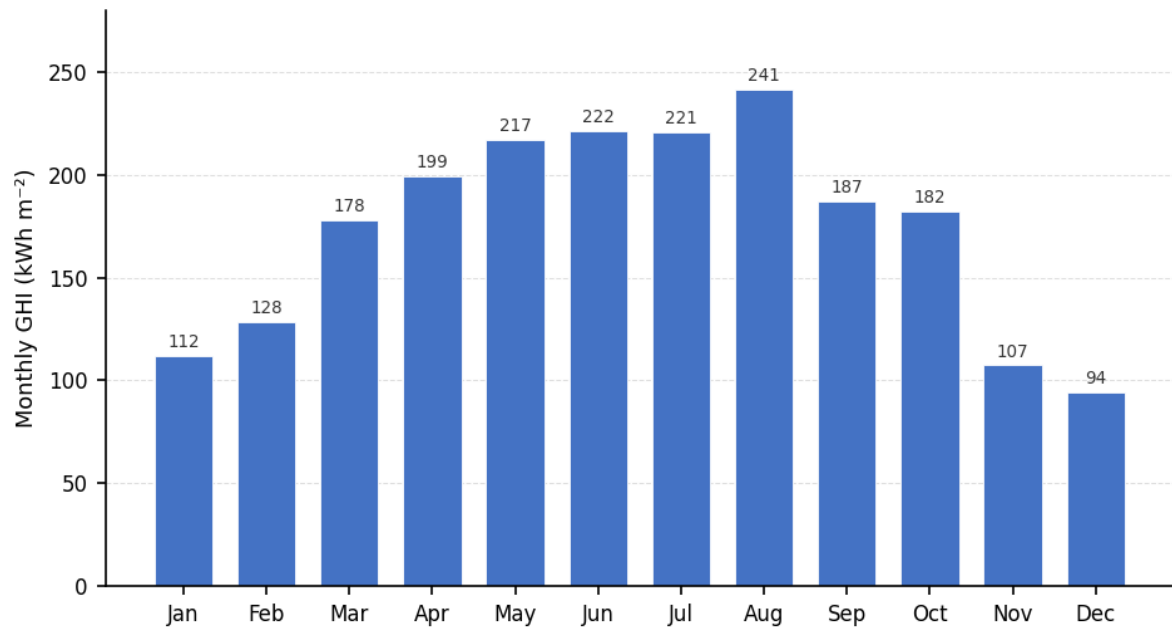


Figure IV.1a –GHI

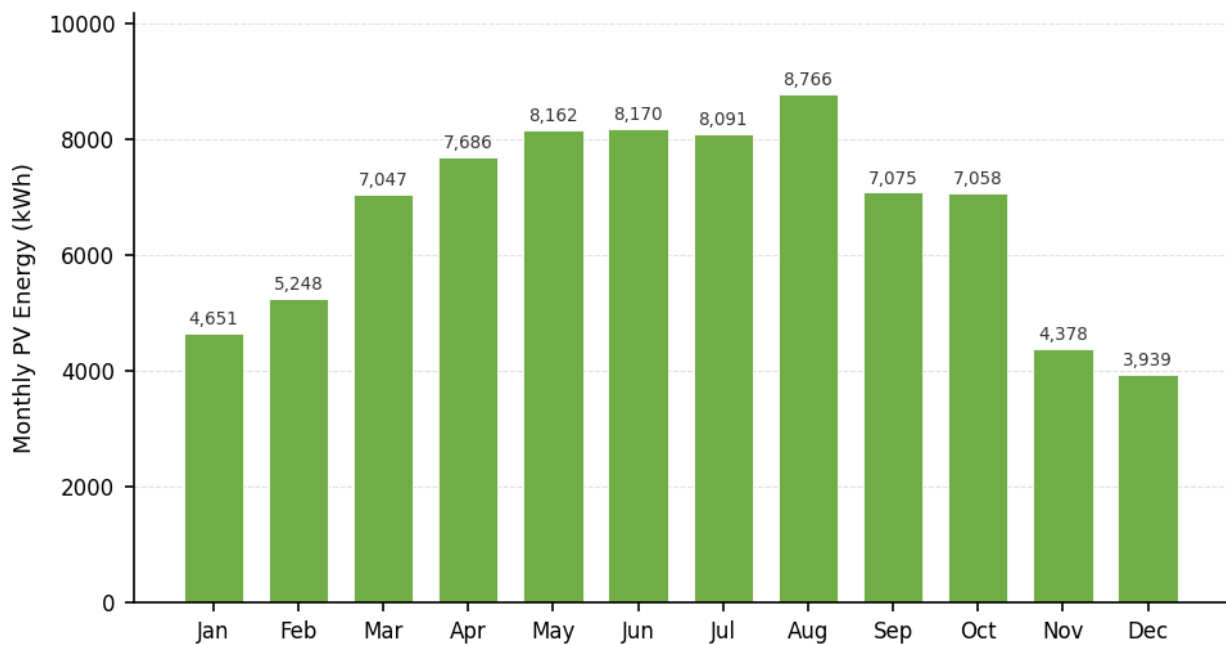


Figure IV.1b –: PV energy

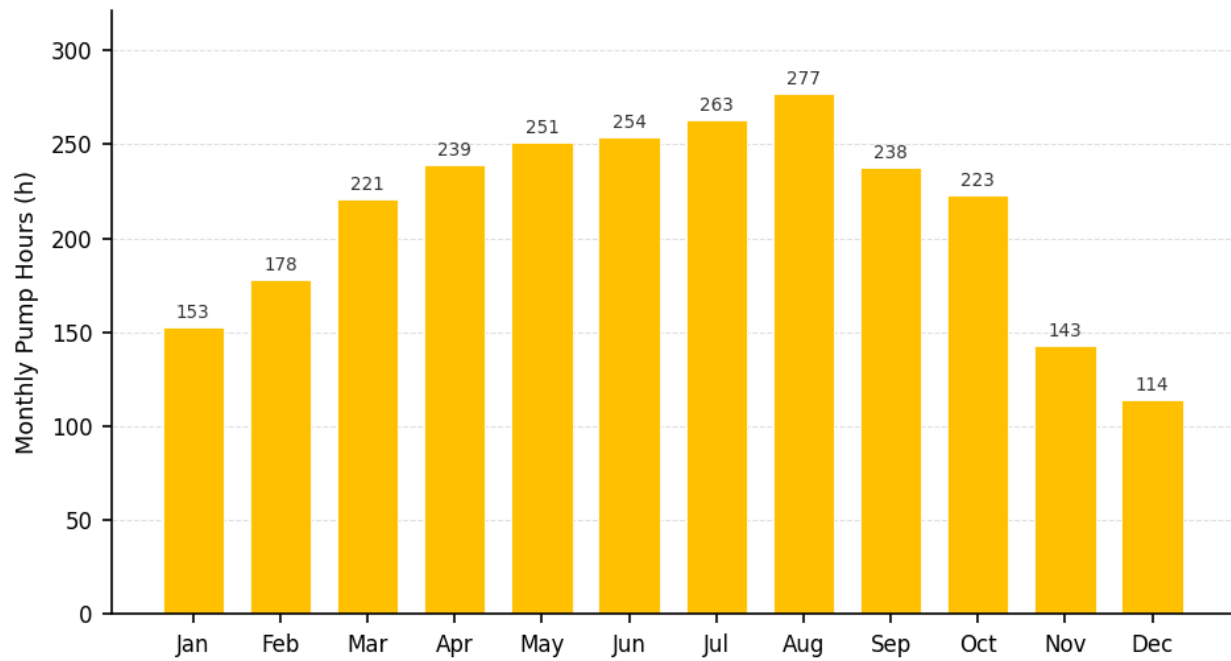


Figure IV.1c –: pump hours

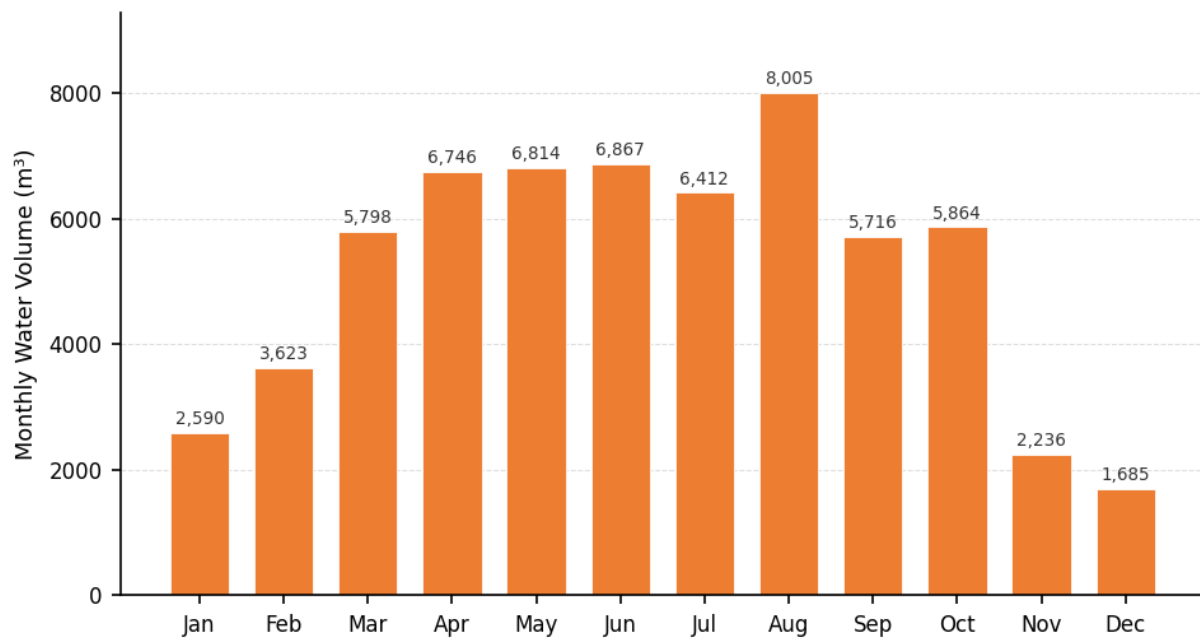


Figure IV.1d –water volume,

Figure IV.1 : Monthly performance histograms for Ouargla

IV.2.2 Monthly and Annual Water Production

The simulated annual water volume at Ouargla is 68 869 m³/year, corresponding to a mean daily output of 188.7 m³/day. Monthly production ranges from 1 831 m³ in December (59.1 m³/day) to 9 023 m³ in August (291.1 m³/day), a seasonal production ratio of 4.9:1 (August peak to December trough). The 2 554 annual pumping hours correspond to an average daily pumping window of 7.0 hours; this window narrows to approximately 4–5 hours in December and extends to nearly 9 hours on midsummer days.

The thermal correction factor f_T averages 0.979 over the year, meaning the array delivers on average 2.1 % less power than its STC rating on an annual basis. During July and August, when cell temperatures reach 45.8°C, f_T drops to 0.927 and the available shaft power is depressed below the motor nominal of 37 kW, preventing the pump from reaching its nominal flow of 52.5 m³/h. The pump reaches its nominal flow of 52.5 m³/h from March through October, when irradiance is sufficient to saturate the 37 kW motor ceiling. The PV-to-water efficiency at Ouargla is 17.5 %, within the 15–22 % range reported by Sontake and Kalamkar [2] for direct-coupled centrifugal systems at 50–100 m head, and consistent with the 17.3 % measured by Boukebbous et al. [36] at Sebseb (Ghardaïa) at 55 m head.

