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Entitled:

**Technical and Economic Analysis of a Photovoltaic
Water Pumping System Using HOMER Pro Software**

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Abstract:

This study is a scientific and engineering response to the most significant challenges facing sustainable agricultural investment in desert environments, as it examines in detail a solar photovoltaic water pumping system designed for irrigation in the Nakhlah region of EL Oued. The study addresses real problems that concern investors in areas isolated from the public grid; most notably, the exorbitant and constantly fluctuating prices of diesel fuel and the maintenance costs of traditional generators, alongside technical challenges such as the impact of high temperatures on panel efficiency, and the difficulty of balancing variable energy production with the constant water needs of potato fields a challenge that often falls into the trap of haphazard design, leading to pump shortages or the waste of massive amounts of excess electricity that go unused, nt to mention the negative environmental impact of carbon emissions. To address this challenge, the research relies on the global simulation software HOMER Pro to model and optimize the system's operational and financial performance through an in-depth engineering and economic comparison of two options: a fully autonomous battery-backed system and a hybrid system that integrates a diesel generator as a backup source. This study culminates in identifying the optimal configuration that achieves the highest financial viability and technical reliability by reducing the net levelized cost of energy and the cost per kilowatt-hour while ensuring agricultural irrigation, and by providing practical solutions that promote the clean energy transition and protect remote agricultural projects from fluctuations in conventional energy prices.

Keywords : Solar Photovoltaic (PV) - Water Pumping System - Hybrid Power System

المخلص :

هذه الدراسة استجابة علمية وهندسية لأبرز التحديات التي تواجه الاستثمار الفلاحي المستدام في البيئات الصحراوية، حيث تضع تحت المجهر نظام ضخ المياه بالطاقة الشمسية الكهروضوئية الموجه للري في منطقة النخلة بولاية الوادي. وتأتي الدراسة لتعالج مشكلات حقيقية تؤرق المستثمرين في المناطق المعزولة عن الشبكة العامة؛ أبرزها الارتفاع الباهظ والتذبذب المستمر في أسعار وقود الديزل وتكاليف صيانة المولدات التقليدية، بالتوازي مع التحديات التقنية المتمثلة في تأثير الحرارة المرتفعة على كفاءة الألواح، وصعوبة الموازنة بين إنتاج الطاقة المتغير والاحتياجات المائية الثابتة لحقول البطاطس، وهو ما يقع غالباً في فخ التصميم العشوائي الذي يتسبب في عجز المضخة أو هدر فائض كهربائي ضخم وضياعه دون استغلال، فضلاً عن الأثر البيئي السلبي للانبعاثات الكربونية. ولتفكيك هذه الإشكالية، يركز البحث على استخدام برمجية المحاكاة العالمية HOMER Pro لنمذجة وتحسين الأداء التشغيلي والمالي للنظام عبر مقارنة هندسية واقتصادية معمقة بين خيارين: النظام المستقل تماماً المدعم بالبطاريات، والنظام الهجين الذي يدمج مولد الديزل كمصدر احتياطي. وتتوج هذه الدراسة باستخلاص التشكيلة المثلى التي تحقق أعلى جدوى مالية وموثوقية تقنية من خلال خفض

التكلفة الإجمالية الصافية وتكلفة إنتاج الكيلوواط الساعي وتأمين الري الفلاحي، مع تقديم حلول عملية تعزز الانتقال الطاقوي النظيف وتحمي المشاريع الفلاحية النائية من تقلبات أسعار الطاقة التقليدية.

الكلمات المفتاحية : الاستثمار الفلاحي - طاقة الشمسية - النظام الهجين

Résumé :

Cette étude constitue une réponse scientifique et technique aux principaux défis auxquels est confronté l'investissement agricole durable dans les environnements désertiques ; elle examine en détail le système de pompage d'eau alimenté par l'énergie solaire photovoltaïque destiné à l'irrigation dans la région de Nakhlah, dans la wilaya de El Oued. Elle vise à résoudre les problèmes concrets qui préoccupent les investisseurs dans les zones isolées du réseau public, notamment la flambée et la fluctuation constante des prix du gazole ainsi que les coûts d'entretien des générateurs traditionnels, parallèlement aux défis techniques liés à l'impact des températures élevées sur le rendement des panneaux, et la difficulté à équilibrer une production d'énergie variable et les besoins en eau constants des champs de pommes de terre. Or, on tombe souvent dans le piège d'une conception aléatoire qui entraîne soit une insuffisance de la pompe, soit un gaspillage considérable d'électricité excédentaire non exploitée, sans compter l'impact environnemental négatif des émissions de carbone. Pour démêler cette problématique, la recherche s'appuie sur l'utilisation du logiciel de simulation globale HOMER Pro afin de modéliser et d'optimiser les performances opérationnelles et financières du système, grâce à une comparaison technique et économique approfondie entre deux options : le système entièrement autonome alimenté par des batteries, et le système hybride intégrant un générateur diesel comme source de secours. Cette étude aboutit à l'identification de la configuration optimale qui offre la meilleure rentabilité financière et la plus grande fiabilité technique, en réduisant le coût total net et le coût de production du kilowattheure tout en garantissant l'irrigation agricole, tout en proposant des solutions pratiques qui favorisent la transition énergétique propre et protègent les projets agricoles isolés des fluctuations des prix de l'énergie traditionnelle.

Mots-clés : Système de pompage d'eau solaire photovoltaïque (PV) – Système d'alimentation hybride

DEDICATION

First and foremost, I would like to express my sincere gratitude to my beloved parents for their unconditional love, patience, and unwavering support, which made this achievement possible. Their encouragement to pursue my goals and overcome challenges has always inspired me.

I extend my deepest thanks to my brothers and sisters for their support and encouragement throughout my academic journey.

I also offer my sincere appreciation to all my teachers throughout my educational journey, from elementary school through to my graduation and the completion of my master's degree; I thank them for their guidance and valuable knowledge.

Finally, I dedicate this work to everyone who supported me and believed in me.

Mondher Hamidatou

DEDICATION

This work is proudly and affectionately dedicated:

To my beloved **parents**, whose unconditional love, endless patience, and unwavering support have been the cornerstone of my life. Your prayers and guidance have illuminated my path and inspired me to reach this milestone.

To my dear **wife**, the partner of my life and journey, for her profound understanding, continuous encouragement, and for standing by my side through every step of this demanding academic endeavor.

To the joys of my heart, my precious **children**: my beautiful daughter, **Haya**, and my beloved son, **Anas**. You are my greatest motivation.

To my dear **brothers and sisters**, for their constant support, care, and cheerfulness throughout my life.

In loving and eternal memory of my eldest brother, **Ali**, may Allah have mercy upon his soul and grant him the highest place in Paradise. Though you are no longer with us, your memory remains alive in my heart, and your spirit continues to inspire me every single day.

And finally, to everyone who believed in me and gave me the strength and determination to continue striving towards achieving my dreams.

Thank you for your support and encouragement.

Mennai Ridha

DEDICATION

To those who paved my path to success with their endless prayers and sacrifices...

To the joy of my heart, my noble parents,

To those whose harvest of labor I reap today, and who never withheld their boundless love and encouragement. I dedicate this achievement to you, hoping it might repay even a small fraction of your immense generosity.

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For being my anchor, my truest friends, and my constants in a changing world. Your unwavering belief in me has been my greatest inspiration.

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Abbreviations

AC: Alternating Current

DC: Direct Current

PV: Photovoltaic

PVA: Photovoltaic Array

GPV: Générateur Photovoltaïque

HRES: Hybrid Renewable Energy Systems

HOMER: Hybrid Optimization of Multiple Energy Resources

NASA: National Aeronautics and Space Administration

NPC: Net Present Cost

COE: Levelized Cost of Energy

LCOE: Levelized Cost of Energy

CRF: Capital Recovery Factor

O&M: Operation and Maintenance

SOC: State of Charge

BSOC: Battery State of Charge

DOD: Depth of Discharge

PDD: Profondeur de Décharge

STC: Standard Test Conditions

MPP: Maximum Power Point

MPPT: Maximum Power Point Tracking

IM: Induction Motor

MAS: Moteur Asynchrone

TDH: Total Dynamic Head

HMT: Hauteur Manométrique Totale

GHG: Greenhouse Gas Emissions

CO₂: Carbon Dioxide

CO: Carbon Monoxide

UHC: Unburned Hydrocarbons

PM: Particulate Matter

SO₂: Sulfur Dioxide

NO_x: Nitrogen Oxides

Symbols and Variables

Δt : Time step duration / Simulation time interval (1 Hour)

Δp : Power variance between PV generation and load demand (kW)

G: Solar Radiation / Insolation (W/m² or kW/m²)

G_{ref} : Reference Solar Radiation under STC (1 kW/m²)

$G_T(t)$: Incident Solar Radiation on the tilted PV module at time step t (kW/m²)

$P_{PV}(t)$: Hourly power production of the PV array (kW)

P_R : Rated capacity of the PV array under STC (kW)

F_{pv} : PV derating factor (%)

α_p : Temperature coefficient of power (%/°C)

$T_c(t)$: PV cell temperature in the current time step (°C)

T_{ref} : PV cell temperature under STC (25 °C)

T_a : Ambient temperature (°C)

I_{ph} : Photocurrent / Light-generated current (A)

I_s : Diode saturation current (A)

I_{cc} : Short circuit current (A)

$I_{cc,STC}$: Short circuit current under Standard Test Conditions (A)

I_{mpp} : Current at maximum power point / Optimum current (A)

V_{co} : Open circuit voltage (V)

V_{mpp} : Voltage at maximum power point (V)

R_s : Series resistance (Ω)

R_{sh} : Shunt resistance (Ω)

P_C : Peak power (Wp)

P_{max} : Maximum power output (W)

F_F : Fill factor

N_s : Number of modules connected in series

N_p : Number of modules connected in parallel

C_{batt} : Nominal capacity of the battery (Ah)

V_{batt} : Battery voltage (V)

I_{batt} : Battery current (A)

R_b : Battery efficiency (%)

N_j : Number of autonomy days of the battery bank (Days)

B_b : Total number of batteries

σ : Hourly self-discharge rate of the battery bank (%/hour)

η_B : Round trip efficiency of the battery bank (%)

η_C : Efficiency of the inverter/converter (%)

$P_C(t)$: Hourly input power required at the DC input of the converter (kW)

$P_{Load}(t)$: Hourly electrical load demand of the submersible water pump (kW)

$E_{pump}(t)$: Power delivered to the pump at time t (kW)

$Q(t)$: Volume of water pumped at time t (m³/h or m³/day)

g : Acceleration due to gravity (9.81 m/s²)

ρ : Density of water / Volumetric mass (1000 kg/m³)

η_{pump} : Pump efficiency (%)

H_{st} : Static Head (m)

H_{dd} : Dynamic Drawdown of the water level (m)

H_f : Friction Head Losses in pipes (m)

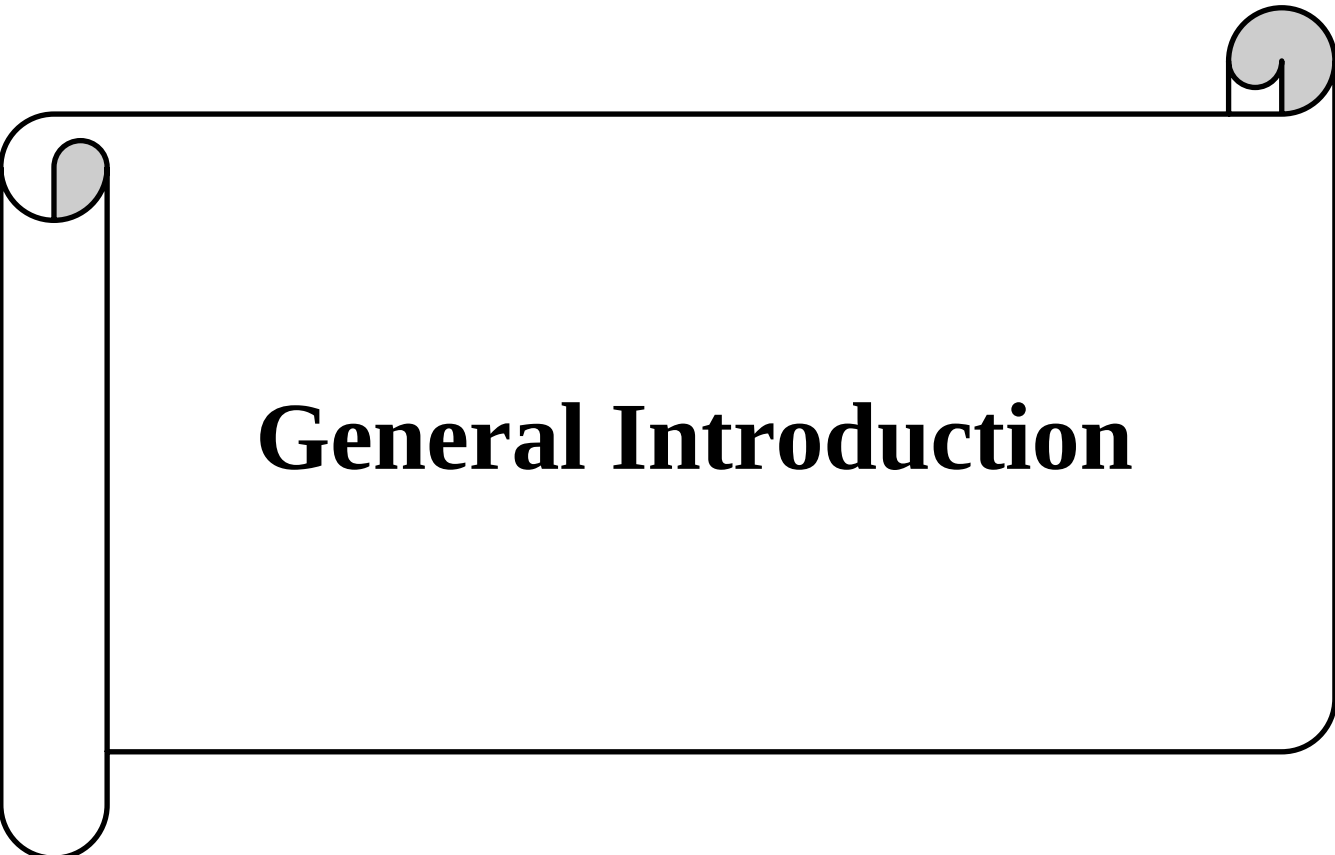
H_v : Velocity head / Dynamic pressure head (m)

D : Internal diameter of the pipe (m)

L : Total length of the pipe (m)

v : Water velocity in the pipe (m/s)
 f : Friction factor coefficient
 P_n : Nominal power of the asynchronous motor (W or kW)
 T_{em} : Electromagnetic torque (N.m)
 T_l : Load torque / Mechanical load resistance (N.m)
 Ω : Mechanical angular speed (rad/s or rpm)
 ω_s : Synchronous speed of the motor (rad/s)
 p : Number of pole pairs in the induction motor
 s : Motor slip (Glissement)
 Φ_{sabc} : Stator flux vectors (Wb)
 Φ_{rabc} : Rotor flux vectors (Wb)
 $R_{s_{motor}}$: Stator resistance of the induction motor (Ω)
 $R_{r_{motor}}$: Rotor resistance of the induction motor (Ω)
 L_s : Stator inductance (H)
 L_r : Rotor inductance (H)
 M : Mutual inductance between stator and rotor (H)
 J : Moment of inertia of the motor-pump shaft (kg.m²)
 f_m : Mechanical friction coefficient of the shaft (N.m.s/rad)
 F : Fuel consumption rate of the generator (L/h)
 F_0 : Generator fuel curve intercept coefficient (L/h/kW)
 F_1 : Generator fuel curve slope (L/h/kW)
 Y_{gen} : Rated capacity of the generator (kW)
 P_{gen} : Electrical power output delivered by the generator (kW)
 $C_{capital}$: Initial capital cost of the system component
 $C_{replace}$: Replacement cost of the system component
 C_{maint} : Operating and maintenance cost
 $C_{salvage}$: Salvage value

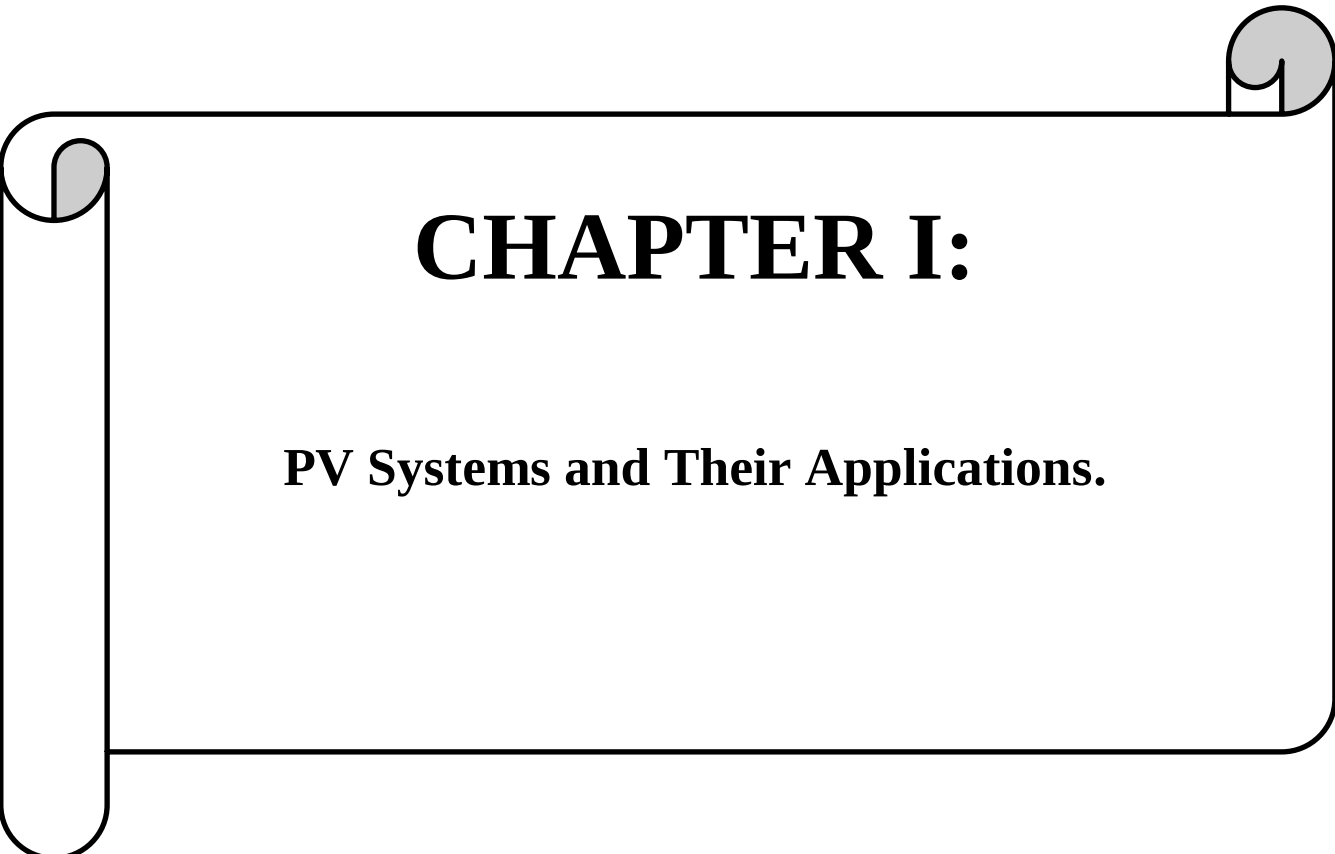
$C_{\text{gen, fixed}}$: Fixed cost of energy for the generator (/h)
 $C_{\text{gen, mar}}$: Marginal cost of energy for the generator (/kWh)
 $C_{\text{om, gen}}$: Generator O&M cost (/operating hour)
 $C_{\text{rep, gen}}$: Replacement cost of the generator (\$)
 R_{gen} : Generator operational lifetime (Hours)
 $C_{\text{fuel, eff}}$: Effective price of fuel (\$/L)
 i : Annual real interest rate (%)
 i_{nominal} : Nominal interest rate (%)
 $f_{\text{inflation}}$: Annual inflation rate (%)
 N : Project lifetime (Years)

A decorative graphic of a scroll. It features a horizontal rectangular body with rounded corners, a vertical tail on the left side, and a small circular loop at the top right corner. The scroll is outlined in black and has a light gray fill. The text "General Introduction" is centered within the horizontal body of the scroll.

General Introduction

The transition to sustainable energy systems has become a global imperative due to the depletion of conventional fossil fuel reserves and growing environmental concerns related to greenhouse gas emissions, and photovoltaic (PV) technology has emerged as a leading renewable energy solution due to its flexibility and ability to convert solar radiation directly into electrical energy with minimal operational emissions [1][3][4]. The rapidly increasing global demand for electricity, driven by industrialization and population growth, calls for rigorous technical and economic planning to ensure energy security and the economic viability of projects; in this context, modeling and optimization tools are essential for evaluating the performance and financial viability of renewable energy systems prior to their implementation. HOMER Pro is among the most widely adopted software programs; it performs energy-hour simulations, economic optimization based on net present cost (NPC), and sensitivity analyses to assess the impact of uncertain variables such as solar irradiance, component costs, and load variations [2] [5][6][7][8][9]. Accordingly, the application of HOMER for the technical and economic analysis of a standalone or hybrid photovoltaic system provides a robust methodological framework for identifying optimal system configurations that maximize energy production while minimizing life cycle costs [10][11][12]. The practical significance of this study becomes evident when applied to the Nakhlah region of EL Oued, particularly the area targeted for Saharan agricultural investment, especially since it is isolated from the public grid and characterized by promising climatic indicators such as solar radiation and suitable temperatures for the utilization of clean energy; To present a comprehensive and systematic engineering study of this project, the work was divided across the chapters of this thesis, beginning with: Chapter 1, which reviews the comprehensive theoretical background and basic concepts of solar photovoltaic technology and the mechanics of solar cells, while highlighting renewable energy powered water pumping systems and their agricultural applications in isolated desert environments; The research then moves on to Chapter 2, which focuses on the economic aspects of modeling, explaining the mathematical formulas and symbols used to calculate financial feasibility indicators such as net present value and cost per kilowatt-hour, in addition to detailing the operational mechanisms of the HOMER Pro software and how it processes climate data and simulates scenarios. This leads to the third and final chapter, which constitutes the practical core of the study, addressing technical modeling and precise hydraulic calculations for the

submersible pump load and the piping network designed to irrigate the potato field, presenting and analyzing the simulation results and the engineering, financial, and environmental comparisons between the battery powered standalone system and the diesel powered hybrid system to identify the optimal and most sustainable energy configuration.

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CHAPTER I:

PV Systems and Their Applications.

I.1. Introduction:

The success and operational reliability of photovoltaic systems are linked to a structural understanding of the physical principles governing their electromechanical components; starting with solar panels, through chemical storage systems in battery banks, inverters, and smart digital converters, all the way to diodes and their pivotal role in directing and protecting electrical currents. Solar radiation in its direct, diffuse, and absorbed forms remains the primary dynamic driver of these systems, granting Algeria and its Saharan gateway exceptional energy potential given the geographically promising levels of irradiance and solar flux. Given the multitude of generations and types of solar panels available on the market, along with their varying technical characteristics, it is imperative to subject them to a rigorous engineering assessment that examines the impact of the surrounding environment; climatic challenges such as heavy dust accumulation, partial shading, and thermal stress resulting from sharp rises in temperature, are decisive factors that directly contribute to reduced cell efficiency and accelerated performance degradation. Framing these theoretical concepts and tracking the diverse applications of solar panels provides a solid scientific foundation for moving from the theoretical realm to the realm of engineering feasibility in environments isolated from the electrical grid.

I.2. Solar Potential in Algeria:

An accurate evaluation of renewable energy development in Algeria necessitates an analysis of its largely untapped natural resources, particularly its solar potential. Covering an area of about 2,381,745 km², the country benefits from highly favorable conditions for solar energy exploitation, making it one of the most promising regions in this field. Solar resource availability varies significantly across the national territory due to geographical and climatic factors. In the northern part of the country, especially along the coastal zones, solar radiation is influenced by seasonal variability and relatively frequent cloud cover. In contrast, the southern Saharan regions are characterized by very high solar irradiance levels, although these areas also experience elevated temperatures, which can impact the efficiency of energy conversion systems, this spatial variability results in an average daily global solar irradiation on a horizontal surface ranging approximately from 4.5 to 7.5 kWh/m².

As depicted , this distribution clearly highlights the strong solar potential available across the Algerian territory, given these favorable conditions, Algeria is widely considered to possess one of the most important solar energy reserves in the Mediterranean basin [2].

I.3. Types of Solar Radiation:

The fraction of solar radiation utilized by photovoltaic systems is mainly the light component, this radiation can be divided into three main types, whose relative proportions vary according to geographic location, atmospheric conditions, and time of day, as illustrated in Figure I.2, which provides a schematic overview illustrating the three primary components of solar radiation: direct beam, diffuse sky, and groundreflected albedo.

I.3.1. Direct Radiation:

Direct radiation corresponds to solar energy that reaches the earth's surface without being scattered or reflected by atmospheric elements such as clouds or surrounding objects, it represents the most intense component of solar radiation under clear sky conditions and is responsible for sharp shadows and high irradiance levels [1][2] [3].

I.3.2. Diffuse Radiation:

Diffuse radiation is produced when direct sunlight is scattered by molecules, aerosols, and clouds in the atmosphere, this scattering process allows sunlight to reach the ground from multiple directions, providing ambient illumination even under overcast skies, although its intensity is lower than that of direct radiation, it constitutes an important portion of the total solar energy available [1] [2] [3].

I.3.3. Albedo (Reflected) Radiation:

Albedo radiation refers to the portion of solar energy reflected by the earth's surface and surrounding environments. Its magnitude depends on the reflectivity of the ground (albedo), being particularly significant in environments such as snow covered areas, water surfaces, or bright sandy regions, this reflected component can contribute noticeably to the total irradiance, especially in highly reflective environments [1] [2] [3].

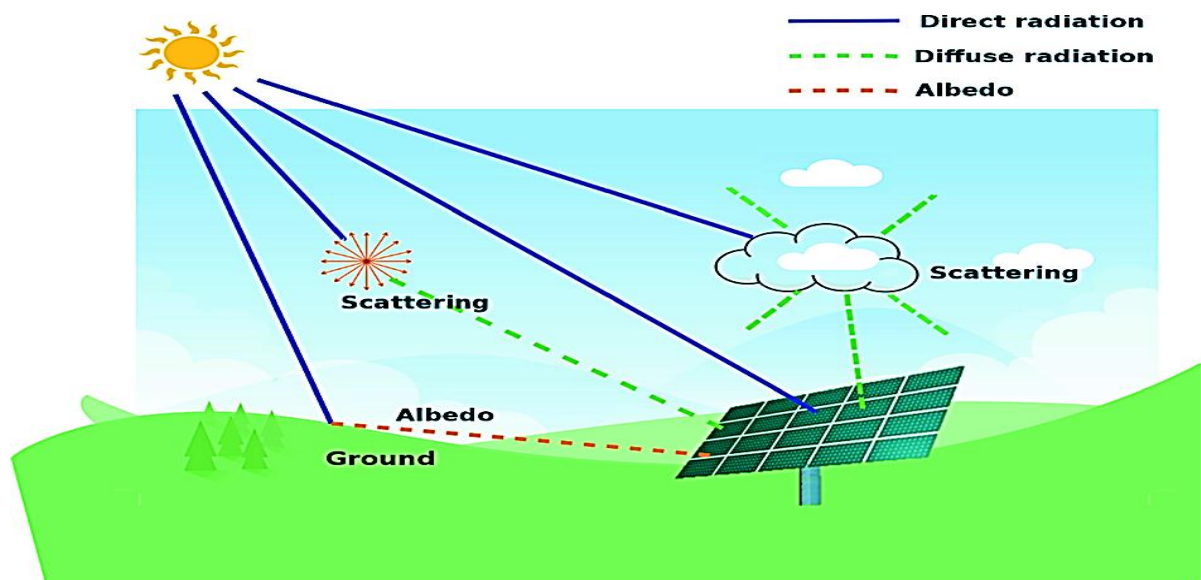


Figure (I.1): Schematic overview illustrating the three primary components of solar radiation: direct beam, diffuse sky, and ground reflected albedo.

I.4. Types of Solar Cells:

I.4.1. Polycrystalline Solar Panels:

Polycrystalline solar panels were among the earliest widely commercialized photovoltaic technologies, they are characterized by a manufacturing process that involves multiple silicon crystals, which makes them relatively cost effective, however, with the rapid development of higher efficiency technologies, their use has progressively decreased in modern photovoltaic installations, although they are still applied in cost sensitive projects [4] [5].

I.4.2. Monocrystalline Solar Panels:

Monocrystalline solar panels are currently one of the most efficient and widely used photovoltaic technologies, they are produced from a single crystal silicon structure, which enhances electron mobility and improves overall conversion efficiency, despite the emergence of advanced technologies such as flexible and transparent solar cells, monocrystalline modules remain the preferred choice for residential, commercial, and industrial applications due to their high performance and reliability [3] [4] [5].

I.4.3. Thin Film Solar Panels:

Thin film solar panels are fabricated by depositing very thin layers of photovoltaic material onto a supporting substrate such as glass, metal, or polymer, this structure significantly reduces weight and allows greater flexibility compared to crystalline silicon technologies.

These characteristics enable their integration into non conventional surfaces, including building facades and curved structures, making them suitable for architectural and urban applications, however, their conversion efficiency is generally lower than that of crystalline silicon panels, despite this limitation, their low material consumption, mechanical flexibility, and adaptability to large surfaces make them advantageous in specific use cases, and adaptability to large surfaces make them advantageous in specific use cases. as illustrated in Figure I.3, which provides a comprehensive technical comparison between polycrystalline, monocrystalline, and thin film solar panel technologies [3] [4] [5].

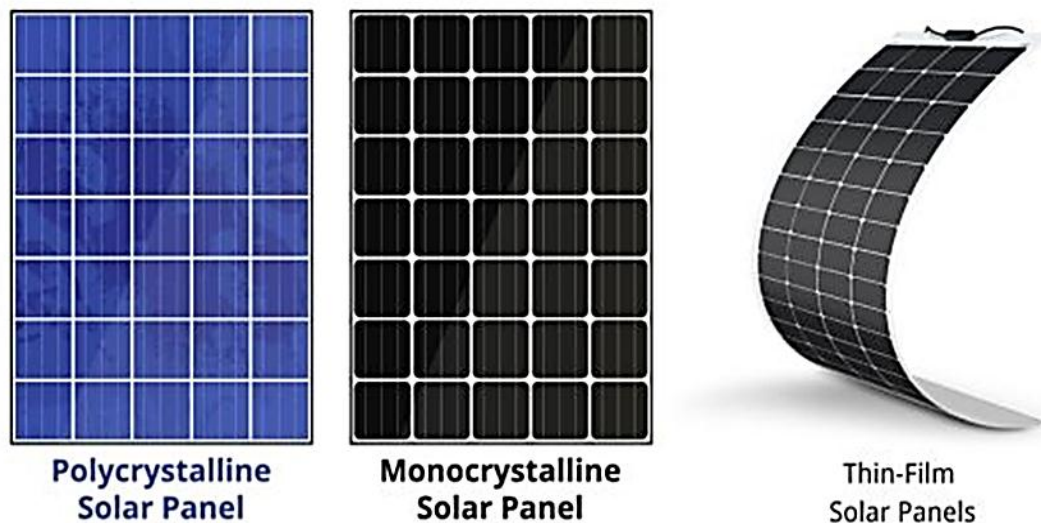


Figure (I.2): Comprehensive technical comparison between polycrystalline, monocrystalline, and thin film solar panel technologies.

I.5. Components of a Photovoltaic System:

I.5.1. Photovoltaic Generator:

The photovoltaic (PV) generator consists of a set of modules interconnected in series or parallel depending on the required output power, each module is itself composed of several photovoltaic cells, which are typically connected in series to achieve a usable voltage level.

I5.1.1. Series Connection:

A series connection increases the output voltage by summing the voltages of individual cells, while the current remains constant, since a single PV cell produces a relatively low voltage, series connection is essential to reach practical voltage levels suitable for electrical loads.

I.5.1.2. Parallel Connection:

A parallel connection increases the output current by summing the currents of individual cells, while the voltage remains unchanged. In practice, series and parallel configurations are combined to obtain the desired voltage and current levels, enabling the PV generator to supply sufficient electrical power to different types of loads [4].

I.5.2. Diodes in Photovoltaic Systems:

Diodes are essential components in photovoltaic systems, as they ensure safe operation and improve system reliability by controlling current flow and protecting components.

I.5.2.1. Bypass Diode:

Bypass diodes are connected across PV modules or strings to provide an alternative current path when a module is shaded or malfunctioning, this prevents power losses and avoids performance degradation of the entire string. [3]

I.5.2.2. Blocking Diode:

Blocking diodes allow current to flow from the PV array toward the battery or load, while preventing reverse current flow, this avoids battery discharge through the PV modules during periods of low or no solar irradiance, such as at night [2] [3].

I.5.3. Charge Regulator:

The charge regulator is a key component in standalone photovoltaic systems. Although it is relatively inexpensive, it plays a crucial role in protecting the system, particularly the battery, by managing energy flow between the PV generator, the battery, and the load, as illustrated in Figure I.4, which shows a commercial solar charge regulator equipped with an LCD display and USB ports, highlighting the physical interface used in standalone photovoltaic configurations. [7]

I.5.3.1. Charge Control:

The regulator controls the charging process of the battery to prevent overcharging. Overcharging can lead to electrolyte decomposition, producing hydrogen and oxygen gases, which may expose battery plates and accelerate aging. In poorly ventilated environments, hydrogen accumulation can also create an explosion risk.

Battery voltage is commonly used as a control parameter because it increases gradually during charging and rises sharply near full charge when the active material is nearly converted and gas evolution begins [6] [7].

I.5.3.2. Discharge Control:

The regulator also prevents excessive discharge by disconnecting the load when the battery state of charge falls below a predefined threshold, this threshold depends on factors such as battery technology, operating temperature, desired lifetime, and load conditions.

While a higher cutoff threshold improves battery lifespan, it reduces the usable capacity of the system. Additionally, battery aging affects its voltage characteristics, requiring periodic adjustment of the control settings.

Deep discharge is particularly harmful, as it can cause irreversible sulfation of the electrodes, reducing battery capacity and, in severe cases, leading to internal short circuits and battery failure [6].



Figure (I.3): Commercial solar charge regulator featuring an LCD display and physical connection terminals for standalone photovoltaic systems.

I.5.4. Batteries:

A battery energy storage system is an electrochemical technology used to store electrical energy for later use. It enables energy to be accumulated when production exceeds demand and to be released when required.

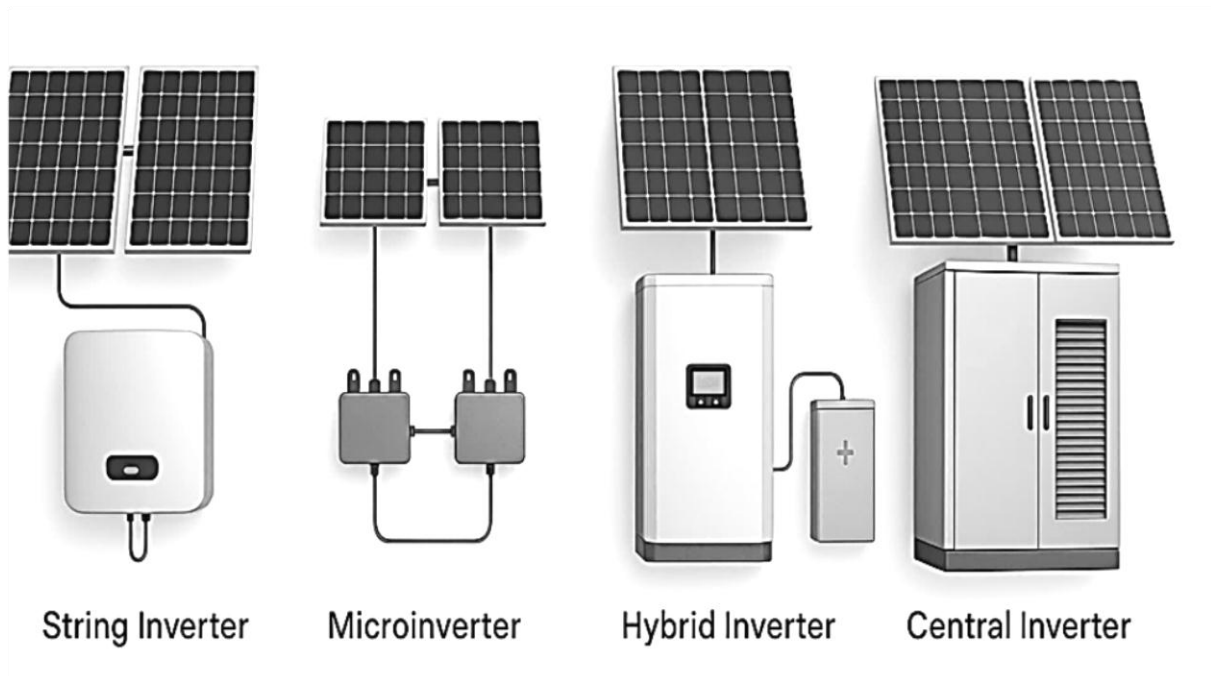
In photovoltaic systems, batteries are mainly used in standalone or hybrid configurations to ensure continuous power supply, particularly in off grid locations or in areas where grid access is unreliable, they provide a practical solution for short term energy backup rather than replacing the electrical grid completely.

Moreover, battery storage systems play a key role in improving the efficiency of renewable energy utilization. They help compensate for the intermittent nature of solar energy by storing excess electricity generated during periods of high irradiance and supplying it during low or non productive periods [6] [43].

I.5.5. Inverters for Photovoltaic Systems:

A solar inverter is an electronic device that converts the direct current (DC) generated by photovoltaic panels into alternating current (AC), which is suitable for use in household,

industrial, or grid connected applications, as illustrated in Figure I.5, which presents a technical comparison illustrating the types of solar inverters, specifically highlighting the configurations of string, micro, hybrid, and central inverter technologies. [6] [41] [44].



Figure(I.4): Technical comparison illustrating the types of solar inverters: string, microinverter, hybrid, and central inverter configurations.

Photovoltaic inverters are available in several configurations depending on system size, architecture, and application requirements, they also differ in power ratings (e.g., 3 kW, 6 kW, 10 kW, and higher), depending on the installation scale.

I.5.5.1. Micro Inverters:

Micro inverters are installed at the module level, meaning each photovoltaic panel is equipped with its own inverter, this configuration is commonly used in small scale systems such as residential rooftops or balcony PV installations. It allows independent operation of each panel, improving system performance under partial shading conditions [8].

I.5.5.2. String Inverters:

In string inverter systems, multiple PV modules are connected in series to form a string. The inverter then converts the combined DC power from the entire string into AC power. In some

configurations, multi string inverters are used to manage several strings simultaneously, improving system flexibility and efficiency [8] [44].

I.5.5.3. Central Inverters:

Central inverters are designed for large scale photovoltaic plants consisting of numerous strings and hundreds or thousands of modules. They collect and convert the aggregated DC power into AC. These inverters are typically installed in dedicated technical rooms or containers [8] [44].

I.5.5.4. Battery Inverters:

Battery inverters are used in PV systems equipped with energy storage. They convert DC energy stored in batteries into AC electricity for local consumption or grid injection, depending on system configuration [8].

I.5.5.5. Hybrid Inverters:

Hybrid inverters combine the functions of both PV inverters and battery inverters in a single unit. They manage energy generation, storage, and consumption, allowing efficient operation of systems that integrate photovoltaic panels and battery storage [8].

I.6. Classification of Photovoltaic Systems:

I.6.1. Standalone Systems:

A standalone photovoltaic (PV) system operates independently from the electrical grid and supplies electricity directly to the load, the connected loads are generally passive or standard electrical devices such as lighting systems, motors, or small appliances.

In most configurations, standalone systems require an energy storage unit, typically batteries, to ensure continuous power supply during periods when solar irradiation is insufficient, such as nighttime or cloudy conditions.

These systems are widely used in remote or isolated locations, including rural areas, islands, and mountainous regions, they are also applied in specific off grid applications such as water pumping systems and remote monitoring installations, standalone photovoltaic systems are

generally divided into two main configurations depending on the presence of energy storage units, encompassing direct coupled systems and systems integrated with energy storage technologies.

I.6.1.1. Direct Systems:

Direct standalone systems operate without any energy storage. In this configuration, electrical energy produced by the PV array is used immediately to supply the load. Therefore, system operation depends entirely on the availability of solar radiation.

Depending on the nature of the load, these systems can be designed for either direct current (DC) or alternating current (AC) applications [8].