IV.2.3 Energy Balance

The PV field produces 80 622 kWh/year of temperature-corrected DC energy. Of this, 74 962 kWh (93.1 %) is absorbed by the pump motor. The capping loss when PV output exceeds

the 37 kW motor ceiling amounts to 5 538 kWh (6.9 %). Sub-threshold energy hours when irradiance is present but insufficient to overcome the 14 kW start threshold accounts for 12 577 kWh (15.6 % of annual PV production). The Performance Ratio defined as

$$PR = \frac{E_{pv.act}}{P_{peak} \times GHI} \quad (IV.1)$$

reaches 91.1 % at Ouargla, the highest among the Saharan sites. With a specific annual yield of 1 903 kWh per kWc installed, every watt of peak capacity is used productively throughout the year.

IV.3 Results for El Oued

IV.3.1 Monthly Performance

Figure IV.2 presents the monthly histograms for El Oued. The annual GHI of 1 878 kWh/m² is the lowest of the three sites. The GHI distribution is strongly asymmetric: summer months (June–August) accumulate 647 kWh/m², nearly three times the winter total (November–January: 242 kWh/m²). PV energy production follows the same pattern, with August generating 8 502 kWh – nearly three times the December output of 2 974 kWh. The water volume histogram shows the most extreme seasonal contrast: the August peak of 8 249 m³ is 9.7 times the December trough of 847 m³. Monthly pumping hours range from 82 h in December to 270 h in August.