I.6.1.2. Systems with energy Storage:

Standalone systems with storage incorporate batteries or other storage technologies to ensure energy availability when solar production is insufficient, during periods of high solar irradiance, excess energy is stored in the batteries, this stored energy is then used during low production periods, such as nighttime or cloudy weather, ensuring a continuous and reliable power supply. as illustrated in Figure I.6, which presents a schematic layout illustrating a standalone off grid photovoltaic system equipped with a batteries [8] [43].

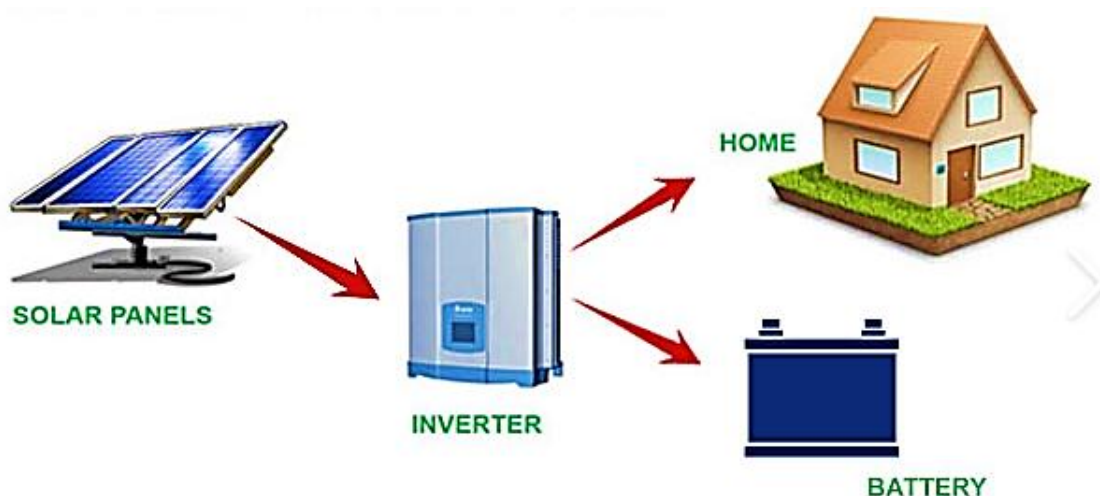


Figure (I.5): Schematic layout illustrating a standalone off grid photovoltaic system equipped with a batteries.

I.6.2. Grid Connected Systems:

Grid connected photovoltaic systems are installations that operate in conjunction with the national electrical grid. In this configuration, the PV system is electrically linked to the utility grid, which acts as an external energy buffer, the electrical grid can absorb excess energy produced by the photovoltaic system when generation exceeds local demand. Conversely, when PV production is insufficient, such as during nighttime or periods of low solar irradiance, electricity is supplied directly from the grid to meet the load requirements, this bidirectional energy exchange improves system reliability and ensures continuous power availability without the need for large energy storage systems. as illustrated in Figure I.7, which presents a schematic layout illustrating a hybrid grid connected photovoltaic system with battery storage [9] [11] [43].

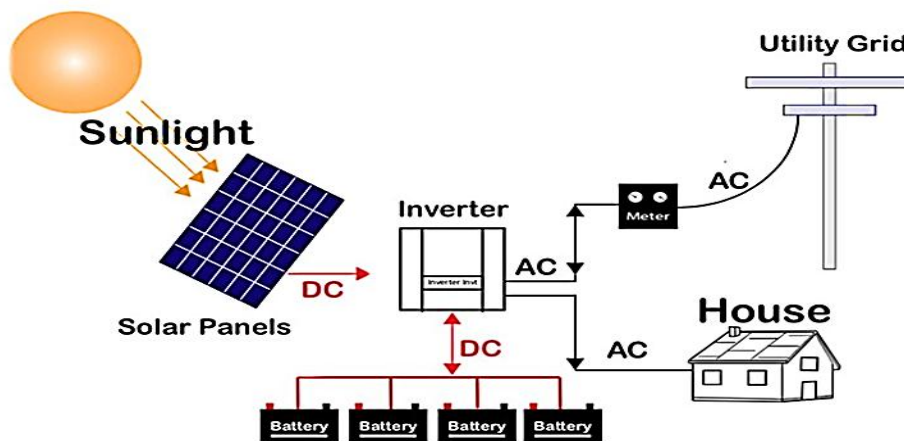


Figure (I.6): Schematic layout illustrating a hybrid grid connected photovoltaic system with battery storage.

I.7. Applications of Photovoltaic Systems:

I.7.1. Agricultural Irrigation:

Photovoltaic pumping systems represent an efficient solution for irrigation in remote agricultural areas. They are widely used to supply electrical energy to water pumps and monitoring devices, particularly in regions where grid extension is technically difficult or economically unfeasible.

By directly converting solar energy into electrical power, these systems reduce dependence on conventional energy sources and provide a sustainable alternative for agricultural water management. as illustrated in Figure I.8, which highlights a photovoltaic solar panel array deployed for agricultural irrigation purposes [10] [12] [13].



Figure (I.7): Photovoltaic solar panel array utilized for agricultural irrigation systems.

I.7.2. Rural and remote area electrification:

In rural and remote regions, particularly in desert and sparsely populated areas, photovoltaic systems provide a reliable and sustainable source of electricity, they are used to supply energy for basic needs such as lighting, cooking support systems, and the operation of essential services, including healthcare facilities.

These systems are especially valuable in areas where access to the national electrical grid is limited or economically impractical, contributing to improved living conditions and local development. as illustrated in Figure I.9, which demonstrates a standalone rooftop photovoltaic system installed to power a remote mountainous residence isolated from the national utility grid [4] [10] [13] [43].



Figure (I.8): Standalone rooftop photovoltaic system supplying electricity to a remote mountainous home isolated from the national grid.

I.7.3. Public lighting and Infrastructure:

Solar energy is widely used in public infrastructure applications such as street lighting and traffic signal systems, these installations improve safety and reliability while reducing the need for extensive electrical wiring and lowering infrastructure costs [10].

I.7.4. telecommunications applications:

In remote and hard to reach areas, such as deserts and mountainous regions, telecommunication towers are often powered by photovoltaic systems, these systems ensure continuous operation of communication and broadcasting equipment while offering a reliable energy supply with low maintenance requirements [10].

I.7.5. Livestock Watering:

Photovoltaic pumping systems are also used in pastoral and semi arid regions, such as the Timimoun area in Algeria, to supply water for livestock, these systems provide a continuous and sustainable water source, supporting animal husbandry in remote environments [11].

I.8. Factors affecting photovoltaic production:

I.8.1. Effect of temperature:

Although photovoltaic modules require sunlight to generate electricity, their performance decreases as temperature increases, high operating temperatures reduce the efficiency of solar cells, proper installation techniques, such as ensuring adequate ventilation and maintaining a gap between the module and the roof, help improve thermal management and overall performance [12] [13] [41].

I.8.2. Effect of shading and dust:

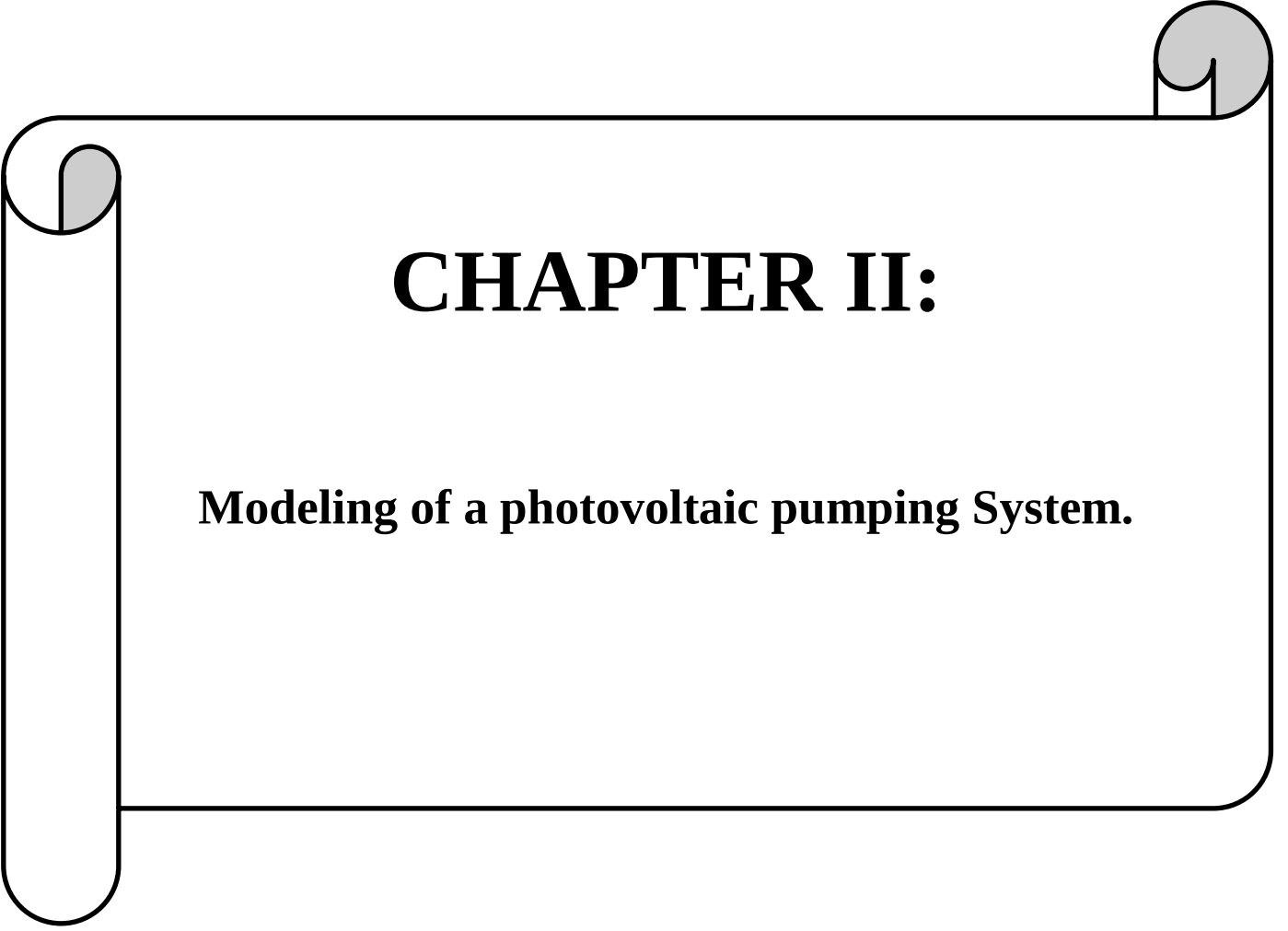
The performance of photovoltaic systems can be significantly affected by partial shading caused by surrounding objects such as trees, buildings, or other structures. In addition, dust and sand accumulation on the surface of the panels reduces the amount of incident radiation reaching the cells, leading to a decrease in power output, for this reason, it is important to install PV modules in unobstructed locations and ensure regular cleaning and maintenance. as illustrated in Figure I.10, which demonstrates the manual cleaning process of removing accumulated dust from the photovoltaic panel surface to restore optimal performance [13] [3] [14] [42].



Figure (I.9): Cleaning process of removing accumulated dust from the photovoltaic panel surface.

I.9. Conclusion:

This chapter highlights photovoltaic solar energy as a sustainable and strategic solution to current energy challenges. Algeria has a high solar potential that makes it well suited for the development of photovoltaic systems. The performance of PV systems depends on understanding solar radiation (direct, diffuse, and reflected) and selecting appropriate solar cell technologies such as monocrystalline, polycrystalline, and thin film, the main system components, including the generator, regulators, and inverters, ensure proper operation, protection, and energy conversion. Photovoltaic systems can be classified into standalone and grid connected systems, showing their flexibility for different applications, they are widely used in irrigation, public lighting, telecommunications, and rural electrification. Finally, environmental factors such as temperature, shading, and dust significantly affect system efficiency, making maintenance and proper installation essential for optimal performance.

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CHAPTER II:

Modeling of a photovoltaic pumping System.

II.1. Introduction:

Modeling plays a crucial role in the analysis of any system, as it provides a structured mathematical description of the technical processes involved. In the case of photovoltaic water pumping systems, such representation is indispensable for understanding and evaluating their performance. The system is composed of several key elements: solar panels, a pump, a controller, a storage tank, and the hydraulic piping network. Figure (II.01) presents a schematic diagram that outlines these components and their interconnections.

The purpose of this chapter is to develop a comprehensive model of the system and to explain the operating principles of the Maximum Power Point Tracking (MPPT) control strategy. In doing so, we will introduce the mathematical models corresponding to each subsystem. The discussion will proceed step by step, beginning with the solar panels, followed by the pump, the controller, the water tank, and finally the hydraulic components and piping.

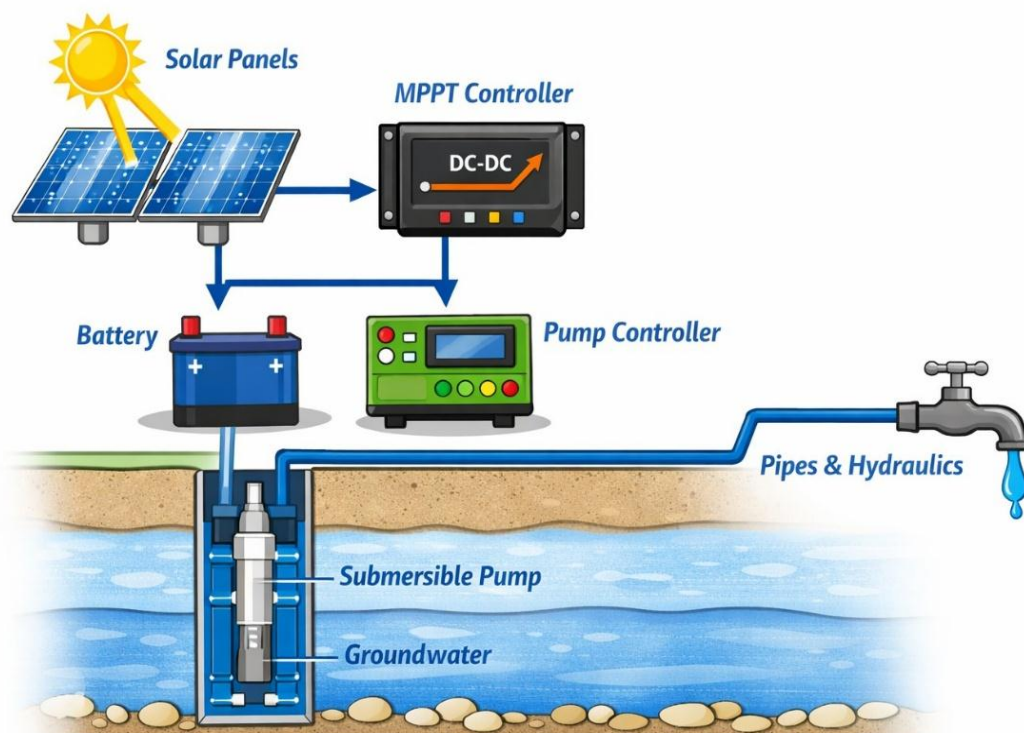


Figure (II.01) Photovoltaic pumping system

Since the solar panels are the system's main energy source, modeling will start with them. The pump, controller, and battery will come next, then the pipelines and hydraulic parts that finish the system's structure.

II.2. Modeling of the Photovoltaic Generator (PVG) :

The equivalent circuit diagram of a photovoltaic cell, which is widely used in the literature, is illustrated in Figure (II.02).

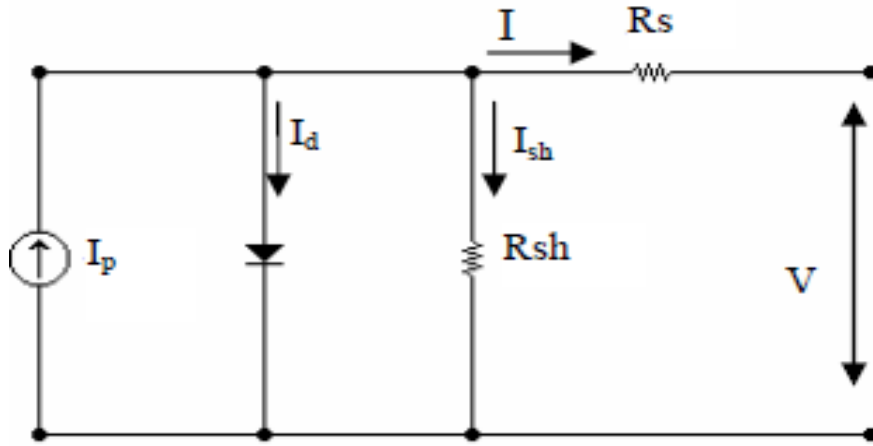


Figure (II.02): Equivalent circuit diagram of the diode model [5].

Figure II.02 shows that the resistance **Rsh** represents the leakage current at the junction level, while the resistance **Rs** represents the various contact and connection resistances [5].

✓ **The nonlinear equation:**

$$I = I_{ph} - I_d - I_p \quad (\text{II_01})$$

$$I_d = I_s \left(e^{\frac{V+I \cdot R_s}{m \cdot V_T}} - 1 \right) \quad (\text{II_02})$$

$$I_p = \frac{V_d}{R_p} = \frac{V+I \cdot R_s}{R_p} \quad (\text{II_03})$$

$$I = I_{ph} - I_s \left(e^{\frac{V+I \cdot R_s}{m \cdot V_T}} - 1 \right) - \frac{V+I \cdot R_s}{R_p} \quad (\text{II_04})$$

With:

- **I_{ph}** : photo current.
- **I_d** : diode current.
- **I_s** : reverse saturation current of the diode.
- **m** : diode ideality factor, $m = 1 \dots 5$. - **V_T** : Thermal voltage [V].
- **K** : Boltzmann constant.
- **T** : absolute temperature, $[T] = K$ (kelvin).
- **e** : charge of an electron.
- **R_p** : parallel resistance simulating the current losses of the solar cell.
- **R_s** : Series resistance that accounts for voltage losses due to external contacts.

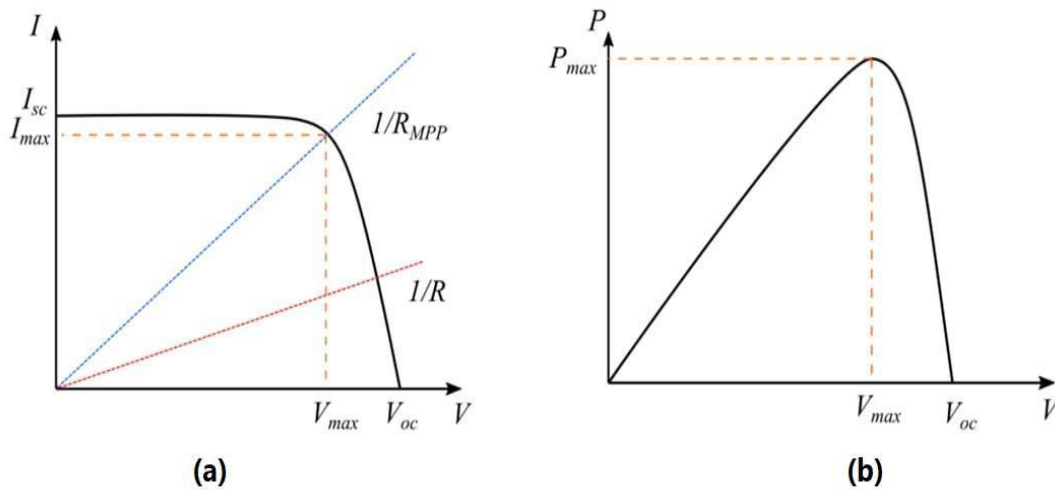


Figure (II.03): (a): Characteristic $I_{pv}=f(V_{pv})$; (b): Characteristic $P_{pv}=f(V_{pv})$

under the conditions: $G_{STC}=1000W/m^2$, $STC=25^\circ C$

A. Influence of Illumination

The increase in sunlight is manifested by a shift of the characteristic $I = f(V)$ along the current axis at a temperature of $t = 25^\circ C$.

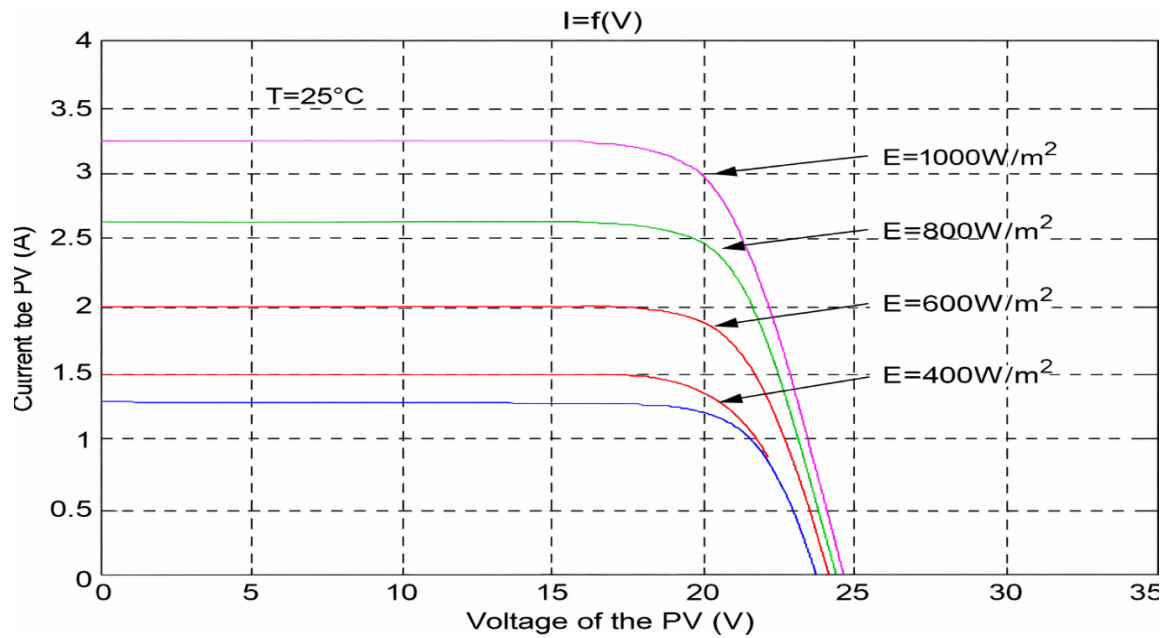


Figure (II.04): The effect of illumination on the $I=f(V)$ characteristic

B. Influence of temperature

The Figure (II.05) shows the influence of temperature on the $I = f(V)$ characteristic for a fixed illumination of $S = 1000 \text{ W/m}^2$.

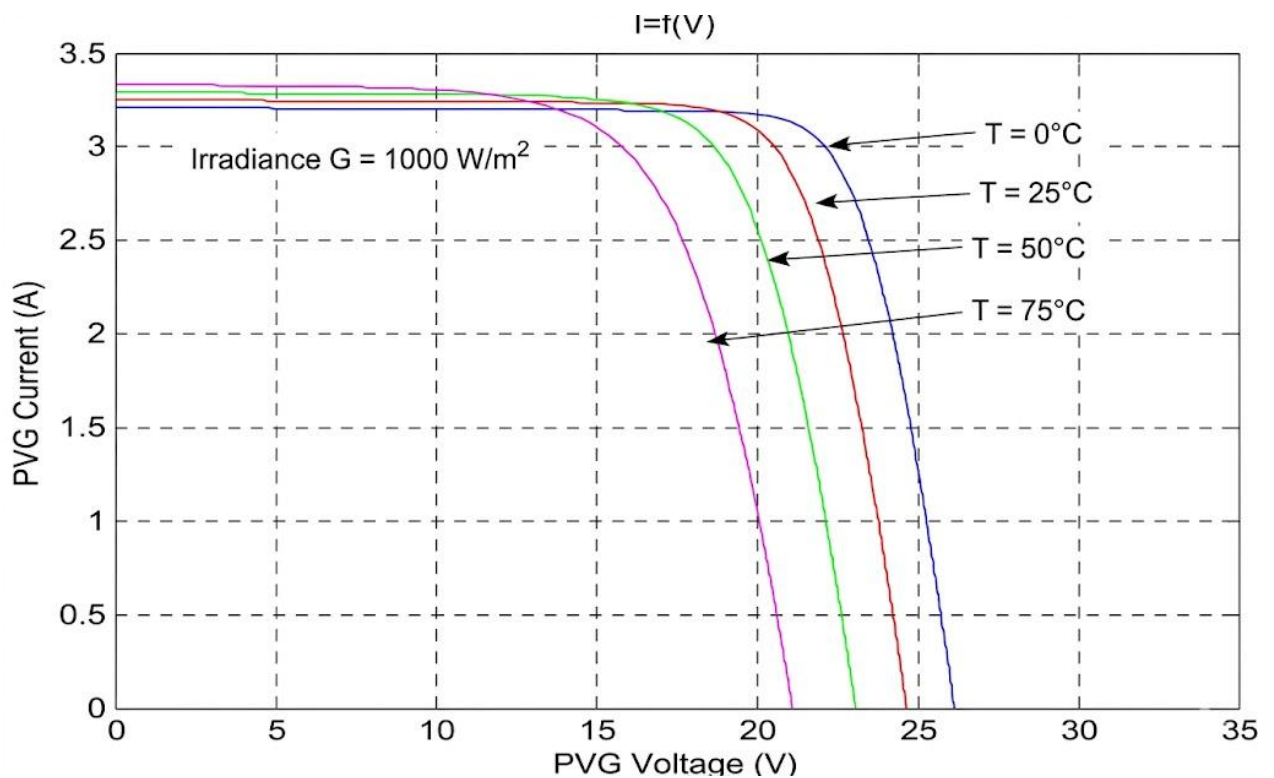


Figure (II.05) : The effect of temperature on the $I=f(V)$ characteristic [16].

II.3. MPPT Control Modeling:

II.3.1. Definition of the MPPT controller:

To ensure that a photovoltaic generator consistently operates at its maximum power output regardless of meteorological conditions (such as solar irradiance and ambient temperature), an MPPT (Maximum Power Point Tracking) controller is employed in conjunction with an intermediate DC/DC converter. This configuration dynamically adjusts the operating point of the system to align with the optimal voltage and current values (V_{opt} , I_{opt}), thereby maximizing energy extraction.

Several techniques have been developed to optimize the power output of photovoltaic arrays [17], including:

- Curve fitting methods
- Look-up table approaches
- Open-circuit voltage-based techniques
- Short-circuit current methods
- Perturb and Observe (P&O) algorithm
- Incremental conductance method
- Advanced strategies such as fuzzy logic and neural networks

In this study, the Perturb and Observe (P&O) method has been selected for MPPT implementation due to its simplicity and ease of integration.

Despite its basic structure, it offers satisfactory efficiency in tracking the maximum power point.

II.3.2. The Perturbation & Observation (P&O) Method:

The Perturb and Observe (P&O) method is among the most widely adopted approaches for Maximum Power Point Tracking (MPPT) in photovoltaic systems. This iterative technique enables the identification of the Maximum Power Point (MPP) by continuously monitoring the electrical characteristics of the PV panel. It operates by introducing a small perturbation in the voltage (or current) and analyzing the resulting change in output power.

As previously discussed, the core principle of the P&O algorithm involves slightly varying the PV voltage V_{pv} around its current value and observing the corresponding change in power P_{pv} . As illustrated in Figure 30, if a positive increment in V_{pv} leads to an increase in P_{pv} , the operating point lies to the left of the MPP. Conversely, if the power decreases, the system has surpassed the MPP. A similar rationale applies when the voltage is decreased.

By evaluating the effect of voltage variations on the power-voltage characteristic $P_{pv}(V_{pv})$, the algorithm can determine the relative position of the operating point with respect to the MPP and adjust the control signal accordingly to converge toward maximum power output.

In summary, if a voltage perturbation results in increased power, the perturbation direction is maintained; otherwise, it is reversed to resume convergence toward the new MPP.

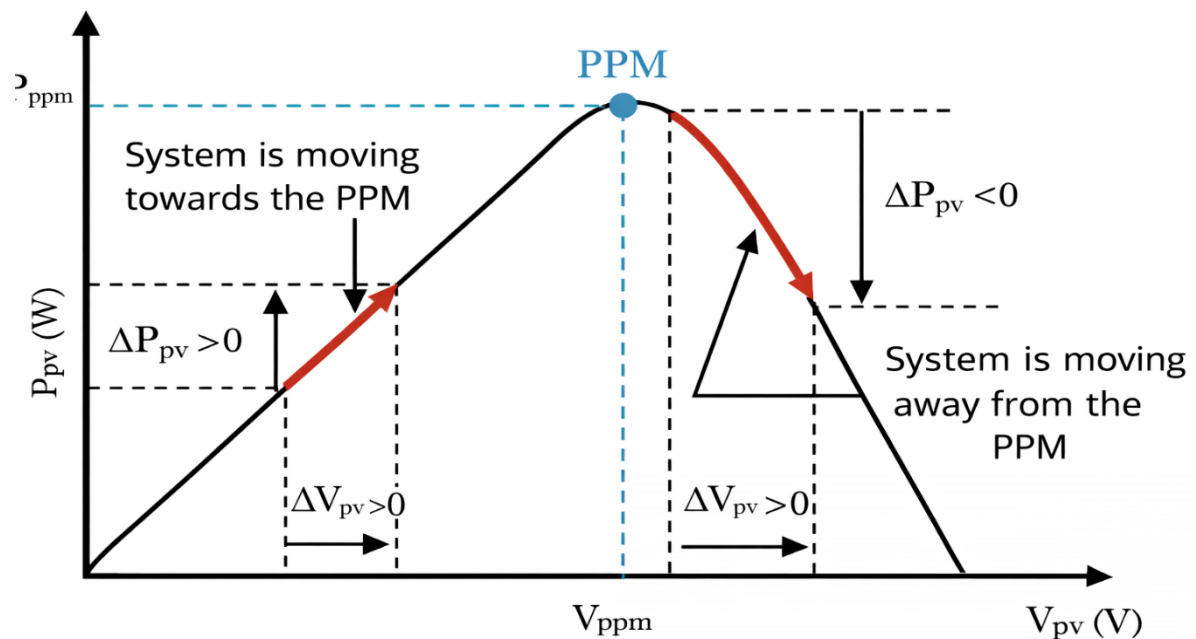


Figure (II.06): Principle of disturbance and observation control

Figure (II.06) illustrates the classical algorithm associated with an MPPT controller of the Perturb and Observe (P&O) type, in which the evolution of output power is analyzed after each voltage perturbation. This control strategy requires two sensors one for current and one for voltage measurement to determine the instantaneous power delivered by the PV modules.

The P&O method is widely adopted due to its ease of implementation. However, it presents certain limitations, notably the occurrence of oscillations around the Maximum Power Point (MPP) under steady-state conditions. These oscillations arise because the algorithm must periodically repeat the search procedure, forcing the operating point to fluctuate continuously around the MPP. One way to mitigate this effect is to reduce the perturbation step size.

Nevertheless, using a smaller increment slows down the convergence toward the MPP, as more iterations are required to reach the optimal operating point. Conversely, a larger increment accelerates convergence but induces excessive oscillations. Striking the right balance between accuracy and speed is therefore critical, yet often challenging to optimize. This requires careful analysis of the specific characteristics of the PV system, complemented by empirical testing to determine the most suitable perturbation step.

In practice, the P&O method performs efficiently under relatively stable irradiance conditions, such as clear sunny days, where the MPP evolves gradually and proportionally with solar intensity. However, under rapidly changing irradiance conditions, this approach may lead to additional power losses due to the finite response time required for the algorithm to track the new MPP. As a result, the system may fail to adapt quickly enough to sudden environmental variations, reducing overall efficiency.

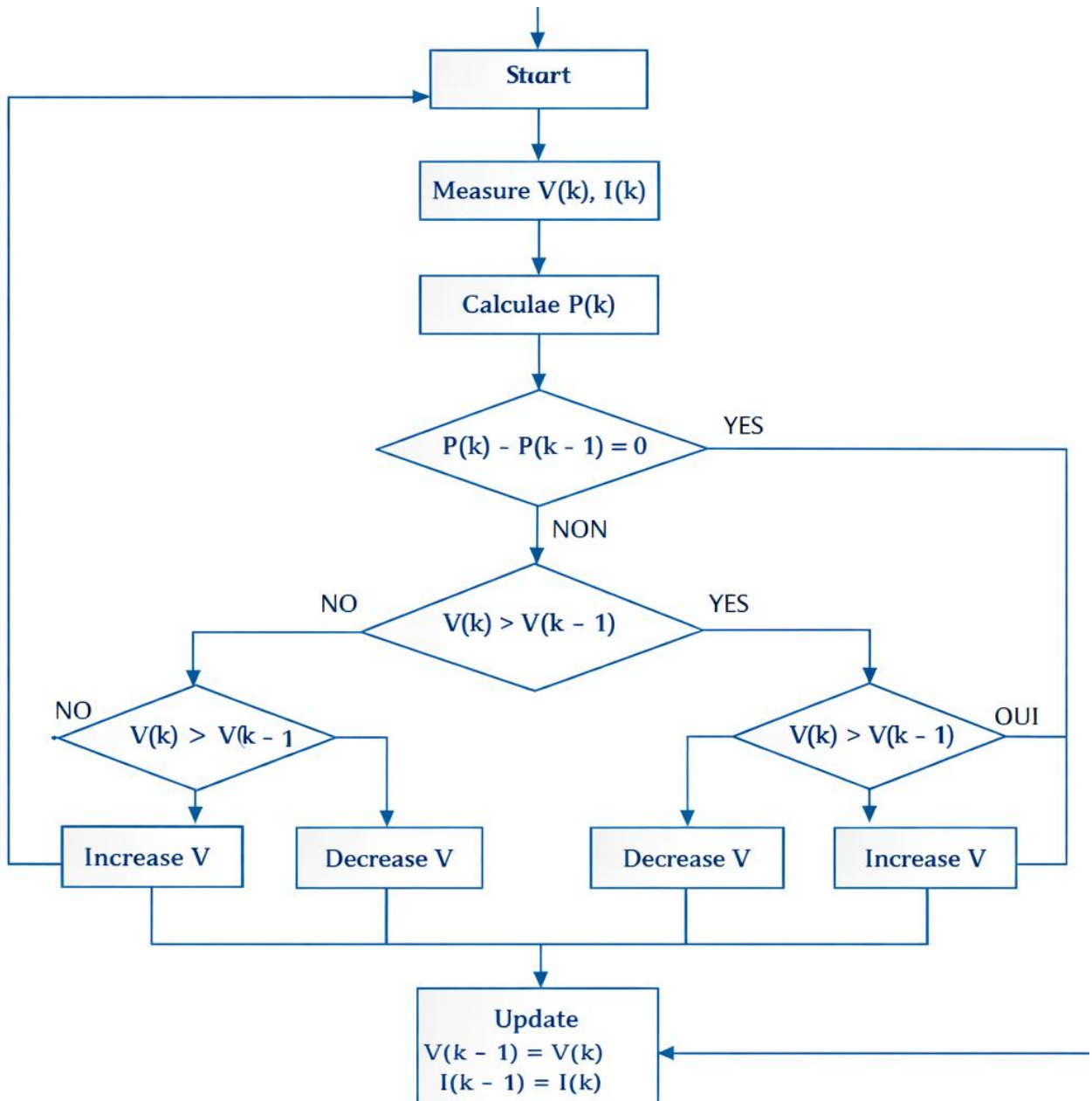


Figure (II.07): P&O method algorithm.

II.4. Modeling of the DC/DC BOOST chopper converter:

To increase the voltage of a DC source, a parallel type BOOST converter can be employed. This power electronics component, classified as a DC-DC converter, enables voltage regulation at the terminals of the photovoltaic panel through a control strategy designed to ensure operation at the Maximum Power Point (MPP) [18].

Under ideal conditions namely, an ideal switch, ideal capacitor, and ideal inductor the BOOST converter can be modeled using the following ordinary differential equations [36]:

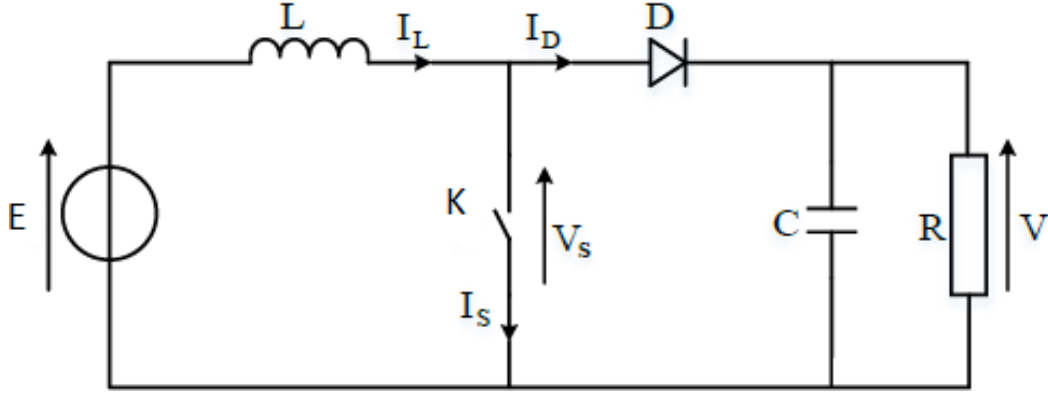


Figure (II.08): Electrical diagram of a BOOST chopper

$$C \cdot \frac{dv_c}{dt} = (1 - u)i_l - \frac{v_c}{R} - i_{(0)} \quad (II - 05)$$

$$L \cdot \frac{di_l}{dt} = V_{in} - (1 - u)V_{(c)} \quad (II - 06)$$

$$V_0 = Ri \quad (II - 07)$$

In practical scenarios, internal resistances associated with the inductor (R_L) and the capacitor (R_C) must be incorporated into the previous model. Consequently,

equations (2.1) and (2.2) are modified to reflect these non-idealities:

$$C \cdot \frac{dv_c}{dt} = (1 - u) - \frac{V_0}{R} - i_0 \quad (II - 08)$$

$$L \cdot \frac{di_l}{dt} = V_{in} - (1 - u)V_0 - R_l i_l \quad (II - 09)$$

$$V_0 = V_c + R_C \cdot C \cdot \frac{dv_c}{dt} \quad (II - 10)$$

By incorporating (II-10) into (II-05):

$$C \cdot \frac{dv_c}{dt} = (1 - u)i_l - \frac{v_c}{R} - \frac{R_s}{R} \cdot C \cdot \frac{dv_c}{dt} - i_0 \quad (II - 11)$$

Which results in:

$$\left(1 + \frac{R_c}{R}\right) \cdot C \cdot \frac{dv_c}{dt} = (1 - u)i_l - \frac{v_c}{R} - i_0 \quad (II - 12)$$

And:

$$\left(\frac{R + R_c}{R}\right) \cdot C \cdot \frac{dv_c}{dt} = (1 - u)i_l - \frac{v_c}{R} - i_0 \quad (II - 13)$$

From where:

$$\frac{dV_c}{dt} = \frac{R}{R + R_c} (1 - u)i_l - \frac{V_c}{R + R_c} - \frac{Ri_0}{R + R_c} \quad (II - 14)$$

The expression (II-10) becomes:

$$V_0 = \frac{RV_c}{R + R_c} + \frac{R_c V_c}{R + R_c} - \frac{R_c V_c}{R + R_c} + \left(\frac{RR_c}{R + R_c}\right) [(1 - u)i_l - i_0] \quad (II - 15)$$

And therefore:

$$V_0 = \frac{RV_c}{R + R_c} + \left(\frac{RR_c}{R + R_c}\right) [(1 - u)i_l - i_0] \quad (II - 16)$$

The expression (II-13) becomes:

$$i_l = \frac{1}{L} \int (V_{in} - (1 - u)V_0 - R_l i_l) dt \quad (II - 17)$$

With:

u: switch position (0 or 1)

II.5. Inverter Modeling:

The primary function of the inverter is to convert the direct current (DC) generated by the photovoltaic (PV) system into alternating current (AC), either single phase or three phase [19].

In this study, we consider the ideal case of a three phase, two level voltage inverter. The model assumes perfect switches with instantaneous commutation. The inverter is treated as an ideal voltage source with negligible internal impedance [19].

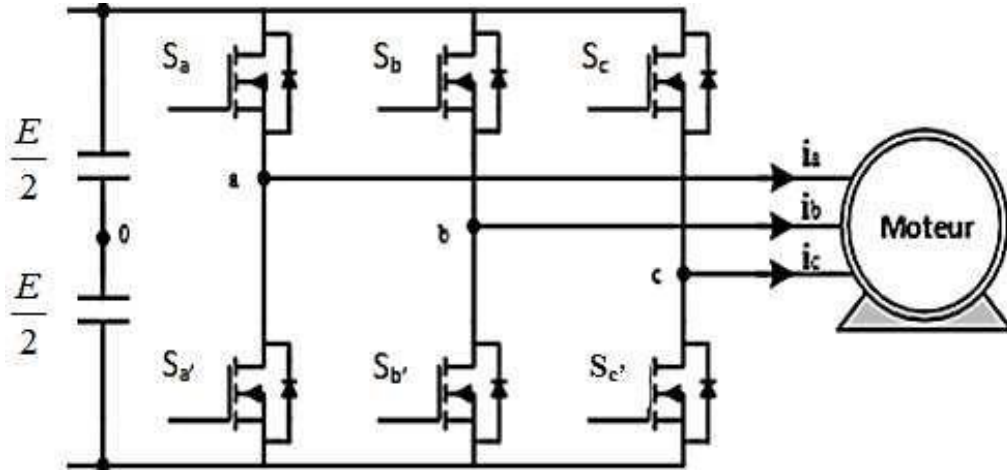


Figure (II.09): Structure of the three-phase voltage inverter.