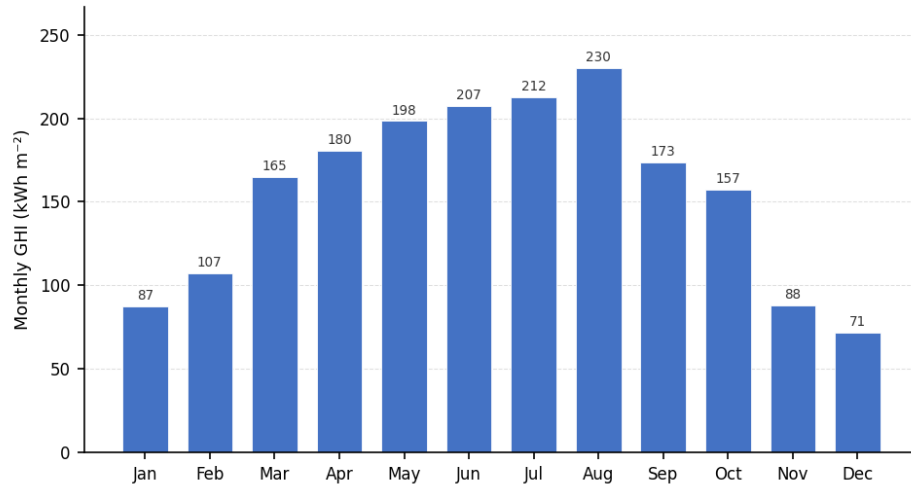


Figure IV.2a –GHI

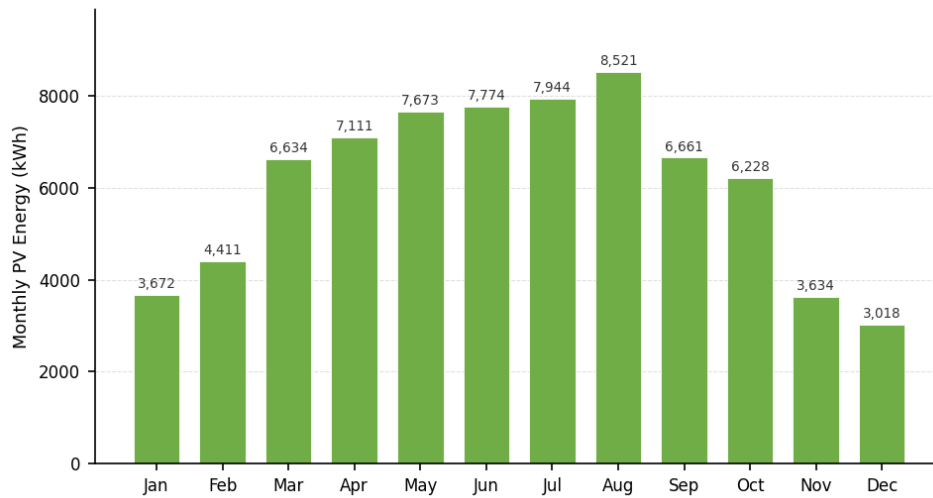


Figure IV.2b –PV energy hours

Figure IV.2c –water volume

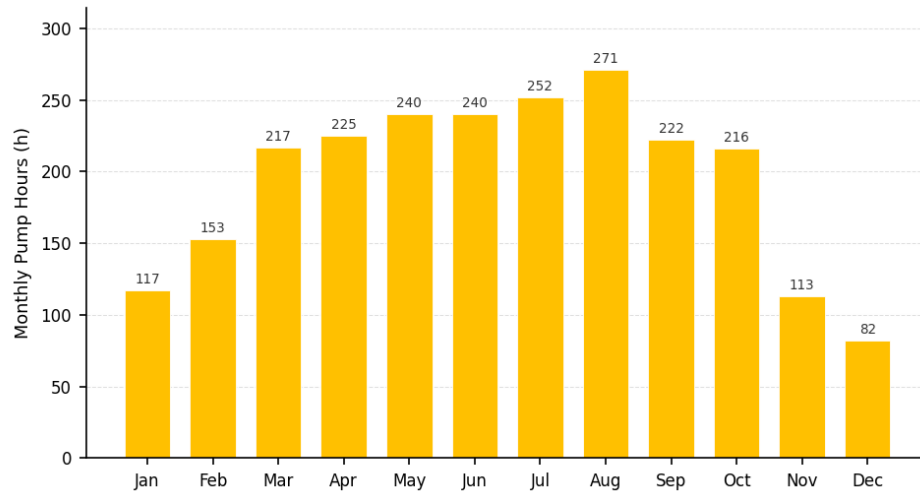


Figure IV.2d–pump hours

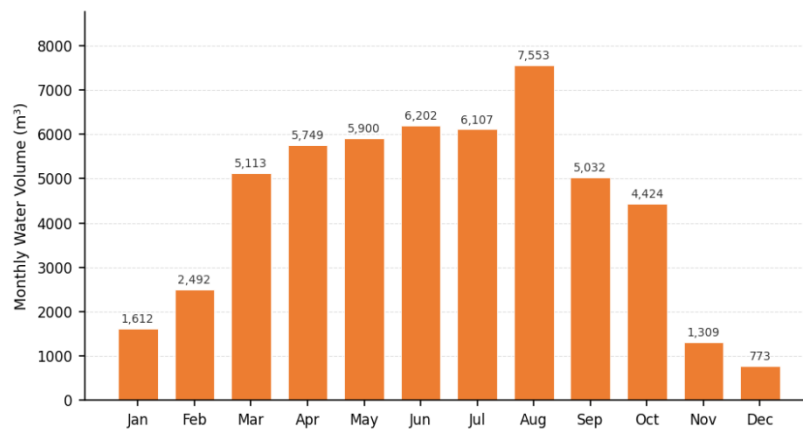


Figure IV.2 Month

ly performance histograms for El Oued

IV.3.2 Monthly and Annual Water Production

The simulated annual water volume at El Oued is 57 546 m³/year (157.7 m³/day mean) the lowest of the three sites. The seasonal ratio of 9.7:1 (December 773 m³ vs August 7 553 m³) is the most pronounced, driven by the pronounced

winter irradiance deficit. The four winter months (November–February) together contribute only 6 186 m³, or 11.8 % of the annual total. The 2 348 annual pumping hours are the fewest of the three sites. The PV-to-water efficiency is 16.0 %, somewhat below Ouargla, because a larger fraction of operating hours falls in the low-irradiance regime where the pump runs well below its nominal duty point.

IV.3.3 Energy Balance

Annual PV production is 73 503 kWh, of which 68 343 kWh (93.1 %) reaches the pump shaft. The sub-threshold energy loss of 13 451 kWh represents 18.3 % of annual PV production the highest proportion among the three sites reflecting the larger number of low-irradiance hours in winter. This indicates that a modest battery buffer would be more beneficial at El Oued than at the other two sites, though the overall economic case for battery-free operation remains valid.

IV.4 Results for Mécheria

IV.4.1 Monthly Performance

Figure IV.3 shows the monthly histograms for Mécheria. The site receives the highest GHI in every month from March to October, with an annual GHI of 2 544 kWh/m² (21.7 % above Ouargla, 35.5 % above El Oued). This is due to Mécheria's altitude (1 126 m) giving a thinner atmosphere. Low ambient temperatures (annual mean 13.8 °C) keep cell temperatures below 25 °C for several winter months, producing ($f_T > 1$) (net thermal gain). The PV field is standardised at 42.375 kWc; at Mécheria this results in saturation of the 37 kW motor ceiling from February to October, delivering nominal flow (52.5 m³/h) for most of those months.