The switching states of the inverter, assumed to be ideal, can be defined by three Boolean control variables S_i with $i=a,b,c$:

- When the upper transistor is conducting, the variable $S_i=1$.
- When the lower transistor is conducting, the variable $S_i=0$.

The phase voltages applied to the three stator phases are expressed with respect to the fictitious neutral point “o” as follows [21]:

$$\begin{cases} V_{an} = V_{a0} + V_{0n} \\ V_{bn} = V_{b0} + V_{0n} \\ V_{cn} = V_{c0} + V_{0n} \end{cases} \quad \#(II - 18)$$

By summation, we obtain:

$$V_{an} + V_{bn} + V_{cn} = V_{a0} + V_{b0} + V_{c0} + 3V_{0n} \quad (II - 19)$$

Since the three-phase stator voltage system is symmetrical:

$$V_{a0} + V_{b0} + V_{c0} + 3V_{0n} = 0 \quad (II - 20)$$

Thus, the fictitious neutral voltage is given by:

$$V_{0n} = \frac{1}{3} (V_{a0} + V_{b0} + V_{c0}) \quad (II - 21)$$

By substituting equation (II-21) into the system of equations (II-18), the phase voltages can be expressed in terms of the inverter switching states and the fictitious neutral point.

$$\begin{cases} V_{an} = \frac{1}{3}(2.V_{a0} - V_{b0} - V_{c0}) \\ V_{bn} = \frac{1}{3}(-V_{a0} + 2.V_{b0} - V_{c0}) \\ V_{cn} = \frac{1}{3}(-V_{a0} - V_{b0} + 2.V_{c0}) \end{cases} \quad \#(II - 22)$$

II.6. Electric motor:

Each Solar pump is integrated with an electric motor which can be either AC or DC motor.

The two types are explained in detail below:

II.6.1. DC motors:

DC motors operate under direct current source, thus makes the motor more applicable where the direct coupling with PV panels is required. The DC motors are widely applied in small applications with a capacity not exceeding 3 kW. When opting DC motors it is necessary to consider a high efficient motor [23].

From an analytical and electrical perspective, the steady-state operation of a DC machine is governed by fundamental electromagnetic equations. The relationship between the armature terminal voltage (V_a), the generated back electromotive force (E_a), and the armature current (I_a) is defined by the following voltage balance equation:

$$V_a = E_a + I_a R_a \quad (II - 23)$$

Where:

V_a : Armature terminal voltage (V).

E_a : Generated back electromotive force (V).

I_a : Armature current (A).

R_a : Armature circuit resistance (Ω).

The analytical fundamentals of the machine show that both the electromagnetic torque (T_{mech}) and the internal generated voltage (E_a) depend on the air-gap magnetic flux (Φ_d) and the mechanical speed (ω_m). These relationships are precisely formulated as follows:

$$T_{mech} = K_a \Phi_d I_a \quad (II - 24)$$

$$E_a = K_a \Phi_d \omega_m \quad (II - 25)$$

Where ω_m represents the mechanical angular velocity, and K_a is the structural motor design constant determined by the physical geometry and winding of the machine, given by:

$$\frac{K_a}{(2 \pi m)} = (poles Ca) \quad (II - 26)$$

Where "poles" is the number of field poles, C_a is the total number of armature conductors, and m is the number of parallel paths in the armature winding. The total electromagnetic power converted within the machine can be linked to the developed mechanical torque by:

$$T_{\text{mech}} = (E_a * I_a) / \omega_m = K_a \Phi_d I_a \quad (\text{II} _ 27)$$

There are common types of DC motors such as:

The Brush Type: The traditional DC motor, in which small carbon blocks called "brushes" conduct current into the spinning portion of the motor. They are used in DC surface pumps and also in some DC submersible pumps. Brushes naturally wear down after years of use and may be easily replaced [22].

The Brushless type: It is a High technology motor that used in centrifugal type DC submersible pumps. The motor is filled with oil to keep the water out. An electronic system [23] that used to precisely alternate the current, causing the spinning of the motor. There is a permanent magnet that exists in brushless DC motor which communicates with the stator electronically to lessen the requirement for brushes [22].

When the motor opted is DC motor type, there is no need to convert the DC from panels to AC by using DC/AC Converter [21]. The DC motors are considered expensive since they require regular maintenance of the brushes [39].

II.6.2. AC motors:

These motors use alternating current to operate. They are widely used and commercially available at different ranges. According to [22] and other studies, induction motors and asynchronous motors are the two fundamental types of motors available. El Shaikh et al. described that AC motors could be further divided into single-phase motors and three-phase motors [24]. Motors with a rating of 1 kW or lower are not suitable for PV-powered systems due to their low efficiencies. Additionally, because of their high starting current requirements, power conditioning circuitry needs to be added [22]. There are about five starting methods for AC motors, namely: DOL, Star Delta, Auto Transformer, Soft Starter, and VFD.

According to Fitzgerald et al. (2003), the operation and performance of induction motors can be described using several fundamental equations. The synchronous speed is given by:

$$N_s = (120f)/P \quad (\text{II} _ 28)$$

where N_s is the synchronous speed (rpm), f is the supply frequency (Hz), and P is the number of poles. The motor slip is expressed as:

$$S = (N_s - N_r)/N_s \quad (\text{II}_-29)$$

The electromagnetic torque developed by the induction motor can be expressed as:

$$T_{\text{mech}} = (1/\omega_s) \times [(n_{\text{ph}} \times V_{1,\text{eq}}^2 \times (R_{2/s})) / ((R_{1,\text{eq}} + (R_{2/s}))^2 + (X_{1,\text{eq}} + X_2)^2)] \quad (\text{II}_-30)$$

where ω_s is the synchronous mechanical angular velocity, n_{ph} is the number of phases, $V_{1,\text{eq}}$ is the equivalent phase voltage, $R_{1,\text{eq}}$ and $X_{1,\text{eq}}$ are the equivalent stator resistance and reactance, R_2 and X_2 are the rotor resistance and reactance, respectively, and s is the motor slip. These equations are commonly used to evaluate the speed, torque, and performance characteristics of induction motors employed in photovoltaic water pumping systems.

Connecting a DC motor directly from the PV system is considered as a least expensive method of pumping water by using solar energy [24], but as mentioned above this should be more applicable to a system with less than 3 kW. Apart from the other comparisons, AC motors are reliable and cheaper compared to DC motors, thus choosing either to use AC or DC motors can be a complicated exercise. Gimma identified five criteria that should be used for choosing a motor pump for a PV system; these criteria are price, efficiency, reliability, availability, and maintenance.

Note: Reference [45] was used as the primary source for the induction motor equations presented in this section. In addition, this reference includes detailed theoretical and practical information related to both induction (asynchronous) motors and DC motors, such as their operating principles, equivalent circuits, performance characteristics, and applications.

II.7. HOMER Software:

II.7.1. HOMER Pro:

The HOMER Pro software serves as a robust platform for designing optimal hybrid energy systems that guarantee reliable and cost-effective electricity supply under diverse operating conditions. Beyond system design, it systematically evaluates key parameters for both grid connected and stand alone configurations, thereby identifying the most efficient hybrid arrangement. By simulating multiple combinations of available energy resources, HOMER

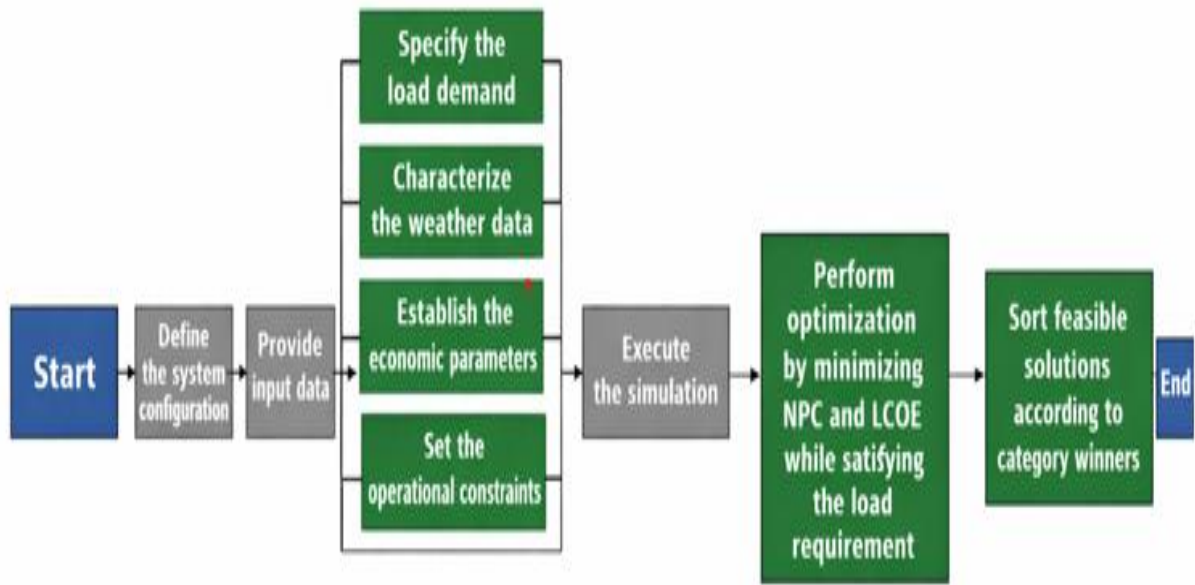
Pro delivers objective and precise results. To assess renewable energy potential, the program integrates meteorological datasets provided by the National Aeronautics and Space Administration (NASA), ensuring sit specific accuracy.

Its workflow unfolds in three distinct phases. The first involves defining project inputs, including geographical location, resource availability, load demand profiles, and system components. The second stage focuses on simulation and optimization, where the software applies user-defined parameters to explore feasible system designs. Finally, the third stage presents the results, offering detailed insights into system sizing, performance indicators, and economic metrics that support decision making [26]. [40].

II.7.2. Methodology of HOMER Pro:

HOMER Pro, developed by the National Renewable Energy Laboratory (NREL, 2021), is widely recognized as the leading software for simulating and optimizing hybrid power systems at specific sites. As the most advanced microgrid modeling platform, it enables comprehensive evaluation of system performance, Net Present Cost (NPC), and Levelized Cost of Energy (LCOE) across a wide range of configurations, whether grid-connected, off-grid, or incorporating energy storage. One of its strengths lies in its ability to process large datasets, running extensive simulations that may require several hours to achieve an optimal balance between energy demand and supply. [40].

Figure II.14 illustrates the flow diagram of HOMER Pro, highlighting its systematic approach to hybrid system design and analysis [27].



Figure(II.10). Streamlined diagram depicting the optimization algorithm of HOMER Pro [27].

a. Net Present Cost

The Net Present Cost (NPC) of a hybrid energy system represents the present value of all expenditures incurred throughout its operational lifetime, adjusted by subtracting the salvage value at the end of the period. These expenditures include the initial capital investment, replacement costs, and ongoing operation and maintenance expenses, as expressed in Equation (II.64). Within HOMER Pro, the NPC is calculated individually for each system component, thereby providing a comprehensive assessment of the overall economic viability of the configuration [28].

$$NPC = \sum (C_{\text{capital}} + C_{\text{replace}} + C_{\text{maint}} - C_{\text{salvage}}) \quad (\text{II_31})$$

Where C_{capital} is an initial cost, C_{replace} is replacement value, and C_{main} is maintenance cost and C_{salvage} is salvage value.

b. Levelized Cost of Electricity

The Levelized Cost of Electricity (LCOE) is defined as the average cost per kilowatt-hour of electrical energy produced by a given system over its lifetime. In HOMER Pro, this metric is determined by dividing the total annualized cost of the system by the total electrical output,

CHAPTER II: Modeling of a photovoltaic pumping System.

expressed as $L' \{AC\}$ and $L' \{DC\}$, as shown in Equation (II.65). This calculation provides a standardized measure for comparing the economic performance of different system configurations [28].

$$LCOE = \frac{\text{Total annualized cost}}{(L_{\text{primAC}} + L_{\text{primDC}})} \quad (\text{II}_-32)$$

Where L_{primAC} is the alternating current primary load and L_{primDC} is the direct current main load. [40].

II.7.3. Interfaces of HOMER Pro:

The HOMER software boasts user-friendly features, with an interface resembling typical software programs. It offers a top menu along with accessible icons, allowing users to navigate without delving into menus extensively. The HOMER interface can be categorized into three key sections, as illustrated in Figure II.15: the system definition area (House), the resource definition area (Design), and the results area (Results) [29]. [40].

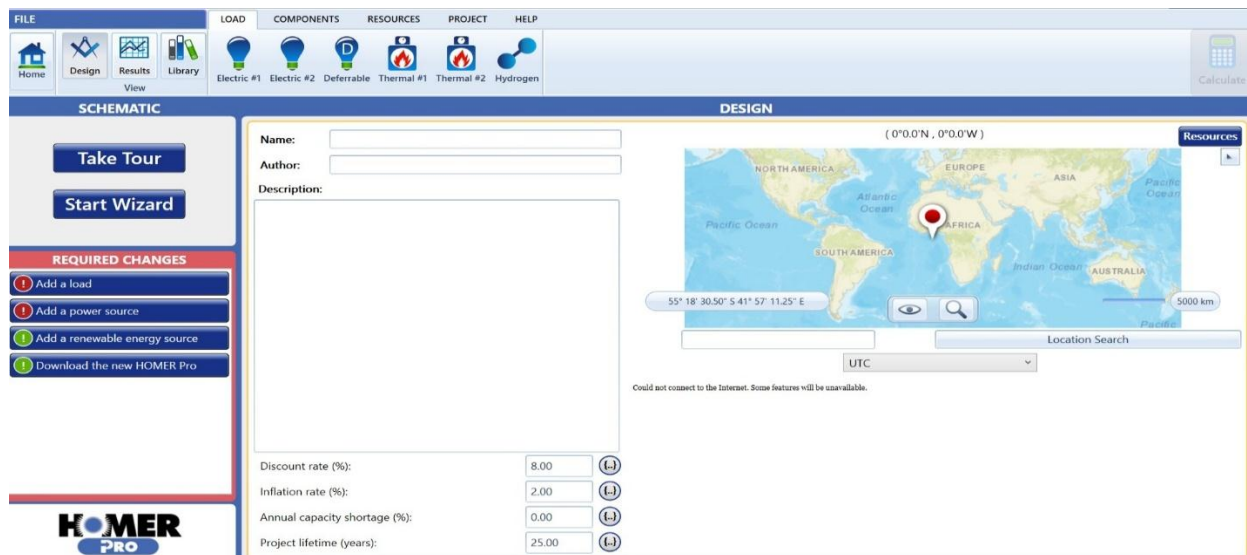


Figure (II.11). Interface of HOMER pro.

II.7.3.1. Components in HOMER pro:

A variety of components can be integrated into a project to facilitate the design and optimization of energy systems. These elements are generally classified into four main categories: power generation sources, energy storage units, conversion devices, and electrical loads.



Figure (II.12). HOMER components

II.7.3.2. Resources in HOMER pro:

Energy system modeling relies on a wide range of input datasets. These include information on renewable energy resources such as solar, wind, and hydro, as well as data on fuel prices and detailed energy demand profiles. Together, these inputs form the basis for accurately simulating system behavior and optimizing hybrid configurations



Figure (II.13). Resources in HOMER.

II.7.3.3. How to start a project:

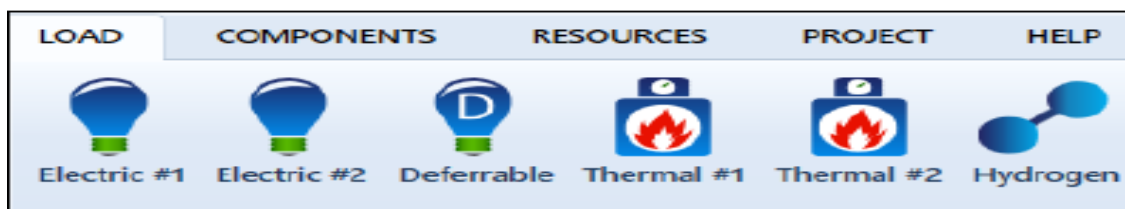
To complete a project in the HOMER Pro program, which is software for designing and optimizing grids, you can follow these steps:

First, we choose the site on which we will study.



Figure(II.14). The site selected for study.

Definition entails specifying electrical demand requirements and energy consumption patterns, aiding in simulating and optimizing system performance by inputting user or appliance energy usage profiles.



Figure(II.15). Choosing the right load for the project.

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Enter the electrical load profiles. This can be done by importing data or manually entering the load values. HOMER Pro allows you to define multiple loads.



Figure (II.16). Electric load set up.

Download solar irradiance data, which can be imported from a file or selected from HOMER's database.

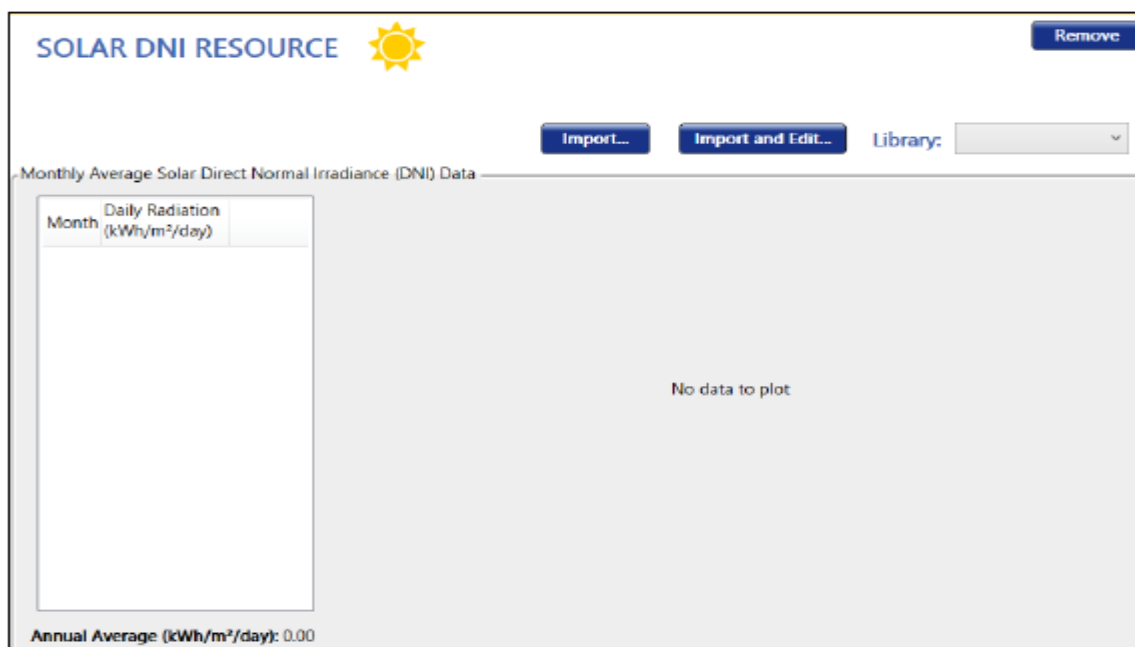


Figure (II.17). Enter the information for Solar Resource.

CHAPTER II: Modeling of a photovoltaic pumping System.

Download wind speed data.

WIND RESOURCE

Choose Data Source: ☒ Enter monthly averages ☐ Import from a time series data file or the library

[Download From Internet...](#) [Import...](#) [Import and Edit...](#) Library:

Choose [Windnavigator](#) for improved wind modeling.

Monthly Average Wind Speed Data

Month	Average (m/s)
Jan	0.000
Feb	0.000
Mar	0.000
Apr	0.000
May	0.000
Jun	0.000
Jul	0.000
Aug	0.000
Sep	0.000
Oct	0.000
Nov	0.000

Annual Average (m/s): 0.00

Average Wind Speed (m/s)

Parameters **Variation With Height** Advanced Parameters

Altitude above sea level (m):

Anemometer height (m):

Figure (II.18). Enter the information for Wind resource.

Add renewable sources solar PV, wind turbines appropriate for the project, and other sources.

PV SET UP

Generic flat plate PV

[Complete Catalog](#)

PROPERTIES

Name: Generic flat plate PV

Abbreviation: PV

Panel Type: Flat plate

Rated Capacity (kW):

Manufacturer: Generic

[www.homerenergy.com](#)

Notes:

This is a generic PV system.

[Add PV](#)

WIND TURBINE SET UP

Generic 3 kW

[Complete Catalog](#)

PROPERTIES

Name: Generic 3 kW

Abbreviation: G3

Rated Capacity (kW): 3

Manufacturer: Generic

[homerenergy.com](#)

Notes:

[Add Wind Turbine](#)

Figure (II.19). Enter characteristics of the PV and the wind turbine in HOMER Pro.

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To choose battery storage appropriate for the project.

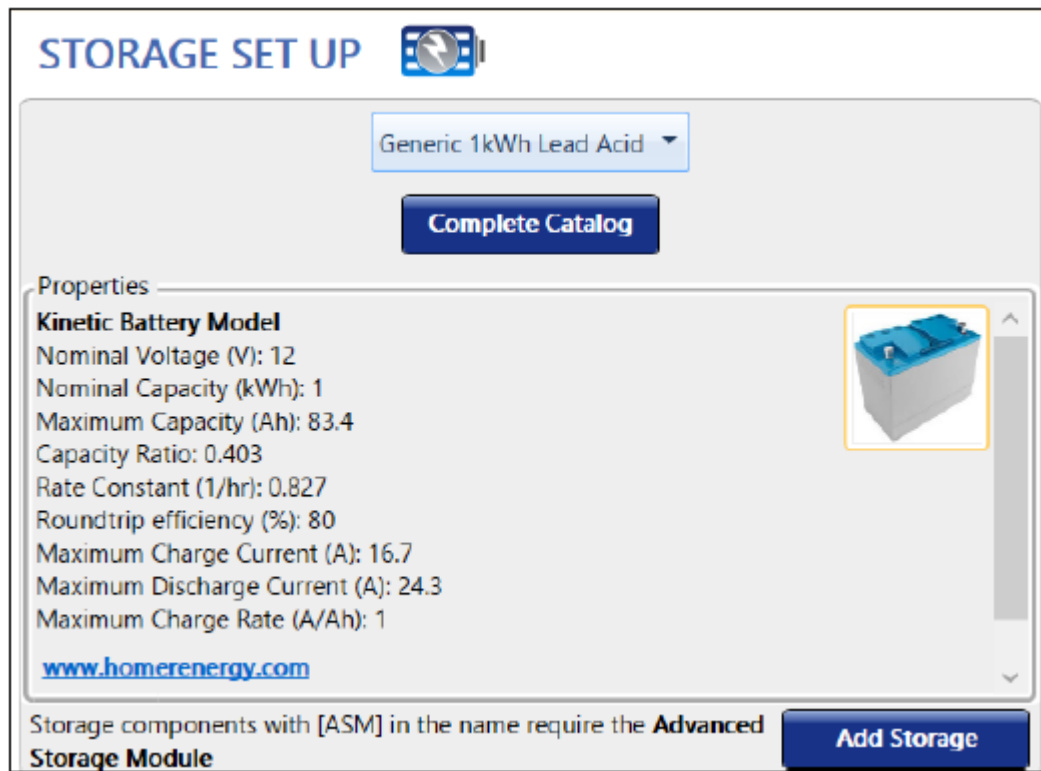


Figure (II.20). Battery characteristics under HOMER Pro.

Add inverters, rectifiers, or other power electronic converters appropriate for the project if necessary.

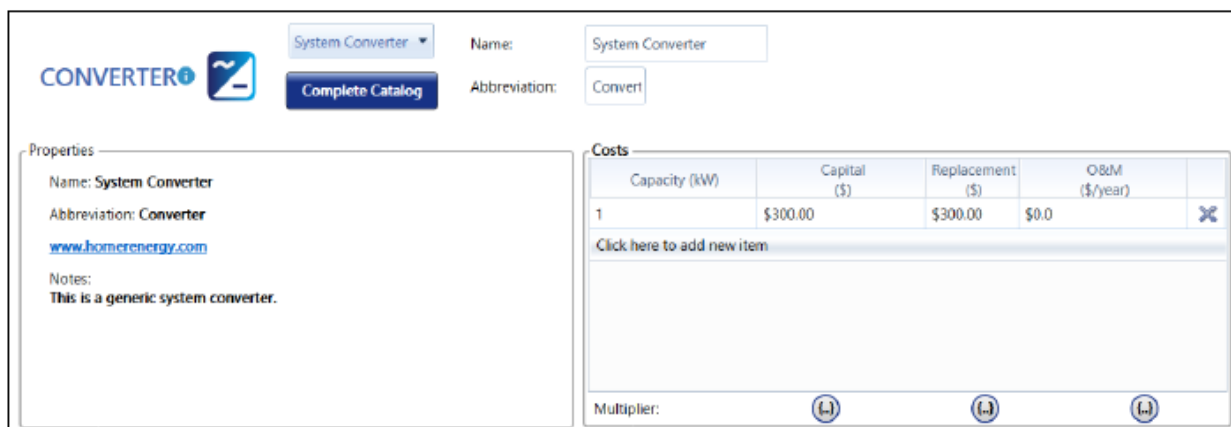


Figure (II.21). Features of the conversion system with HOMER Pro.

CHAPTER II: Modeling of a photovoltaic pumping System.

Enter economic parameters such as the project lifetime, discount rate, inflation rate, and others.

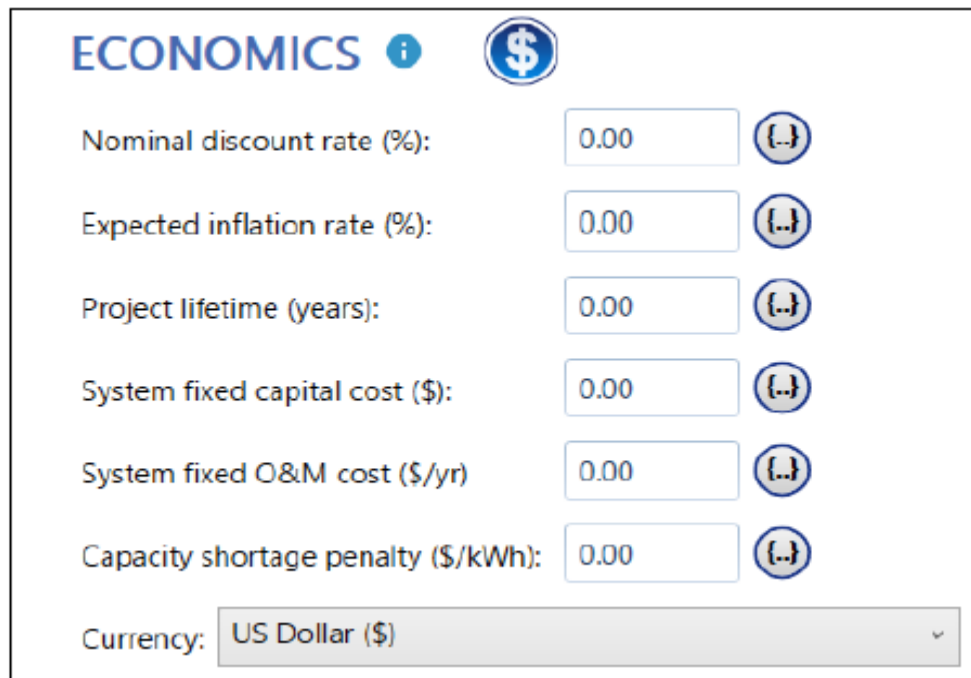


Figure (II.22). Enter economic information for the project.

Click on the "Simulate" button to run the simulation. HOMER Pro will analyze the different configurations and find the optimal system based on the inputs and constraints.

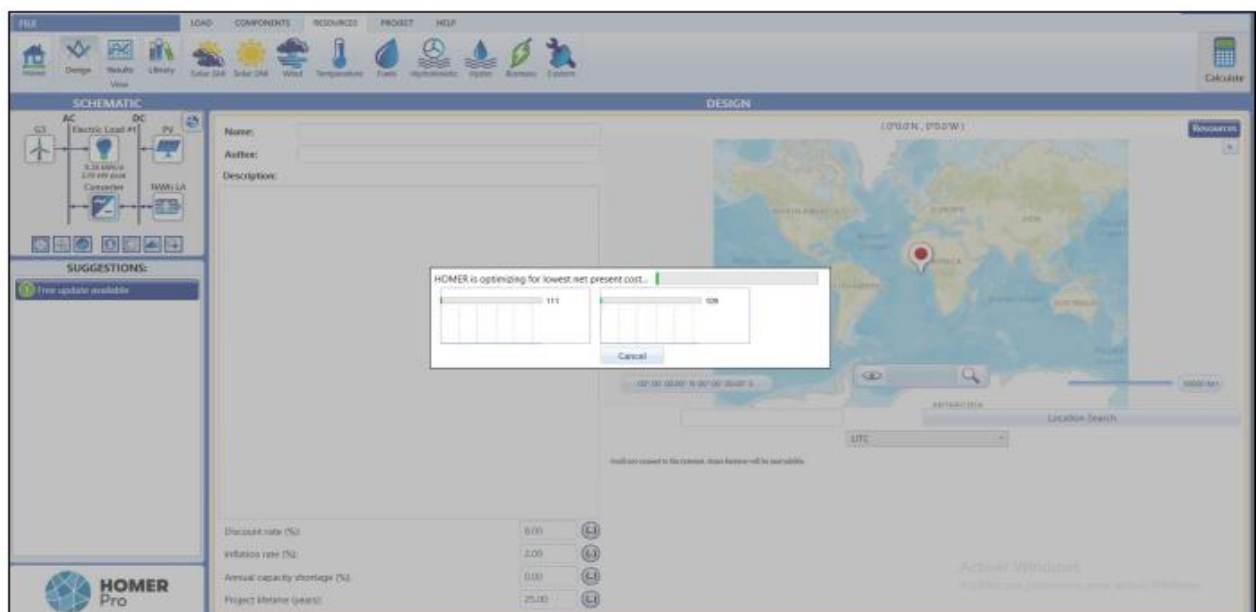


Figure (II.23). The beginning of a process simulate.

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After the simulation is complete, review the results in the results section.

Summary

Tables

Graphs

Calculation Report

Compare Economics

Column Choices

Export

Optimization Results

Left double click on a particular system to see its detailed Simulation Results.

Categorized

Overall

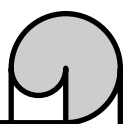
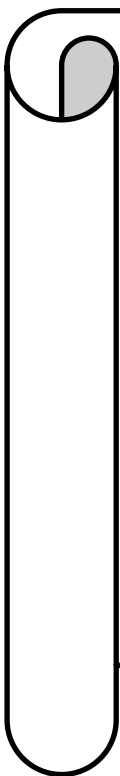
Architecture				Cost				System		PV		G3			kWh		
   PV (kW)	 1kWh/LA	Converter (kW)	Dispatch	NPC (\$)	CCE (\$)	Operating cost (\$/yr)	Initial capital (\$)	Ren. Frac. (%)	Total Fuel (\$/yr)	Capital Cost (\$)	Production (kWh/yr)	Capital Cost (\$)	Production (kWh/yr)	O&M Cost (\$)	Autonomy (hr)	Annual TI (kWh)	
   4.64	31	2.17	CC	\$33,641	\$0.634	\$934.72	\$21,557	100	0	11,607	7,922				39.7	2,511	
   4.00	1	25	2.67	CC	\$50,803	\$0.958	\$1,128	\$36,300	100	0	10,000	6,825	18,000	4,003	180	32.0	1,615
   4	68	4.68	CC	\$137,983	\$2.60	\$3,417	\$93,004	100	0			72,000	16,013	720	87.0	1,752	

Figure (II.24). Optimal result for the hybrid system by Homer Pro.

Once the simulation process is completed, HOMER Pro ranks all feasible system configurations according to their Net Present Cost (NPC), beginning with the lowest value. The NPC represents the total lifetime cost of the system, discounted to present value, and thus serves as a key economic indicator. The software output provides a list of viable options ordered by NPC, with the configuration exhibiting the lowest NPC identified as the most cost-effective and optimal solution. This top-ranked design reflects the best composition of energy system components for the project, as illustrated in Figure II.20. By examining HOMER's ranking, users can readily identify the most economically viable configuration and its associated components.

II.8. Conclusion:

In this chapter, we have examined the modeling of the various components of the photovoltaic pumping system and their control strategies, namely: the photovoltaic generator (PVG), the converters, the asynchronous machine, and the water pump. In the following chapter, we will present the simulation results for each component of the system, followed by a techno-economic study of a representative example of a photovoltaic water pumping system operating under direct solar irradiation.



CHAPTER III:

**Technical Modeling and Economic Study of the
Solar Pumping System via HOMER Pro
Software.**

III.1. Introduction:

The modern agriculture sector in southern Algeria, particularly in the province of El Oued, is experiencing a significant leap forward based on the utilization of available natural resources to ensure sustainable food security. In light of drought related climate challenges and the rising costs of fossil fuels, solar photovoltaic systems are emerging as a strategic and clean alternative that balances engineering efficiency with economic viability.

To evaluate the feasibility of a solar powered agricultural farm located in the Nakhlah area of El Oued Province, the HOMER Pro simulation platform was employed in conjunction with NASA solar radiation databases. The study focused on the development of detailed daily and yearly electricity demand profiles associated with potato irrigation pumping systems and on the comparison of different technical configurations, including standalone and hybrid energy systems. A comprehensive techno economic assessment was carried out to identify the most suitable system design, optimize component capacities, estimate the Net Present Cost (NPC) and the Cost of Energy (COE), and analyze the energy performance and environmental benefits of the proposed solutions. The results provide a valuable framework for promoting sustainable and economically viable agricultural investments in the region.

To ensure the transparency and reproducibility of this research, the complete HOMER simulation models for both the PV Diesel Battery and PV Battery stand alone scenarios, along with their detailed technical reports, have been publicly archived and are accessible via [37].

III.2. Geographic and Climatic Characteristics of the Study Site:

III.2.1. Site Geographical Coordinates:

El Oued Province is situated in the southeastern part of Algeria, approximately 510 km from the capital city, Algiers. The region is characterized by an arid desert climate with relatively mild winters and extremely hot summers. Average temperatures during January are close to 11 °C, while summer temperatures typically average around 32 °C, with maximum values often exceeding 40 °C and occasionally reaching nearly 50 °C. Precipitation levels are generally low and irregular throughout the year, with very limited rainfall during the summer season. Geographically, El Oued is located at approximately 33°21' North latitude and 6°05'

East longitude. Figure III.1 illustrates the location of El Oued within Algeria and presents the map of the governorate as displayed in the HOMER Pro software environment [1].



Figure(III.1): Geographic location of El Oued Province, Algeria, as represented in the HOMER Pro software.

III.2.2. Solar Radiation and Temperature Assessment:

Global Horizontal Irradiance (GHI) is one of the key parameters used to estimate the electrical energy production of photovoltaic (PV) systems. It represents the total solar radiation received on a horizontal surface and can be expressed as the sum of the direct and diffuse components:

$$GHI = DHI + DIF \quad (III_01)$$

where:

DHI (Direct Horizontal Irradiance) refers to the portion of solar radiation that reaches a horizontal surface directly from the sun.

DIF (Diffuse Horizontal Irradiance) represents the fraction of solar radiation that arrives at the Earth's surface after being scattered by atmospheric constituents such as air molecules, aerosols, clouds, and other particles.

CHAPTER III: Technical Modeling and Economic Study of the Solar Pumping System via HOMER Pro Software.

Direct irradiance is received without undergoing atmospheric scattering, whereas diffuse irradiance is generated through interactions between solar rays and the atmosphere. In the absence of an atmosphere, diffuse irradiance would not exist. Figure III.2 presents the solar radiation characteristics of El Oued, Algeria, based on data obtained from NASA's solar resource database and integrated into the HOMER Pro simulation software [1].

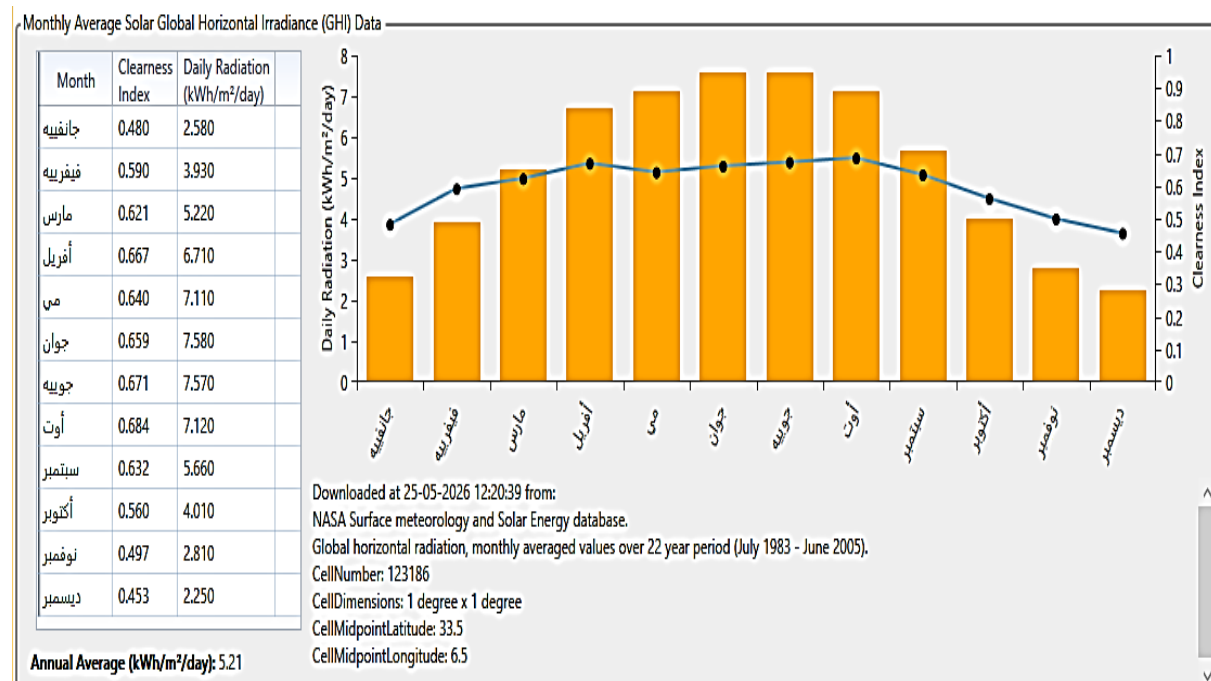


Figure (III.2): Global solar radiation data for El Oued, Algeria, obtained from NASA's solar resource database and processed using HOMER Pro [38].

III.3. Irrigation Load Profile and Water Demand Modeling:

III.3.1. Daily Energy Consumption

A technical economic study was carried out on an agricultural farm supplied by photovoltaic solar energy. The irrigation system consists of an 8 kW submersible pump operating during daylight hours to irrigate two center pivot sections, with each irrigation cycle lasting approximately six hours. In addition, a 0.5 kW auxiliary pump is used to fill a 40 m³ water

storage reservoir during periods of maximum solar irradiance, operating for about six hours per day.

During nighttime, a 1.5 kW pump transfers water from the storage reservoir to a 0.5 hectare cultivated area equipped with a drip irrigation system. This pump operates exclusively at night for approximately ten hours, ensuring continuous water supply while reducing daytime energy demand. The location of the studied farm in the Nakhla region of El Oued was identified using satellite imagery from Google Maps, as illustrated in Figure III.3.



Figure (III.3): *Satellite view of the studied agricultural farm located in the Nakhla region, El Oued Province, Algeria, obtained using Google Maps.*

The farm is dedicated to potato cultivation and operates over two agricultural seasons each year. The first growing season extends from September to January, while the second season covers the period from February to June.

During July and August, irrigation activities are suspended, resulting in the shutdown of both the center pivot and drip irrigation pumps. Throughout this period, the electrical energy generated by the photovoltaic system is redirected to potato seed storage and cooling facilities intended for the following planting season. These facilities are equipped with two air conditioning units rated at 2 kW each. During daytime hours, both units operate simultaneously, whereas only one unit remains in operation during the night.

To enhance system reliability and ensure uninterrupted irrigation during periods of low solar resource availability, such as cloudy days, a diesel generator and a bank of lead acid batteries were incorporated into the system design.

An essential step in the sizing of any standalone or hybrid energy system is the accurate assessment of electrical load requirements. In the present study, all electrical demands associated with irrigation and storage operations were considered. Furthermore, the daily load profile was developed based on the operational schedule of the equipment and the energy requirements recorded at the study site.