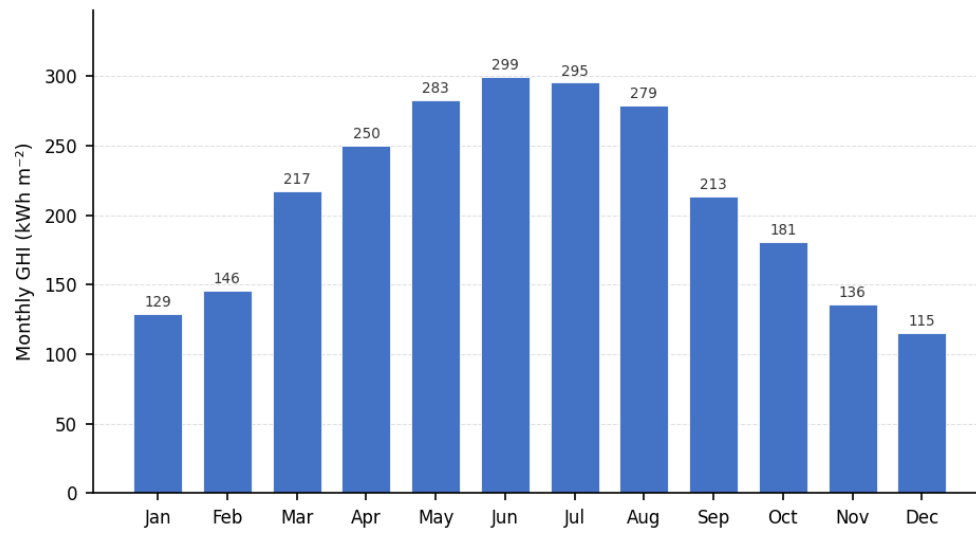


Figure IV.3a –: GHI

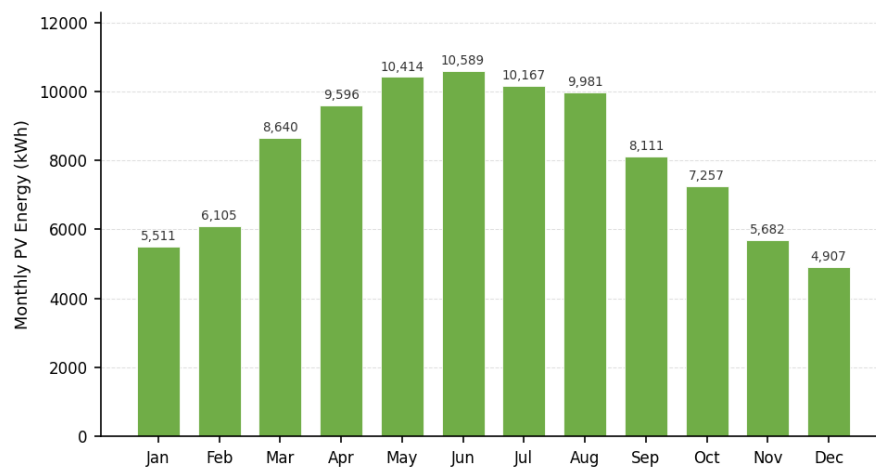


Figure IV.3b–PV energy,

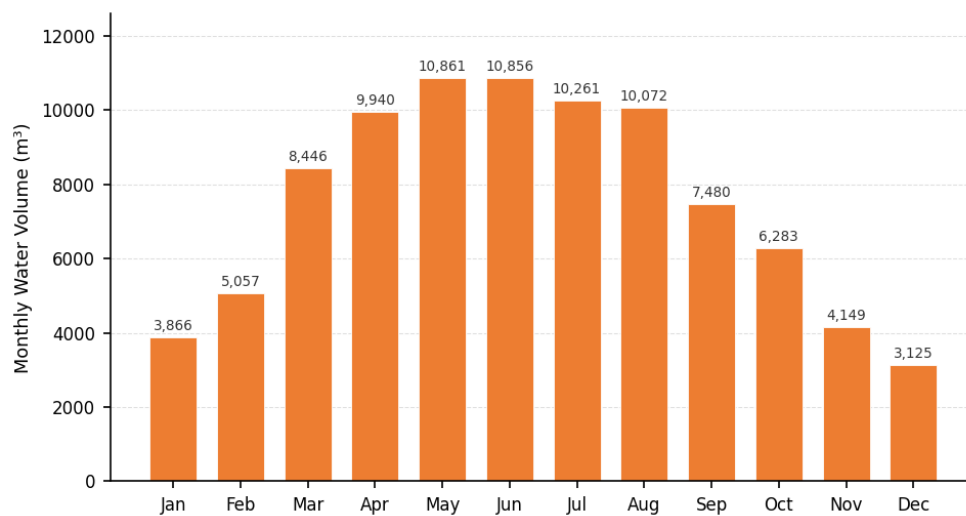


Figure IV.3c –water volume

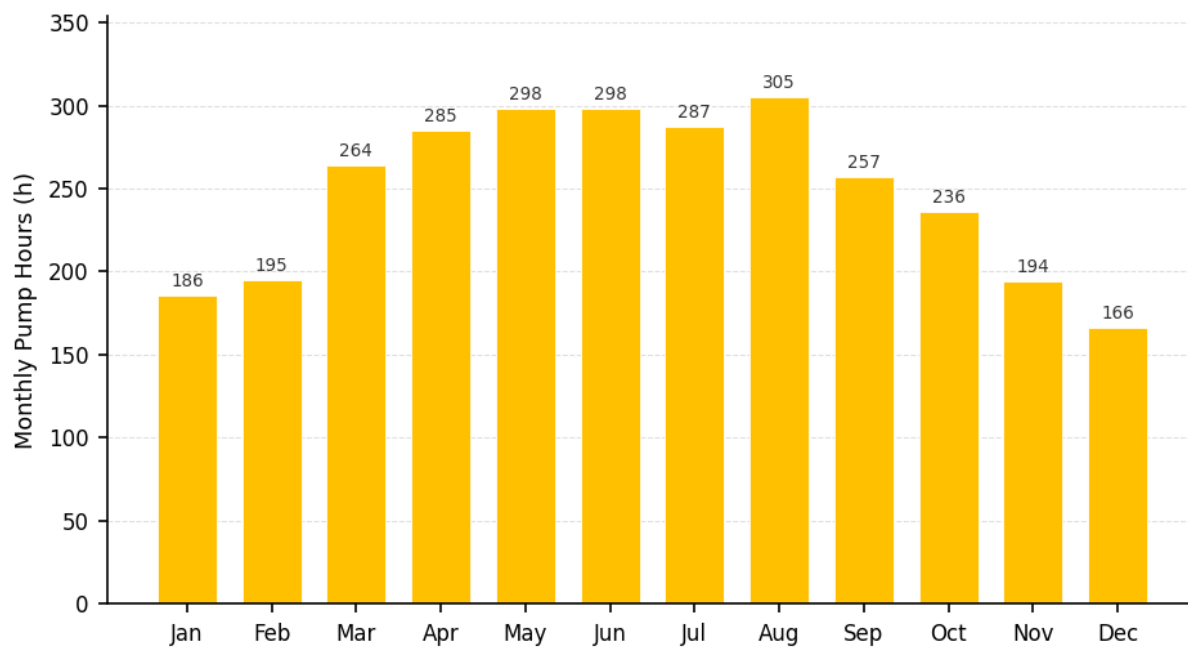


Figure IV.3d –pump hours

Figure IV.3 Monthly performance histograms for Mécheria

IV.4.2 Monthly and Annual Water Production

Mécheria produces 99 510 m³/year (272.6 m³/day mean). Monthly production ranges from 3 125 m³ in December to 10 861 m³ in May, a seasonal ratio of 3.6:1 the most balanced of the three sites. The pump reaches its nominal flow of 52.5 m³/h in seven months (February through October in Table IV.3), reflecting the site's high irradiance and low temperatures allowing simultaneous saturation of the motor ceiling. The 2 971 annual pumping hours are the most of the three sites. The PV-to-water efficiency reaches 20.4 %, above both Saharan sites, because the lower operating temperature allows the motor to run closer to its rated duty for a larger fraction of the year. However, these production figures must be contextualised: Mécheria serves a significantly smaller urban population than Ouargla, and its remote location on the high plateau entails logistical challenges for equipment installation and maintenance that are not reflected in the simulation output.

IV.4.3 Energy Balance

Annual PV production at Mécheria is 99 769 kWh, of which 90 468 kWh (93.1 %) reaches the pump shaft. The sub-threshold energy loss of 10 077 kWh (10.1 %) is the lowest of the three sites, because Mécheria's stronger irradiance more frequently exceeds the 14 kW start threshold even in winter.

IV.5 Cross-Site Comparative Analysis

Table IV.4 consolidates the principal annual performance indicators for all three sites. The annual summary is presented first to frame the detailed discussion that follows.

Table IV.4 – Annual performance summary for Ouargla, El Oued and Mécheria

Performance indicator	Ouargla	El Oued	Mécheria
Annual GHI (kWh m ⁻² yr ⁻¹)	2 089	1 878	2 544
Annual mean T_amb (°C)	23.7	21.4	13.9
Annual mean T_cell (°C)	31.1	28.1	23.0
Annual mean f_T	0.979	0.989	1.007
Annual thermal derating loss (%)	8.92	7.63	−0.7 (net thermal gain)
Annual PV energy produced (kWh)	80 622	73 503	99 769
Annual pump energy consumed (kWh)	74 962	68 343	90 468
Sub-threshold wasted energy (kWh)	12 577	13 451	10 077
Sub-threshold loss (% of E_PV)	15.6	18.4	10.1
Annual pumping hours (h yr ⁻¹)	2 554	2 348	2 971
Annual water volume (m ³ yr ⁻¹)	68 869	57 546	99 510
Mean daily volume (m ³ day ⁻¹)	188.7	157.7	272.6
Peak monthly volume (m ³)	9 023	8 249	11 810
Minimum monthly volume (m ³)	1 831	847	3 387
Best-to-worst month ratio	4.9:1	9.7:1	3.6:1
Max instantaneous flow (m ³ /h)	52.5	52.5	52.5

Performance indicator	Ouargla	El Oued	Mécheria
PV-to-water efficiency (%)	17.5	16.0	20.4
Specific annual yield (kWh/kWc installed)	1 902	1 734	2 354

IV.5.1 Monthly Volume and Irradiance

Comparison

Table IV.5 presents monthly water volumes for all three sites. Mécheria leads in every month without exception. The cross-site histograms in Figure IV.4 reveal two important patterns: first, the monthly GHI gap between Mécheria and the Saharan sites is widest in spring (April–June), when Mécheria’s high-altitude clear sky provides irradiance well above 280 kWh/m²/month; second, the winter GHI at El Oued drops to only 70.5 kWh/m² in December far below Mécheria’s 112.1 kWh/m² despite Mécheria being at a higher latitude, a direct consequence of El Oued’s cloudier winter climate.

Table IV.5 – Monthly water volumes (m³) at the three sites

Month	Ouargla (m ³)	El Oued (m ³)	Mécheria (m ³)	MC/OQ	MC/EL
Jan	2 836	1 766	4 234	1.49	2.40
Feb	4 211	2 891	5 800	1.38	2.01
Mar	6 382	5 729	9 154	1.43	1.60
Apr	7 500	6 220	10 641	1.42	1.71
May	7 429	6 624	11 810	1.59	1.78
Jun	7 703	6 774	12 214	1.59	1.80

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Month	Ouargla (m ³)	El Oued (m ³)	Mécheria (m ³)	MC/OQ	MC/EL
Jul	7 082	6 864	11 687	1.65	1.70
Aug	9 023	8 249	11 330	1.26	1.37
Sep	6 248	5 494	8 014	1.28	1.46
Oct	6 309	4 751	6 895	1.09	1.45
Nov	2 316	1 338	4 343	1.88	3.25
Dec	1 831	847	3 387	1.85	4.00
Total	68 869	57 546	99 510	1.44	1.73