Irrigation pumping is primarily scheduled between 08:00 and 16:00, corresponding to periods of high solar availability, while reduced demand occurs between 17:00 and 08:00. Monthly variations in sunrise time were also taken into account when defining the operating schedule. Irrigation requirements remain relatively stable throughout the ten months corresponding to the two cultivation seasons, whereas energy demand decreases during July and August due to the exclusive use of solar power for cooling potato seed storage rooms.

Based on the annual operating schedule and the distribution of electrical loads, the demand profile was modeled in HOMER Pro using a **Synthetic Load** approach. For simulation purposes, the average daily energy consumption was set at **15.00 kWh/day**, with a maximum peak demand of **2.65 kW** and an estimated load factor of **0.2509**.

III.3.2. Sizing of Water Pumping Volume:

In the irrigation system under study, electrical energy is converted into hydraulic energy through the water pump, producing the volume of water required to meet crop irrigation demands. The pumped water volume corresponding to a given energy input is estimated using the mathematical relationships expressed in Equations (1) and (2).

$$E_{\text{pump}}(t) = (\rho \times g \times Q(t) \times \text{TDH}) / (\eta_{\text{pump}} \times 3.6 \times 10^6) \quad (\text{III_02})$$

$$\text{TDH} = H_{\text{st}} + H_{\text{dd}} + H_{\text{f}} \quad (\text{III_03})$$

TDH : is the total dynamic head in meters. It is the sum of Hst (static head), Hdd (drawdown head), and Hf (friction head loss in pipes) [14].

III.3.3. Irrigation Scheduling and Random Variability:

Irrigation pumping operations are scheduled between **08:00 and 16:00**, corresponding to periods of high water demand and maximum solar energy availability, while lower demand occurs between **17:00 and 08:00**. Monthly variations in sunrise time were also considered when establishing the operating schedule. Irrigation activities are maintained throughout the ten months corresponding to the two potato growing seasons, with relatively stable water requirements based on crop demand. During **July and August**, irrigation activities are significantly reduced because the electricity generated by the photovoltaic system is allocated primarily to the cooling facilities used for potato seed storage.

The resulting load profile is particularly well suited for photovoltaic applications, as the majority of the energy demand occurs during daylight hours when solar energy production is highest. Similar load characteristics are commonly observed in agricultural irrigation systems worldwide, highlighting the effectiveness of solar-powered water pumping systems as a sustainable and environmentally friendly alternative to conventional energy sources.

To evaluate the performance of the proposed system configurations, site specific climatic data and detailed load profiles were incorporated into the optimization process. This approach enables the identification of the most appropriate photovoltaic water pumping system based on technical performance, economic viability, and environmental impact under realistic operating conditions [2]. The hourly operating schedule of the submersible pump, center pivot irrigation units, drip irrigation system, and water storage tank is presented in **Table III.1**.

Table (III.1): *Twenty four hour operational schedule and load distribution of the submersible pump, center pivot irrigation systems, drip irrigation system, and water storage tank.*

Time	Submersible Pump (8.0 kW)	Pivot 1 (1.5 kW)	Pivot 2 (1.5 kW)	Drip Pump + Lighting (2.0 kW)	Tank Pump (0.5 kW)	Total Load (kW)
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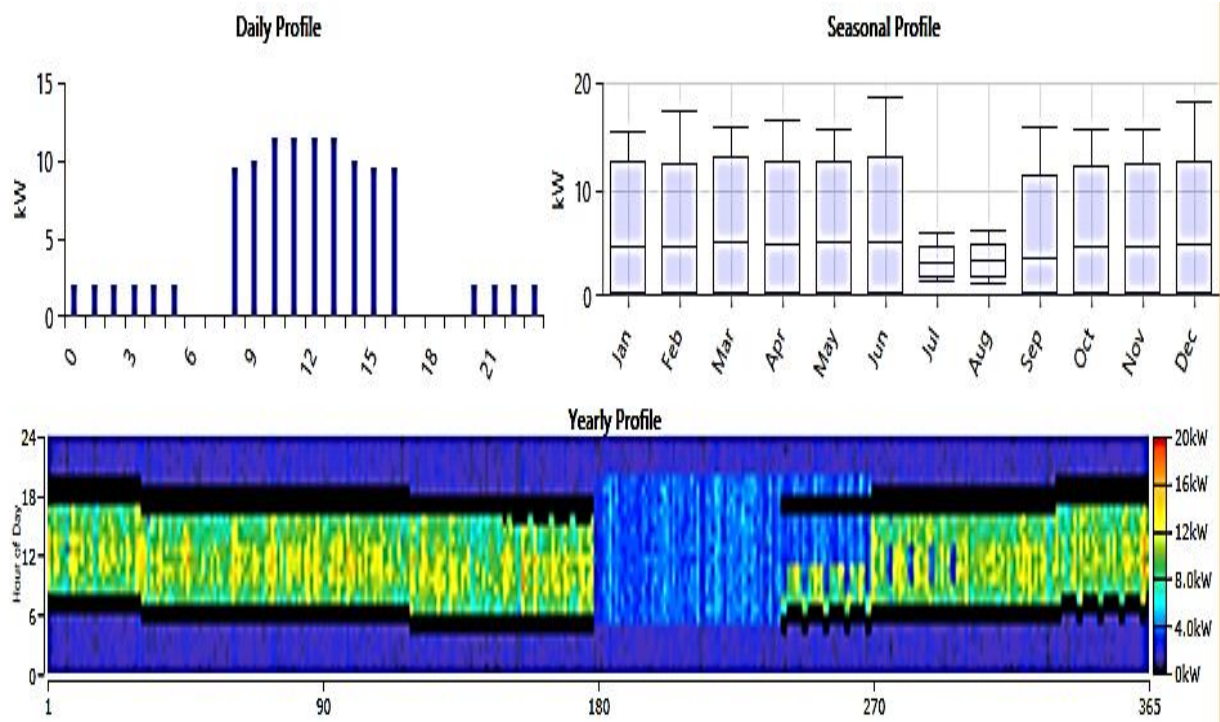
CHAPTER III: Technical Modeling and Economic Study of the Solar Pumping System via HOMER Pro Software.

00:00 - 01:00	Offline	Offline	Offline	Operational	Offline	2
01:00 - 02:00	Offline	Offline	Offline	Operational	Offline	2
02:00 - 03:00	Offline	Offline	Offline	Operational	Offline	2
03:00 - 04:00	Offline	Offline	Offline	Operational	Offline	2
04:00 - 05:00	Offline	Offline	Offline	Operational	Offline	2
05:00 - 06:00	Offline	Offline	Offline	Operational	Offline	2
06:00 - 07:00	Offline	Offline	Offline	Offline	Offline	0
07:00 - 08:00	Offline	Offline	Offline	Offline	Offline	0
08:00 - 09:00	Operational (Pivot 1 + Surplus to Tank)	Operational	Offline	Offline	Offline	9.5
09:00 - 10:00	Operational (Pivot 1 + Surplus to Tank)	Operational	Offline	Offline	Operational	10
10:00 - 11:00	Operational (Dual Pivots Only)	Operational	Operational	Offline	Operational	11.5
11:00 - 12:00	Operational (Dual Pivots Only)	Operational	Operational	Offline	Operational	11.5
12:00 - 13:00	Operational (Dual Pivots Only)	Operational	Operational	Offline	Operational	11.5
13:00 - 14:00	Operational (Dual Pivots Only)	Operational	Operational	Offline	Operational	11.5
14:00 -	Operational (Pivot	Offline	Operational	Offline	Operational	10

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15:00	2 + Surplus to Tank)					
15:00 - 16:00	Operational (Pivot 2 + Surplus to Tank)	Offline	Operational	Offline	Offline	9.5
16:00 - 17:00	Operational (Pivot 2 + Surplus to Tank)	Offline	Operational	Offline	Offline	9.5
17:00 - 18:00	Offline	Offline	Offline	Offline	Offline	0
18:00 - 19:00	Offline	Offline	Offline	Offline	Offline	0
19:00 - 20:00	Offline	Offline	Offline	Offline	Offline	0
20:00 - 21:00	Offline	Offline	Offline	Operational	Offline	2
21:00 - 22:00	Offline	Offline	Offline	Operational	Offline	2
22:00 - 23:00	Offline	Offline	Offline	Operational	Offline	2
23:00 - 24:00	Offline	Offline	Offline	Operational	Offline	2

To better represent real operating conditions in the El Oued region, the **Random Variability** parameters in HOMER Pro were configured to account for fluctuations in weather conditions and load demand. A **Daily Noise** value of **15%** was applied to simulate day to day variations, while an **Hourly Noise** value of **10%** was introduced to reflect short term changes occurring throughout the day. These settings improve the realism of the simulation by incorporating uncertainties associated with solar resource availability and energy consumption patterns. The configuration of the primary electrical load and the corresponding random variability parameters within the HOMER Pro environment are illustrated in Figure III.4.



Figure(III.4): Representation of the farm's electrical demand in HOMER Pro, including daily and seasonal load characteristics, annual load data, and the random variability factors incorporated into the model.

III.4. Technical Specifications of System Components

III.4.1. Photovoltaic Array (PV Modules):

In the present study, **monocrystalline silicon photovoltaic modules** were selected due to their high conversion efficiency, favorable thermal performance, and strong response to solar irradiance. These characteristics make them particularly suitable for the climatic conditions of El Oued, where solar resources are abundant. Within HOMER Pro, the hourly electrical output of the PV array is estimated based on local meteorological conditions using the mathematical model expressed in Equation (3) [3]:

$$P_{PV}(t) = P_R \times f_{pv} \times (G_T(t) / G_{ref}) \times [1 + \alpha_p \times (T_C(t) - T_{ref})] \quad (III_04)$$

where the generated power depends on the rated capacity of the PV array, solar irradiance, temperature conditions, and the PV derating factor.

III.4.2. Battery Energy Storage System:

The integration of a battery bank is essential for enhancing the reliability of the photovoltaic irrigation system. Excess electrical energy generated by the PV array is stored in the batteries and later supplied to the load whenever solar generation is insufficient. HOMER Pro simulates battery behavior on an hourly basis by considering both charging and discharging operating modes [3].

Battery Charging Mode

$$BSOC(t) = BSOC(t - 1) \times (1 - \sigma) + [P_{PV}(t) - P_{Load}(t) \eta_c] \Delta t \times \eta_B \quad (III_05)$$

Battery Discharging Mode

$$BSOC(t) = BSOC(t - 1) \times (1 - \sigma) - [P_{Load}(t) \eta_c - P_{PV}(t)] \Delta t \times \eta_B \quad (III_06)$$

These equations describe the variation of the battery state of charge (SOC) while accounting for self discharge losses and conversion efficiencies.

III.4.3. Power Converter:

The power converter plays a key role in photovoltaic pumping systems by converting direct current (DC) produced by the PV modules or batteries into alternating current (AC) required by electrical loads. In HOMER Pro, the converter capacity is determined according to the AC demand and conversion efficiency, as expressed in Equation (6) [3]:

$$P_c(t) = P_{Load}(t) / \eta_c \quad (III_07)$$

This relationship ensures that the converter is adequately sized to satisfy the hourly load requirements.

III.4.4. Backup Diesel Generator:

To improve system reliability, a **2 kW diesel generator** was incorporated into the hybrid configuration as an auxiliary energy source. The generator operates during periods of insufficient solar radiation or when the battery state of charge falls below the required threshold, thereby ensuring uninterrupted irrigation.

HOMER Pro models generator fuel consumption using a linear fuel curve characterized by a fixed component and a variable component proportional to the electrical output power [4]:

$$F = F_0 Y_{\text{gen}} + F_1 P_{\text{gen}} \quad (\text{III} _ 08)$$

For the technical economic evaluation, HOMER Pro calculates both the fixed operating cost and the marginal energy cost of the generator while considering maintenance expenses, replacement costs, fuel prices, and generator lifetime [4]:

Fixed Cost

$$C_{\text{gen;fixed}} = C_{\text{om;gen}} + (C_{\text{rep;gen}} / R_{\text{gen}}) + F_0 \times Y_{\text{gen}} \times C_{\text{fuel;eff}} \quad (\text{III} _ 09)$$

Marginal Cost

$$C_{\text{gen;mar}} = F_1 C_{\text{fuel;eff}} \quad (\text{III} _ 10)$$

These cost functions enable a comprehensive assessment of the economic performance of the hybrid system and its long term operational feasibility.

III.5. Energy Management and Dispatch Strategy(Cycle Charging Strategy):

The **Cycle Charging (CC)** dispatch strategy is based on a continuous comparison between the electrical load demand and the power generated by the photovoltaic system at each simulation time step. When the PV output is sufficient to meet the load requirements, the demand is supplied directly by the renewable source. However, when the generated power exceeds the instantaneous load, the battery bank state of charge (SOC) is evaluated. If the

batteries have available storage capacity and the SOC remains below its maximum allowable limit, the surplus energy is stored. Conversely, when the batteries are fully charged, any excess energy is diverted to dump loads. During periods when the load demand exceeds the available photovoltaic generation, the stored energy in the battery bank is utilized to compensate for the deficit and maintain uninterrupted system operation [5].

III.6. Simulation Results and Analysis for Configuration 1: Hybrid System (PV + Generator + Battery):

After completing the configuration within the Homer Pro software, including the inputs and variables for solar radiation and temperature associated with the specific study site, as well as the technical specifications of the panels, battery bank, inverter, and backup diesel generator with prices based on those prevailing in the Algerian local market and the International Renewable Energy Agency (IRENA) and based on the load schedule and daily random variations, the program implemented hourly simulation and dynamic optimization algorithms throughout the year,

evaluating the hybrid system's efficiency in achieving hydraulic and electrical balance and meeting crop needs with the highest reliability and lowest possible cost. The figure III.5. illustrates a simulation of the hybrid system within the Homer Pro software.

After running the calculation in Homer Pro and viewing the simulation results for the hybrid system, a message appears in the Results section informing us that the software simulated 37,872 separate hourly solutions to meet the irrigation loads. These solutions were classified and distributed geometrically as follows:

Feasible Solutions: 36,768 combinations were classified as feasible, as they fully succeeded in meeting the base load peak of 2.65 kW within all technical and operational constraints.

Infeasible Solutions: In contrast, 1,104 solutions were deemed infeasible due to a capacity shortage constraint, indicating an inability to meet reliability criteria during periods of low generation.

Omitted Solutions: 3,240 engineering configurations were excluded from the final output; while 0 were excluded due to infeasibility, 2,520 solutions were excluded for lacking a converter.

Engineering Explanation for Omission:

This omission is directly related to the limits of the search space [0–4 kW]; setting the converter capacity to zero (0 kW) completely cut off the bidirectional power flow between the DC lines (panels and battery) and the AC load. This absence caused the inverter circuits, which operate at 96% efficiency, and the rectifier circuits, which operate at 98% efficiency, to malfunction. As a result, these structurally flawed configurations were automatically eliminated by the software.

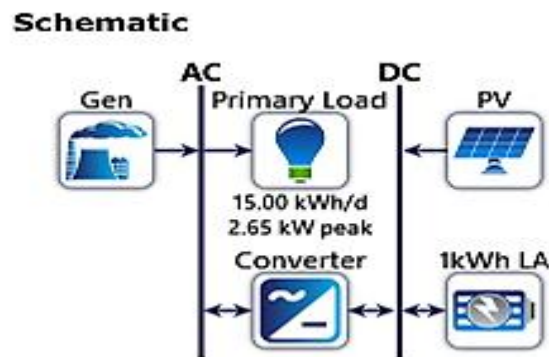


Figure (III.5): shows a diagram of the hybrid system within the Homer Pro program, illustrating daily energy consumption and peak demand.

III.6.1. Economic Valuation and Net Present Cost (NPC):

The results of the calculation in the Homer Pro application for the hybrid system showed that it achieved a total Net Present Cost (NPC) of 24,149 \$ over the project's lifetime, and a Levelized Cost of Energy (COE) of 0.341 \$ per kilowatt hour. These are highly competitive costs and very close to the values provided by the International Renewable Energy Agency (IRENA) for 2024 , [35]. as these values guarantee the investor in this project a return on investment in the shortest possible time.

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To standardize financial evaluations, cost conversions from U.S. dollars (USD) to Algerian dinars (DZD) were calculated based on the official exchange rate provided by the Bank of Algeria as of [June 5, 2026], at a rate of 1 USD = 133.25 DZD. [15]

To provide a comprehensive financial analysis of the hybrid configuration, the simulation results from HOMER Pro regarding the cost categories for each component are structured in Table III.2 (Net Present Costs) and Table III.3 (Annualized Costs).

Table (III.2): Net Present Cost (NPC) Breakdown by System Component.

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Converter	390.95 \$	67.39 \$	143.75 \$	-27.06 \$	0.00 \$	575.04 \$
Diesel Generator	600.00 \$	27.30 \$	0.00 \$	-14.95 \$	5,176 \$	5,788 \$
Generic 1kWh Lead Acid	4,200 \$	1,810 \$	7,683 \$	-822.53 \$	0.00 \$	12,870 \$
PV	4,140 \$	775.65 \$	0.00 \$	0.00 \$	0.00 \$	4,916 \$
System	9,331 \$	2,680 \$	7,827 \$	-864.54 \$	5,176 \$	24,149 \$

Table (III.3): Annualized Cost Distribution for the Hybrid System Components

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Converter	30.24 \$	5.21 \$	11.12 \$	-2.09 \$	0.00 \$	44.48 \$
Diesel Generator	46.41 \$	2.11 \$	0.00 \$	-1.16 \$	400.37 \$	447.74 \$
Generic 1kWh Lead Acid	324.89 \$	140.00 \$	594.32 \$	-63.63 \$	0.00 \$	995.59 \$
PV	320.25 \$	60.00 \$	0.00 \$	0.00 \$	0.00 \$	380.25 \$
System	721.79 \$	207.32 \$	605.44 \$	-66.88 \$	400.37 \$	1,868 \$

III.6.2. Electrical Production and Operating Statistics:

The technical and engineering results obtained from the simulation of the proposed hybrid system indicate a high level of operational reliability and flexibility in meeting the annual energy demand. The analysis revealed that the available energy resources are utilized

efficiently, with the photovoltaic (PV) array contributing approximately **90.6%** of the total annual electricity generation.

This significant share of renewable energy highlights the effectiveness of exploiting the abundant solar resource available in the El Oued region. As a result, the majority of irrigation requirements are supplied by clean and sustainable energy during daylight hours, particularly during periods of maximum solar irradiance.

In contrast, the backup diesel generator accounted for only **9.35%** of the total annual electricity production. This relatively small contribution confirms that the system depends primarily on renewable energy, while the generator serves only as a supplementary source during exceptional circumstances, such as prolonged periods of low solar radiation, unfavorable weather conditions, or when the battery bank reaches its minimum allowable state of charge. The integration of the generator therefore enhances system reliability and guarantees uninterrupted irrigation operations throughout the year.

Since the proposed configuration is an off grid hybrid system, surplus electricity cannot be exported to the national utility network. Consequently, whenever the batteries are fully charged (**SOC = 100%**) and the electrical load is lower than the power generated by the PV array, HOMER Pro classifies the unused energy as **Excess Electricity**. In the present study, the annual excess electricity was estimated at approximately **3,996 kWh**.

To manage this surplus energy safely, the system employs protective control mechanisms such as **dump loads** or **braking resistors**. The charge controller and inverter operate together to prevent battery overcharging and protect the electrical system from overvoltage conditions. When excess generation occurs, the unused energy is dissipated as heat through dedicated dissipation devices or curtailed by automatically reducing or disconnecting PV production when it is no longer required. This strategy ensures stable and secure system operation while maintaining the integrity of the storage components. The quantitative engineering metrics defining the overall system performance are structured into three distinct operational summaries. Table III.4 outlines the annual critical electrical parameters, including excess generation. Furthermore, the explicit contribution shares of the energy sources are detailed in

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Table III.5, while the total electricity consumption characteristics required to meet the farm's load demand are summarized in Table III.6.

Table (III.4): Annual Electrical Operational Parameters and Surplus Energy.

Electrical Summary	Value	Units
Excess Electricity	3,996	kWh/yr
Unmet Electric Load	0	kWh/yr
Capacity Shortage	0	kWh/yr

Table (III.5): Annual Electricity Production Breakdown and Generation Shares

Production Summary	Value	Percent
PV	9,146	90.6 %
Diesel Generator	944	9.35 %
Total Production	10,090	100 %

Table (III.6): Primary Load Consumption Characteristics of the Hybrid System

Consumption Summary	Value	Percent
AC Primary Load	5,475	100 %
DC Primary Load	0	0 %
Total Consumption	5,475	100 %

III.7. Simulation Results and Analysis for Configuration 2: Standalone System (PV + Battery):

Following the configuration of the second **standalone photovoltaic system** in HOMER Pro, all relevant site specific parameters were incorporated into the model, including solar radiation data, ambient temperature profiles, load characteristics, and stochastic variations. The technical specifications of the photovoltaic modules, battery storage system, and power converter were also defined using cost data representative of the Algerian market and reference values provided by the **International Renewable Energy Agency (IRENA)**.

Based on these inputs, HOMER Pro conducted hourly simulations and optimization procedures over an entire year of operation. The objective of this analysis was to assess the performance of the A fully independent system in maintaining both electrical and hydraulic balance while satisfying the irrigation requirements of the cultivated area. In addition, the optimization process aimed to identify the most reliable and cost effective system configuration capable of ensuring continuous operation under the prevailing climatic conditions of the study region. Where the figure III.8, shows a completely independent system.

After running the calculation in Homer Pro and viewing the simulation results for the fully isolated Pure Standalone System, a message appears in the Results section informing us that the program simulated 4,880 separate hourly solutions to meet irrigation demands. These solutions have been classified and distributed geometrically as follows:

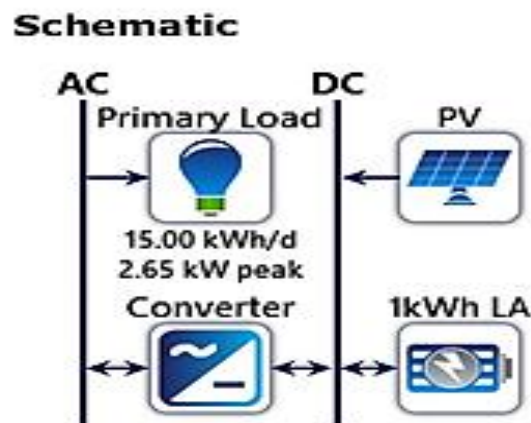
Feasible Solutions: 1,840 configurations were classified as feasible, as they successfully met the base load peak of 2.65 kW by relying exclusively on photovoltaic generation and battery storage within the specified technical constraints.

Infeasible Solutions: Conversely, the number of infeasible solutions rose significantly to 3,040 due to the capacity shortage constraint, which technically explains the absence of a backup generator, resulting in the system's inability in some configurations to meet reliability standards during periods of no sunlight or severe low-irradiance conditions.

Omitted Solutions: 1,720 engineering configurations were excluded from the final outputs; while 0 were excluded due to infeasibility, 1,640 solutions were excluded due to a complete lack of power generation sources.

Engineering Explanation for the Exclusion:

This exclusion of 1,640 solutions is directly related to the possibilities the program evaluated in the search space when it set the solar panel array capacity to zero (0 kW). Since this system is structurally designed without a diesel generator, setting the panel capacity to zero means, from an engineering standpoint, a system completely devoid of any source of electrical power generation (only batteries and an inverter), which is physically and operationally impossible; there is no source to charge the battery bank or operate the potato irrigation pump. As a result, the HOMER Pro software automatically removed these structurally flawed configurations to maintain the simulation's programming and computational logic.



***Figure(III.6):** Diagram of a fully independent system within the Homer Pro program, showing daily energy consumption and peak demand.*

III.7.1. Economic Impact of High PV Capacity:

The simulation results obtained from HOMER Pro for the **fully standalone photovoltaic system** indicated a **Net Present Cost (NPC)** of **29,404.05 USD** over the project lifetime and a **Levelized Cost of Energy (COE)** of **0.416 USD/kWh**.

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To standardize financial evaluations, cost conversions from U.S. dollars (USD) to Algerian dinars (DZD) were calculated based on the official exchange rate provided by the Bank of Algeria as of [June 5, 2026], at a rate of 1 USD = 133.25 DZD. [15]

Compared with the hybrid configuration analyzed previously, the standalone system exhibited higher overall costs. This increase is mainly attributed to the absence of the backup generator, which requires the optimization process to rely entirely on renewable generation and energy storage to ensure uninterrupted operation.

To satisfy irrigation demands under all operating conditions, including nighttime pumping periods and random load variations, HOMER Pro increased the optimal photovoltaic array capacity to **15.8 kW**. This larger PV capacity enables sufficient energy production not only to meet the immediate electrical demand but also to fully charge the battery bank, thereby ensuring reliable system performance throughout the year without energy deficits.

The results demonstrate that, although the standalone configuration provides complete energy independence and eliminates fuel consumption, it requires greater investment in photovoltaic generation and storage components. Consequently, the overall project cost increases compared with the hybrid alternative. To provide a clear financial breakdown of this independent standalone, the total economic life cycle costs have been organized into two distinct formats. The total investment, operating, replacement, and salvage flows are detailed in terms of net present costs in Table III.7, while their equivalent annual values are detailed in Table III.8.

Table (III.7): Net Present Cost (NPC) Breakdown for the Standalone PV-Battery System.

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Converter	467.26 \$	80.54 \$	171.81 \$	-32.34 \$	0.00 \$	687.28 \$
Generic 1kWh Lead Acid	7,200 \$	3,103 \$	6,361 \$	-862.41 \$	0.00 \$	15,801 \$
PV	10,878 \$	2,038 \$	0.00 \$	0.00 \$	0.00 \$	12,916 \$
System	18,545 \$	5,221 \$	6,533 \$	-894.75 \$	0.00 \$	29,404 \$

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Table (III.8): Annualized Cost Distribution for the Standalone PV-Battery System Components.

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Converter	36.14 \$	5.23 \$	13.29 \$	-2.50 \$	0.00 \$	53.16 \$
Generic 1kWh Lead Acid	556.95 \$	240.00 \$	492.03 \$	-66.71 \$	0.00 \$	1,222 \$
PV	841.45 \$	157.65 \$	0.00 \$	0.00 \$	0.00 \$	999.10 \$
System	1,435 \$	403.88 \$	505.32 \$	-69.21 \$	0.00 \$	2,275 \$

III.7.2. Excess Electricity and Power Wastage Analysis:

The simulation results of the standalone photovoltaic system revealed a substantial amount of **excess electricity**, estimated at **13,294 kWh/year**, which exceeds the farm's annual energy demand. This significant surplus is primarily due to the increase in the photovoltaic array capacity to **15.8 kW**, a sizing decision required to ensure complete energy autonomy in the absence of a backup generator.

During periods of high solar irradiance, particularly when the battery bank reaches its maximum state of charge (**SOC = 100%**), the photovoltaic system continues to generate energy beyond the instantaneous demand of the farm. This excess electricity can be utilized to supply additional agricultural loads, creating opportunities for future expansion and the integration of value added activities such as water treatment, agricultural processing, refrigeration, or other energy intensive operations that could enhance farm productivity and sustainability.

When no additional loads are available, the surplus energy must be managed to maintain system stability and protect the storage components. In such cases, excess power is either dissipated through dedicated dump loads or braking resistors, converting the unused electricity into heat, or curtailed through the system control strategy, which automatically reduces or disconnects photovoltaic generation when it is no longer required. These mechanisms prevent battery overcharging and protect the system from overvoltage conditions.

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The results indicate that although the standalone configuration ensures complete energy independence and high reliability, it may lead to considerable energy overproduction if the photovoltaic system is oversized to guarantee uninterrupted operation throughout the year. The explicit technical performance data characterizing this standalone operation are documented across three distinct analytical indices. Table III.9 provides the detailed annual electrical balances and excess energy metrics. Additionally, the standalone energy source contribution shares are presented in Table III.10, while the cumulative primary AC load consumption characteristics are summarized in Table III.11.

Table (III.9): Annual Electrical Parameters and Excess Generation for the Standalone Configuration

Electrical Summary	Value	Units
Excess Electricity	13,294	kWh/yr
Unmet Electric Load	3.23	kWh/yr
Capacity Shortage	5.34	kWh/yr

Table (III.10): Photovoltaic Generation Shares for the Standalone System

Production Summary	Production (kWh/yr)	Percent
PV	19,149	100 %
Total	19,149	100 %

Table (III.11): Primary Load Electricity Consumption Breakdown under Standalone Operation

Consumption Summary	Consumption (kWh/yr)	Percent
AC Primary Load	5,472	100 %
DC Primary Load	0	0 %
Total	5,472	100 %

III.8. Comparative Discussion and Environmental Assessment:

A comprehensive comparative analysis was conducted to evaluate the performance of the proposed **hybrid** and **standalone** energy systems for agricultural irrigation. The assessment focuses on the technical performance, economic feasibility, energy storage requirements, and environmental impacts of each configuration. Key indicators such as system reliability, energy production, excess electricity, Net Present Cost (NPC), Levelized Cost of Energy (COE), and renewable energy contribution were examined to identify the most effective solution. The objective of this comparison is to determine the energy system that offers the best balance between operational efficiency, economic sustainability, and environmental benefits, thereby supporting long term agricultural investment in potato cultivation in the El Oued region.

III.8.1. Techno Economic Comparison and Battery Lifetime:

The comparative economic analysis demonstrated that the **hybrid configuration** offers superior financial performance compared with the fully standalone system. This advantage is primarily attributed to the integration of a small **2 kW backup generator**, which provides supplementary energy during periods of insufficient solar radiation. As a result, the required photovoltaic capacity was reduced to **6 kW**, leading to a lower **Net Present Cost (NPC)** of **24,149 USD** and a more competitive **Levelized Cost of Energy (COE)** of **0.341 USD/kWh**.

In contrast, the complete removal of the generator in the standalone configuration imposed additional requirements on both the photovoltaic array and the storage system. To ensure uninterrupted operation and eliminate any energy deficit, HOMER Pro optimized the system by increasing the PV capacity to **15.8 kW** and expanding the battery bank. Consequently, the **NPC** increased to **29,404 USD**, while the **COE** rose to **0.416 USD/kWh**. These results indicate a substantial increase in overall investment costs relative to the hybrid alternative.

From a technical perspective, the operating conditions of the lead-acid battery bank differ significantly between the two configurations. In the hybrid system, the batteries experience more frequent charging and discharging cycles, particularly during nighttime operation and periods of low solar availability. Although the backup generator is programmed to operate

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when the battery state of charge (SOC) reaches critical levels, the storage system is still exposed to higher electrochemical stress, which accelerates battery aging and reduces its operational lifetime. Under these conditions, the estimated battery lifespan is approximately **5.98 years**, requiring multiple replacements throughout the **25 year project lifetime**.

Conversely, in the standalone system, the larger photovoltaic array provides abundant energy during daylight hours, allowing the batteries to be recharged rapidly and maintained at high state of charge levels. This operating strategy reduces the depth of discharge and minimizes electrochemical degradation, thereby extending battery life and decreasing long term maintenance requirements. As a result, the battery bank requires fewer replacements over the project lifetime, contributing to improved storage reliability despite the higher initial investment cost.

The comparison also highlights an important trade off between economic performance and storage durability. While the hybrid system achieves lower investment and energy costs, the standalone configuration offers enhanced battery longevity and complete energy independence. Therefore, the selection of the optimal system depends on the priorities of the investor, whether minimizing costs or maximizing autonomy and storage lifespan. As shown in the table III.2.

Table(III.12): Comparative technical economic assessment between the fully standalone and hybrid configurations, with emphasis on energy storage system behavior.

Metric / Technical Indicator	Standalone Configuration (PV + Battery)	Hybrid Configuration (PV + Generator + Battery)
Optimal PV Capacity	15.8 kW	6 kW
Backup Generator Capacity	None	2 kW
Total Net Present Cost (NPC)	\$29,404	\$24,149
Cost of Energy (COE)	\$0.416/kWh	\$0.341 kWh
Annualized System Cost	\$2,275/ yr	\$1,868 /yr

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Annual Excess Electricity	13,294 kWh/yr	3,996 kWh/yr
Storage System Layout	Larger, technically expanded lead-acid battery bank configuration to compensate for the absence of the generator.	Smaller, economically optimized lead-acid battery bank configuration supported by the generator.
Daily State of Charge (SOC)	Rapid charging, sustained high state of charge (SOC = 100%), and shallow daily discharge cycles.	Frequent deep discharge cycling overnight and during low-solar daytime hours.
Battery Operational Lifetime	10.0 years	5.98 years
Battery Bank Replacements	2 times only over the 25 year project lifespan	3 to 4 times over the 25 year project lifespan

III.8.2. Environmental Impact and Carbon Emissions:

The environmental impact assessment of the proposed energy system was conducted in accordance with the Algerian Constitution, as amended in 2020 (Official Gazette, Issue 82). Article 21 clearly stipulates that the State is responsible for protecting agricultural land, ensuring a healthy environment for human well being, promoting awareness of environmental risks, and guaranteeing the rational use of natural resources such as water and fossil fuels. It also emphasizes the protection of the environment across its terrestrial, marine, and atmospheric dimensions, while enforcing appropriate measures against environmental pollution.

Furthermore, Article 64 reinforces this constitutional commitment by affirming that citizens have the right to a healthy environment within the framework of sustainable development, while assigning legal responsibilities to both individuals and organizations regarding environmental protection.

From a regulatory and financial perspective, Algerian environmental policy remains supportive of small scale and micro projects. In particular, no specific environmental taxation is imposed on low capacity generators with limited carbon emissions, such as the backup

CHAPTER III: Technical Modeling and Economic Study of the Solar Pumping System via HOMER Pro Software.

generator used in this study, unlike regulatory frameworks in certain other countries that apply strict carbon taxes and emission penalties across all fossil fuel based systems.

Within this context, the HOMER Pro simulation results indicate that the use of a diesel generator with an annual fuel consumption of approximately **1,820 liters** leads to measurable greenhouse gas emissions. To provide an aligned numerical verification of these environmental evaluations, the detailed operational dataset is structured into two statistical frameworks. The explicit generator fuel usage metrics are itemized in Table III.12, while the specific cumulative quantities of greenhouse gases and atmospheric pollutants generated by the hybrid configuration are detailed in Table III.13.

Table (III.13): Annual Diesel Fuel Consumption Statistics for the Hybrid System.

Quantity	Value	Units
Total fuel consumed	1,820	L
Avg fuel per day	4.99	L/day
Avg fuel per hour	0.208	L/hour

Table (III.14): Annual Environmental Pollutants and Greenhouse Gas Emissions Breakdown.

Pollutant	Quantity	Unit
Carbon Dioxide	4,792	kg/yr
Carbon Monoxide	11.8	kg/yr
Unburned Hydrocarbons	1.31	kg/yr
Particulate Matter	0.892	kg/yr
Sulfur Dioxide	11.7	kg/yr
Nitrogen Oxides	106	kg/yr

III.9. Conclusion:

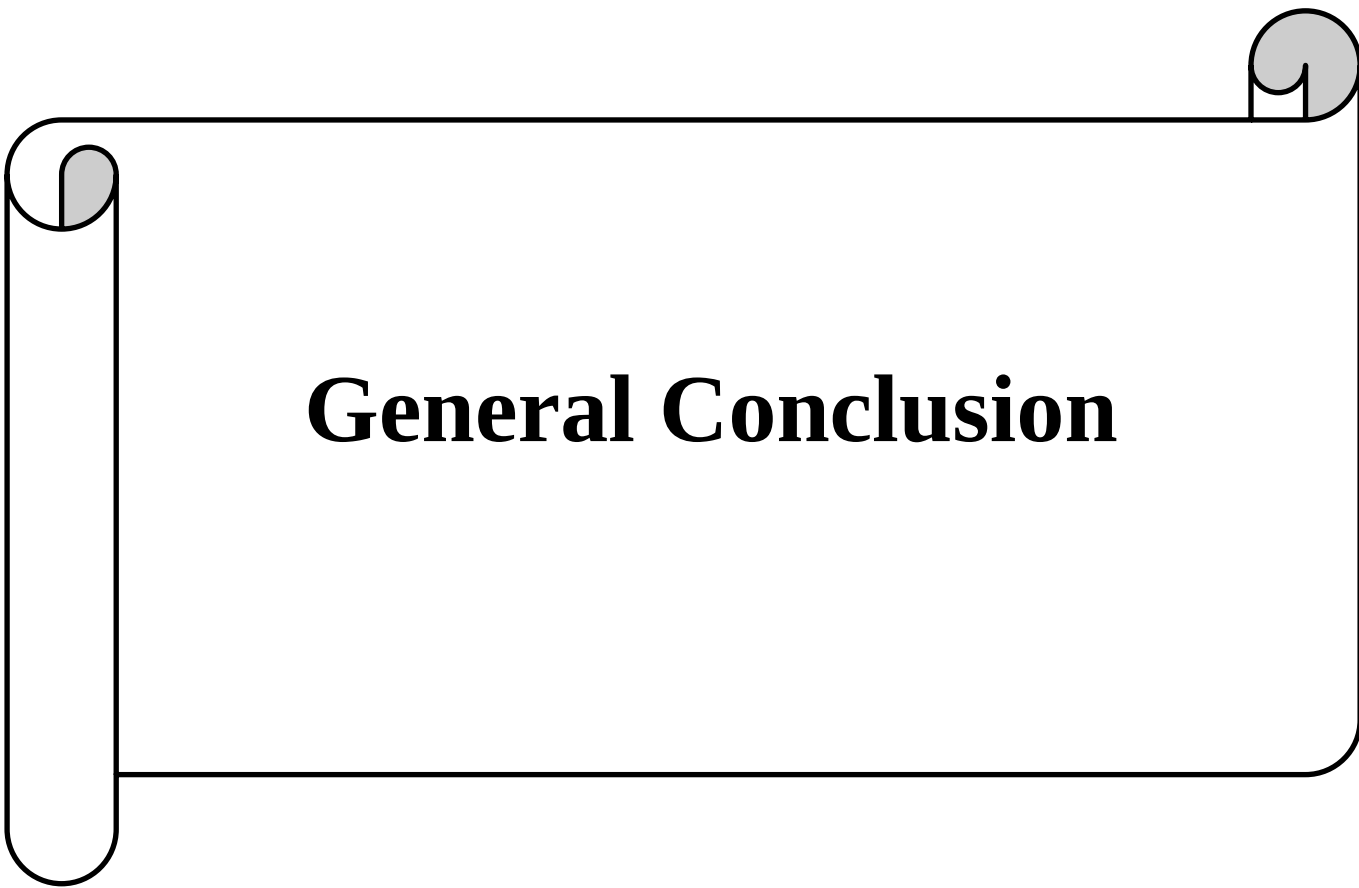
The dynamic simulation and optimization results obtained using HOMER Pro, supported by NASA meteorological data, clearly demonstrate the superiority of the **hybrid energy system** over the fully standalone configuration for potato irrigation in the Nakhlah region of El Oued Province.

From an economic perspective, the hybrid system exhibits significantly better performance by minimizing the **Net Present Cost (NPC)** and achieving a lower **Levelized Cost of Energy (COE)**. These results confirm its stronger investment viability and ensure a faster and more favorable return on investment compared with the considerably higher financial requirements associated with a fully standalone system.

This economic advantage is primarily the result of a more balanced system design. The inclusion of a small backup generator acts as a reliability buffer, preventing unnecessary oversizing of the photovoltaic array while still ensuring full satisfaction of irrigation demand. As a result, the hybrid configuration operates with a more optimized PV capacity and reduced energy waste. In contrast, the standalone system requires substantial oversizing of the PV array, which leads to significant amounts of excess electricity that cannot be effectively utilized.

Although the hybrid system imposes higher operational stress on the battery bank due to deeper cycling, resulting in a reduced battery lifespan compared to the standalone configuration, it remains the most practical and robust solution. It ensures continuous and reliable irrigation under variable climatic conditions while maintaining acceptable environmental performance.

Overall, the hybrid system represents the most efficient compromise between cost, reliability, and energy utilization, making it the most suitable configuration for sustainable agricultural development in the El Oued region under current technical and economic constraints.



General Conclusion

The findings obtained from the techno-economic simulation using HOMER software substantiate that solar photovoltaic systems constitute a technically reliable and economically competitive alternative to conventional power generation, particularly in regions with favorable solar resources. The optimization results demonstrate that HOMER effectively determines the least-cost system configuration by integrating technical performance metrics with economic indicators, including Net Present Cost, Cost of Energy, and payback period,[13][14][9][15][16].

Furthermore, sensitivity analysis performed by HOMER reveals the degree of influence of key variables such as solar irradiance levels, PV module efficiency, and battery storage costs on the overall economic feasibility of the system. These insights are indispensable for risk assessment and for designing resilient renewable energy systems under uncertain conditions.[17][18]

In conclusion, the integration of HOMER-based techno-economic analysis into the planning phase enhances the accuracy of feasibility studies and contributes significantly to the sustainable deployment of solar energy technologies. The methodology employed herein provides a replicable framework for future research and for guiding policymakers and investors toward cost-effective and environmentally sustainable energy solutions.[19][20].

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