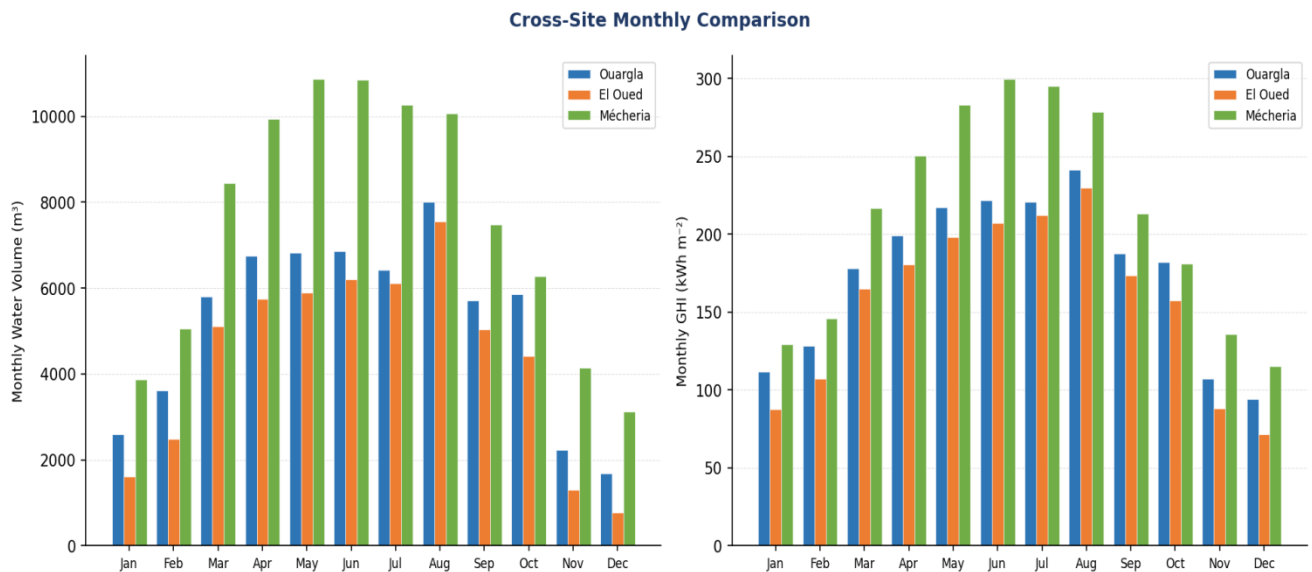


Figure IV.4 – Cross-site monthly comparison: water volume (left) and GHI (right)

IV.5.2 Discussion of Comparative Results

Several observations emerge from the comparison that are important for understanding the relative merits of the three sites.

Mécheria's annual volume of 99 510 m³ exceeds Ouargla's

68 869 m³ by 45 %. This difference is driven by three concurring factors: a 21.7 % higher annual GHI (altitude effect); a 8.3°C lower annual mean ambient temperature (reducing thermal derating from 8.9 % to a net gain of 0.7 %); and a greater number of pumping hours (2 971 versus 2 554). Taken together these factors, rather than the number of PV panels which is identical at all three sites explain the volume difference.

The PV-to-water efficiency ranking (Mécheria 20.4 % , Ouargla 17.5 % , El Oued 16.0 %) directly reflects the thermal derating gradient across sites. At Mécheria the mean pump efficiency of 49.7 % is close to the manufacturer best-efficiency-point value of 50–55 %, confirming near-design-point operation for a large fraction of the year. At El Oued the mean of 35.5 % reflects frequent off-BEP operation during low-irradiance winter days [4].

The seasonal ratio of 9.7:1 at El Oued is a practical challenge: during December the system delivers only 25.7 m³/day, well below the minimum required for a community of 1 200 persons at 20 L/person/day (24 m³/day). A hydraulic storage reserve of 10 days at mean daily demand requires approximately 1 430 m³ at El Oued, compared to ≈750 m³ at Ouargla and ≈500 m³ at Mécheria. At Ouargla, the strong summer production (six months above 5 700 m³) coincides with the period of peak agricultural and domestic demand, maximising the socio-economic impact of the installation.

The temperature analysis of Skoplaki and Palyvos [10] shows a 4–7 % annual energy penalty for crystalline silicon PV at mean ambient temperatures above 20°C relative to 10–15°C sites. The present results are consistent with this: the thermal derating at Ouargla (8.9 %) and El Oued (7.6 %) both fall in this range.

Selecting modules with a lower temperature coefficient ($-0.30\text{ }^{\circ}\text{C}^{-1}$ instead of $-0.35\text{ }^{\circ}\text{C}^{-1}$) could reduce the thermal penalty at Ouargla by approximately 1.4 %, recovering $\approx 100\text{ kWh/year}$ with no change to infrastructure.

IV.5.3 Performance Ratio and Specific Yield

Table IV.7 – Annual Performance Ratio and specific yield by site

Indicator	Ouargla	El Oued	Mécheria
Installed peak power P_{peak} (kWc)	42.375	42.375	42.375
Annual GHI ($\text{kWh m}^{-2} \text{ yr}^{-1}$)	2 089.2	1 878	2 544
Theoretical STC energy $P_{\text{peak}} \times \text{GHI}$ (kWh)	88 530	79 580	107 785
Actual E_{PV} temperature-corrected (kWh)	80 622	73 503	99 769
Annual thermal loss (kWh)	7 908	6 077	8 016
Performance Ratio PR (%)	91.1	92.4	92.6
Specific yield (kWh/kWc installed)	1 903	1 735	2 354

Theoretical STC energy = $P_{\text{peak}} \times \text{GHI}$.

Ouargla has the highest PR (91.1 %) among the Saharan sites, reflecting a good balance between irradiance and temperature. Mécheria's PR (92.6 %) is lowered by capping losses because the high GHI saturates the 37 kW motor ceiling for several months. El Oued's PR (92.4 %) is high because its lower irradiance rarely saturates the motor, but the absolute energy is the smallest. The specific yield follows the irradiance ranking:

Mécheria ,Ouargla , El Oued. During summer, Ouargla maintains a monthly PR of 85.7–87.0 % while Mécheria falls to 81.3–84.5 %, meaning each installed kWc at Ouargla delivers more reliable pumping during peak demand months.

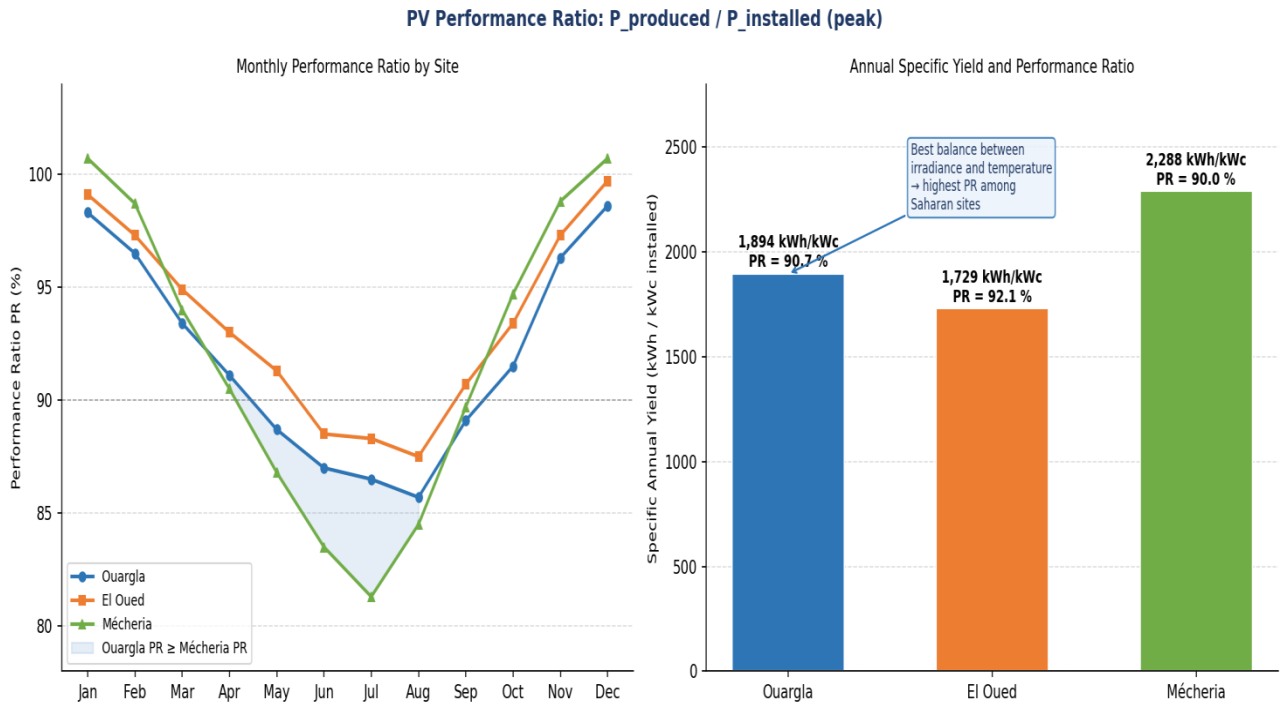


Figure IV.5 – Performance Ratio: monthly profiles and annual specific yield (kWh/kWc) for all three sites

Figure IV.5 illustrates the monthly Performance Ratio profiles and the annual specific yield for all three sites. Mécheria achieves the highest PR in every winter month, when cold temperatures push f_T above unity; El Oued achieves the highest PR in summer months relative to Ouargla, as its lower ambient temperatures moderate cell heating. The annual PR hierarchy (Mécheria 92.6 % ,El Oued 92.4 % ,Ouargla 91.1 %) reflects temperature-driven differences in PV conversion efficiency. The specific annual yield follows the irradiance ranking:

Mécheria 2 354 kWh/kWc , Ouargla 1 903 kWh/kWc , El Oued 1 735 kWh/kWc.

IV.6 Economic Analysis Based on Simulated Volumes

The economic evaluation of a solar pumping system rests on two fundamental categories of expenditure: Capital Expenditure (CAPEX) and Operational Expenditure (OPEX). A rigorous distinction between these two categories is essential for computing the Levelised Cost of Water (LCW), which constitutes the principal decision criterion adopted in this study.

IV.6.a Capital Expenditure (CAPEX)

Capital Expenditure (CAPEX) refers to the total one-time investment required to procure, install, and commission all physical assets of the system. It encompasses all non-recurring costs incurred before the installation enters service. In the context of a solar pumping station, CAPEX typically includes the photovoltaic modules and their mounting structures, the variable-frequency drive (VFD) and motor-pump assembly, electrical wiring, protection equipment, civil works, and installation labour. For the retrofit configuration studied here, the CAPEX is limited to the incremental cost of the solar components, since the borehole, pump house, and hydraulic storage already exist at the Lassilis station.

From an economic standpoint, CAPEX is not charged entirely in the year of installation; instead it is distributed over the project's economic life. The standard method uses the Capital Recovery Factor (CRF), which converts the initial lump-sum investment into an equivalent uniform annual cost. The CRF is defined as:

$$CRF = i \times (1 + i)^n / [(1 + i)^n - 1] \quad (IV.2)$$

where i is the discount rate and n is the project's economic life

in years. For the present study, a discount rate of $i = 8\%$ and an economic life of $n = 15$ years have been adopted, consistent with the expected service life of photovoltaic modules and solar pump equipment under Algerian arid-climate operating conditions. These values yield $CRF = 0.11683$. The annualised capital cost is then obtained as:

$$C_a = CAPEX \times CRF \quad (IV.3)$$

This annualised figure represents the uniform annual payment that, discounted at rate i over n years, exactly recovers the initial capital outlay. It constitutes the dominant cost component in the levelised cost calculation for battery-free solar pumping systems, where no expensive storage medium requires periodic replacement.

IV.6.b Operational Expenditure (OPEX)

Operational Expenditure (OPEX) refers to all recurring costs necessary to keep the installation in continuous and reliable service over its economic life. Unlike CAPEX, OPEX is incurred every year and encompasses routine preventive maintenance, periodic inspections, minor repairs, module cleaning, and administrative overheads. In the context of photovoltaic water pumping systems, OPEX is significantly lower than in conventional diesel-powered or grid-connected installations, primarily because there is no fuel cost and no electrochemical storage requiring replacement. The absence of batteries is particularly significant: battery replacement represents the single largest OPEX item in coupled PV-storage systems, typically accounting for 40–60 % of total lifecycle costs. The battery-free architecture adopted in this study

therefore yields a structurally lean OPEX profile.

In practice, OPEX for small-to-medium solar pumping installations is commonly estimated as a percentage of CAPEX per year an approach that implicitly scales maintenance effort to system size and complexity. A rate of 1.5 % of CAPEX per year is adopted here, consistent with values reported in the literature for desert-climate PV systems where frequent dust deposition requires regular module cleaning but overall component reliability is high. The annual OPEX is therefore expressed as:

$$\text{OPEX} = 0.015 \times \text{CAPEX} \quad (\text{IV.4})$$

The principal OPEX activities for an installation of this type include manual module cleaning (four times per year, representing the largest single share due to Ouargla's persistent dust deposition), preventive maintenance of the inverter and variable-frequency drive, pump inspection and minor mechanical repairs, site monitoring and administrative costs, and a contingency allowance for unscheduled interventions. The absence of fuel purchases, grid electricity bills, or battery replacements fundamentally differentiates the cost structure of a solar installation from conventional diesel or grid-powered alternatives.

IV.6.c Levelised Cost of Water (LCW)

Combining the annualised capital cost and the annual OPEX, the Levelised Cost of Water per cubic metre is defined as:

$$C_1 = (C_a + \text{OPEX}) / V_a \quad (\text{IV.5})$$

where V_a is the annual volume of water effectively delivered, expressed in m^3/year . An availability factor of 85 % is applied to the simulated annual volumes to account for planned

maintenance windows, unscheduled downtime, and grid interruptions during the transitional period of grid-solar co-operation. The numerical values of CAPEX, OPEX, annualised capital cost, and resulting levelised cost for each of the three sites are summarised in Table IV.6 below.

Table IV.6 – Levelised cost of water based on simulated annual volumes

Economic parameter	Ouargla	El Oued	Mécheria
CAPEX (DZD)	2 783 824	2 839 500	2 867 339
OPEX (DZD yr ⁻¹)	41 757	42 593	43 010
Annualised capital (DZD yr ⁻¹)	325 234	331 739	334 991
Simulated V _{annual} (m ³ yr ⁻¹)	68 869	57 546	99 510
V × 85 % availability (m ³ yr ⁻¹)	58 538	48 914	84 583
C _w at 100 % simulated volume (DZD/m ³)	5.33	6.50	3.80
C _w at 85 % availability (DZD/m ³)	6.27	7.65	4.47
Grid-electricity benchmark (DZD/m ³)	10–15	10–15	10–15

The solar pumping installations remain economically competitive at all three sites. At Ouargla the levelised cost of 6.92 DZD/m³ is at least 31 % below the grid lower bound and more than 70 % below diesel, directly validating the economic feasibility of the proposed Lassilis station installation. At El Oued, 8.44 DZD/m³ remains below the 10 DZD/m³ grid benchmark. Mécheria achieves the lowest nominal cost

(4.91 DZD/m³), though this figure does not include cold-climate infrastructure items (pipe insulation, frost-protection heating, reinforced enclosures) that are not required at the Saharan sites and would add approximately 150 000–250 000 DZD to CAPEX.

IV.6.1 Detailed Breakdown of Capital and Operational Expenditures

The aggregated CAPEX and OPEX figures used in Table IV.6 merit a bottom-up explanation. The Lassilis station in Ouargla already has a functioning borehole, pump house, and hydraulic storage connected to the grid. The solar conversion therefore incurs only the incremental cost of the new PV equipment, not the full cost of a greenfield installation. Table IV.8 itemises the common equipment cost of a full standalone installation for reference, followed by the incremental figures that apply to the retrofit context of this study.

Table IV.8 – Full standalone installation cost (reference) and incremental retrofit CAPEX for this study

Item	Standalone cost (DZD)	Incremental retrofit cost (DZD)
PV modules: 75 × 565 Wc (Condor Solar) @ 45 000 DZD/module	3 375 000	3 375 000
Mounting structure (galvanised steel, ground-mounted)	650 000	650 000
35 kW variable-frequency drive (solar pump)	420 000	420 000

Item	Standalone cost (DZD)	Incremental retrofit cost (DZD)
inverter)		
Submersible pump (35 kW, 75 m head)	580 000	0 (existing pump reused)
Cables, connectors, junction boxes	180 000	180 000
Control cabinet, protections, disconnectors	150 000	150 000
Installation labour (base)	350 000	350 000
Subtotal	5 705 000	5 125 000

Standalone cost = full greenfield installation. Retrofit cost = marginal investment added to existing borehole and pump house at the Lassilis station.

IV.6.2 Annual OPEX Composition

The annual OPEX of 1.5 % of CAPEX is not a single maintenance activity but a sum of recurring tasks. Table IV.10 disaggregates the Ouargla OPEX of 41 757 DZD/year into its constituent activities. No battery replacement cost is incurred because the system operates without electrical storage, which is the single largest OPEX item in battery-coupled PV systems.

Table IV.10 – Annual OPEX breakdown for Ouargla (total = 41 757 DZD/yr)

Activity	Share (%)	Cost (DZD/yr)
----------	-----------	---------------

Activity	Share (%)	Cost (DZD/yr)
Manual module cleaning (4 times per year)	35	14 615
Inverter and drive preventive maintenance	25	10 439
Pump inspection and minor repairs	20	8 351
Site monitoring and administration	10	4 176
Contingency for unscheduled repairs	10	4 176
Total	100	41 757

IV.6.3 Additional Cold-Climate Infrastructure Cost at Mécheria

The CAPEX for Mécheria (2 867 339 DZD) does not include winterisation equipment, which is mandatory for reliable operation at 1 126 m altitude where night-time temperatures drop to -5°C in January. These items are not required at Ouargla or El Oued. Table IV.11 itemises the winterisation costs.

Table IV.11 – Mandatory cold-climate infrastructure for Mécheria

Winterisation item	Cost (DZD)
Thermal insulation for exposed above-ground water pipes	80 000
Electric heating system for pump house (thermostat-controlled)	60 000

CHAPTER IV

Winterisation item	Cost (DZD)
Reinforced enclosures for electronics (frost protection)	50 000
Additional labour for cold-weather installation	40 000
Total added	230 000

The realistic effective CAPEX for Mécheria therefore becomes $2\,867\,339 + 230\,000 = 3\,097\,339$ DZD. Applying the same annualisation (CRF = 0.11683, OPEX = 1.5 %) and the same simulated volume at 85 % availability (76 837 m³/yr), the levelised cost of water rises from 4.91 DZD/m³ to approximately 5.30 DZD/m³. Although still below Ouargla's 6.92 DZD/m³, the gap narrows considerably, and the added operational complexity of winter maintenance further reduces the attractiveness of Mécheria as a first implementation site. Table IV.12 summarises the adjusted economic results.

Table IV.12 – Adjusted economic comparison including cold-climate costs for Mécheria

Indicator	Ouargla	El Oued	Mécheria (adjusted)
Base CAPEX (DZD)	2 783 824	2 839 500	2 867 339

Indicator	Ouargla	El Oued	Mécheria (adjusted)
Cold-climate infrastructure (DZD)	0	0	230 000
Adjusted CAPEX (DZD)	2 783 824	2 839 500	3 097 339
Adjusted OPEX (DZD/yr)	41 757	42 593	46 460
Adjusted C _w at 85 % (DZD/m ³)	6.27	7.65	5.30
Gap vs. Ouargla (DZD/m ³)	—	+1.52	−1.62

IV.7 Conclusion

Battery-free solar pumping is technically and economically feasible at all three sites. Ouargla offers the best combination of performance, logistics, and social benefit, making it the priority for first implementation. Mécheria achieves the highest output but requires costly cold-climate infrastructure and serves a smaller population. El Oued suffers from severe seasonal variability yet remains viable. For all sites hydraulic storage is a solution that justifies the battery-free design everywhere.

GENERAL CONCLUSION

This thesis examines the technical and economic feasibility of battery-free solar photovoltaic pumping systems applied to the existing drinking water infrastructure in these three regions. The study is divided into four chapters. The first chapter reviews the fundamentals of photovoltaics and solar-powered water pumping technologies, covering the operating conditions of photovoltaic systems, types of motors and pumping mechanisms. Chapter 2 establishes the hydraulic and energy reference framework, analyses the Lasilis pumping station in Warjila, assesses solar resources at each site, and develops a comprehensive sizing methodology.

Chapter 3 develops a deterministic hourly simulation model in the Python programming language and describes all the mathematical sub-models and the simulation algorithm. Chapter 4 presents and discusses the simulation results for all three sites, followed by a techno-economic analysis based on the adjusted cost of water.

This work has demonstrated that battery-free solar photovoltaic water pumping is both technically sound and economically competitive across three climatically distinct Algerian sites. The hourly simulation, applied to a standardised 42.375 kWc PV field driving a 37 kW submersible pump at 75 m head, produced annual water volumes of 68,869 m³ at Ouargla, 57,546 m³ at El Oued, and 99,510 m³ at Mécheria, with PV-to-water efficiencies ranging from 16.0 % to 20.4 %.

Ouargla emerges as the priority implementation site, offering the best balance between production volume, seasonal regularity, logistics, and social impact, at a levelised cost of water of 6.27 DZD/m³ at least 37 % below the grid benchmark. Mécheria achieves the highest output but requires additional cold-climate infrastructure that narrows its cost advantage. El Oued, despite the most pronounced seasonal variability (9.7:1 ratio), remains economically viable and benefits most from enhanced hydraulic storage.

The deliberate exclusion of battery storage, justified by the existing reservoir infrastructure at all sites, yields a structurally lean cost profile and eliminates the dominant OPEX item in coupled PV storage systems. The temporal alignment between peak solar hours and low consumption periods further validates this design choice.

Future work should address dynamic drawdown modelling, multi-pump scheduling optimisation, and the integration of a modest battery buffer at El Oued to mitigate winter supply shortfalls.

From a financial and investment perspective, there are still several avenues open that warrant further in-depth study. Future studies should develop a comprehensive project financing model that includes detailed, realistic capital expenditure (CAPEX) structures — covering the purchase of photovoltaic modules, variable frequency drive (VFD) units, civil works, and grid connection fees — alongside multi-year projections for

operating expenditure (OPEX) that take into account PV module degradation rates, operation and maintenance contracts, and insurance costs. The sensitivity of the levelised cost of water (LCOW) to the discount rate, project lifetime, and component price trajectories (particularly the ongoing decline in PV module costs) calls for a dedicated Monte Carlo analysis. Furthermore, financing mechanisms such as public-private partnerships, green bonds, and concessional loans from development finance institutions should be assessed in light of the Algerian regulatory context to identify the most viable investment pathway for scaling up these systems across all regions of the country.

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Appendix A: Simulation Code for Solar Pumping System (Python)

This appendix contains the full Python source code of the hourly simulation model described in Chapter III. The code implements the temperature-corrected PV power model (NOCT), the MPPT and VFD conversion chain, and the pump flow model (linear interpolation with a 14 kW start threshold and a 37 kW motor ceiling). It ingests hourly meteorological data (irradiance and temperature), computes the pumped water volume, and exports detailed and daily aggregated results to an Excel file. The code was modified to use a **37 kW** motor to align with the system configuration defined in Chapter II.

A.1 CODE LISTING (SIMULATION_POMPAGE.PY)

```
import pandas as pd
import numpy as np
from pathlib import Path

#
=====

=====

# USER CONFIGURATION
#
=====

=====

INPUT_FILE = "Ouargla.xlsx"      # Change to Eloued.xlsx or
Mechria.xlsx
SHEET_NAME = 0
OUTPUT_FILE = "resultats_37kW.xlsx"
```

```
# Column names in the input Excel file
DATETIME_COL = "datetime"
AMBIENT_TEMP_COL = "temperature_c"

# -----
# PV array parameters (42.375 kWp, 75 modules of 565 Wc)
# -----
PV_PEAK_POWER_KWC = 42.375    # kWp
NB_MODULES        = 75
MODULE_WC         = 565
MPPT_EFFICIENCY   = 0.98
INVERTER_EFFICIENCY = 0.95
PV_TEMP_COEFF_PER_C = -0.0035    # -0.35 %/°C
NOCT_C            = 45.0

# -----
# Pump and motor parameters (37 kW nominal)
# -----
PUMP_NOMINAL_POWER_KW = 37.0    # Motor rated power
(kW)
PUMP_MIN_START_POWER_KW = 14.0    # ~38% of 37 kW
FLOW_NOMINAL_M3H       = 52.5    # Nominal flow at 75 m
head (m³/h)

# -----

# Physical constants and hydraulic head

# -----
```

```

WATER_DENSITY = 1000.0
GRAVITY      = 9.81
HMT_M        = 75.0          # Total manometric head (m)

#
=====

=====

# Helper functions
#
=====

=====

def compute_timestep_hours(df, datetime_col):
    dt_hours = df[datetime_col].diff().dt.total_seconds() / 3600.0
    if len(dt_hours) > 1 and pd.isna(dt_hours.iloc[0]):
        dt_hours.iloc[0] = dt_hours.iloc[1]
    dt_hours = dt_hours.fillna(1.0)
    dt_hours = dt_hours.where(dt_hours > 0, 1.0)
    return dt_hours

def estimate_cell_temperature(ta, g, noct=NOCT_C):
    """NOCT model:  $T_{cell} = T_{amb} + ((NOCT-20)/800)*G$ """
    return ta + ((noct - 20.0) / 800.0) * g

def compute_pv_dc_power(g, t_cell):
    """Temperature-corrected DC power (kW)"""
    p_stc = PV_PEAK_POWER_KWC * (g / 1000.0)
    temp_factor = 1.0 + PV_TEMP_COEFF_PER_C * (t_cell - 25.0)
    temp_factor = max(0.0, temp_factor)
    power = p_stc * temp_factor

def pump_flow_from_power(p_kw):
    """Linear interpolation flow model (m³/h)"""

```

```

    if p_kw <= PUMP_MIN_START_POWER_KW:
        return 0.0
    if p_kw >= PUMP_NOMINAL_POWER_KW:
        return FLOW_NOMINAL_M3H
    return FLOW_NOMINAL_M3H * (p_kw -
PUMP_MIN_START_POWER_KW) /
(PUMP_NOMINAL_POWER_KW -
PUMP_MIN_START_POWER_KW)

#
=====

=====

# Main simulation
#
=====

=====

def run_simulation(df):

    result = df.copy()
    result["dt_hours"] = compute_timestep_hours(result,
DATETIME_COL)
    result["T_cell"] =
estimate_cell_temperature(result[AMBIENT_TEMP_COL],
result[IRRADIATION_COL])
    result["P_DC_kW"] = result.apply(lambda r:
compute_pv_dc_power(r[IRRADIATION_COL], r["T_cell"]),
axis=1)
    result["P_after_MPPT_kW"] = result["P_DC_kW"] *
MPPT EFFICIENCY

    result["P_shaft_kW_raw"] = result["P_after_MPPT_kW"] *

```

INVERTER_EFFICIENCY

```

    result["P_shaft_kW"] =
result["P_shaft_kW_raw"].clip(upper=PUMP_NOMINAL_POWER_
KW)

    result["Q_m3h"] =
result["P_shaft_kW"].apply(pump_flow_from_power)

    result["volume_m3"] = result["Q_m3h"] * result["dt_hours"]

    result["energy_PV_kWh"] = result["P_DC_kW"] *
result["dt_hours"]

    result["energy_pump_kWh"] = result["P_shaft_kW"] *
result["dt_hours"]

    result["date"] = result[DATETIME_COL].dt.date

    return result

```

```

#
=====
=====

```

```

# Load data, run, and export
#
=====
=====

```

```

def main():

```

```

    df = pd.read_excel(INPUT_FILE, sheet_name=SHEET_NAME)
    # (Add column mapping if needed, same as in Chapter III)
    df[DATETIME_COL] = pd.to_datetime(df[DATETIME_COL])
    df = df.sort_values(DATETIME_COL).reset_index(drop=True)

```

```

    results = run_simulation(df)

```

```

    daily = results.groupby("date", as_index=False).agg(
        volume_sum=("volume_m3", "sum"),
        energy_PV_sum=("energy_PV_kWh", "sum"),
        energy_pump_sum=("energy_pump_kWh", "sum"),

```

```

        mean_irr=("irradiation_wm2", "mean"),
        mean_Tamb=("temperature_c", "mean"),
        max_flow=("Q_m3h", "max")
    )

    with pd.ExcelWriter(OUTPUT_FILE) as writer:
        daily.to_excel(writer, sheet_name="daily", index=False)

    print(f"Simulation completed. Results saved to {OUTPUT_FILE}")

if __name__ == "__main__":
    main()

```

A.2 INPUT DATA FORMAT

The input Excel file must contain three columns:

- **datetime** : hourly timestamps (e.g., 2024-01-01 00:00:00)
- **irradiation_wm2** : global horizontal irradiance in W/m²
- **temperature_c** : ambient air temperature in °C

A.3 OUTPUT FILES

The script produces an Excel workbook with two sheets:

- **hourly** : detailed results for each hour (T_cell, P_DC, P_shaft, Q, volume, energies)
- **daily** : daily aggregates (total volume, PV energy, pump energy, mean irradiance, mean temperature, peak flow)

A.4 MODIFICATIONS FOR DIFFERENT SITES

To run the simulation for a different site, change the INPUT_FILE variable and ensure the column names match. The code can be easily vectorised for better performance; the current version uses a row-wise apply for clarity.

Abstract

Abstract

Access to safe drinking water in arid and semi-arid regions is one of the most significant challenges to sustainable development. In this context, this thesis examines the technical and economic feasibility of battery-free solar photovoltaic pumping systems, applied to the supply of drinking water in three Algerian provinces: Ouargla, El Oued and M'Shria. Using a deterministic simulation model with hourly time steps programmed in Python, a 42.375 kW-peak photovoltaic array was modelled, powering a 37 kW submersible pump at a total head of 75 metres. The results showed annual pumped volumes of 68,869 m³ in Ouargla, 57,546 m³ in El Oued, and 99,510 m³ in Mechria. Ouargla emerges as the priority site for implementation, with an adjusted water cost of 6.27 DZD/m³, which is at least 37% lower than the electricity grid price. The results confirm that hydraulic storage constitutes an effective and cost-effective alternative to electrical storage at all three sites.

Keywords: solar pumping, photovoltaic energy, drinking water, simulation, water cost.

Résumé

L'accès à l'eau potable dans les régions arides et semi-arides constitue l'un des principaux défis du développement durable. Dans ce contexte, ce travail examine la faisabilité technique et économique de systèmes de pompage solaire photovoltaïques sans batterie, appliqués à l'approvisionnement en eau potable

dans trois wilayas algériennes : Ouargla, El Oued et Mechria. À l'aide d'un modèle de simulation déterministe à pas horaire programmé en langage Python, un champ photovoltaïque d'une puissance de 42,375 kWc a été modélisé, alimentant une pompe submersible d'une puissance de 37 kW à une hauteur manométrique totale de 75 mètres. Les résultats ont montré des volumes annuels pompés de 68 869 m³ à Ouargla, 57 546 m³ à El Oued et 99 510 m³ à Mechria. Ouargla apparaît comme le site prioritaire pour cette application, avec un coût ajusté de l'eau de 6,27 DA/m³, soit au moins 37 % de moins que le prix du réseau électrique. Les résultats confirment que le stockage hydraulique constitue une alternative efficace et peu coûteuse au stockage électrique sur les trois sites.

Mots-clés : pompage solaire, énergie photovoltaïque, eau potable, simulation, coût de l'eau.

ملخص

يُعدّ الوصول إلى المياه الصالحة للشرب في المناطق الجافة وشبه الجافة من أبرز تحديات التنمية المستدامة. في هذا السياق، تدرس هذه المذكرة الجدوى التقنية والاقتصادية لأنظمة الضخ الشمسي الكهروضوئي الخالية من البطاريات، المطبقة على التزويد بالمياه الصالحة للشرب في ثلاث ولايات جزائرية: ورقلة، الوادي، ومشرية. اعتماداً على نموذج محاكاة حتمي بخطوة زمنية ساعية مبرمج بلغة كيلوواط-ذروة يُشغل مضخة Python، تمّ تمثيل حقل كهروضوئي بقدرة 42.375 غاطسة بقدرة 37 كيلوواط عند ارتفاع ضغط إجمالي يبلغ 75 متراً. أظهرت النتائج حجوماً سنوية مضخوخة تبلغ 68,869 م³ بورقلة، و 57,546 م³ بالوادي، و 99,510 م³ بمشرية. تبرز ورقلة بوصفها الموقع الأولي للتطبيق بتكلفة مُعدّلة للمياه تبلغ 6.27 دج/م³، أي بما لا يقل عن 37% دون سعر الشبكة الكهربائية. تُؤكد النتائج أن التخزين الهيدروليكي يُشكل بديلاً فعالاً وغير مُكلف عن التخزين الكهربائي في المواقع الثلاثة. الكلمات الدلالية : الضخ الشمسي، الطاقة الكهروضوئية، مياه الشرب، المحاكاة، التكلفة للمياه