

People's Democratic Republic of Algeria

Ministry of Higher Education and Scientific Research

A.M. OULHADJ UNIVERSITY – Bouira

FACULTY OF SCIENCES AND APPLIED SCIENCES



MASTER'S THESIS

Field: Sciences and technologies

DEPARTMENT: Electrical engineering

Specialty: Renewable Energies in Electrotechnics

THEME

**Design and sizing of a hybrid agricultural microgrid incorporating
water pumping and optimized energy management**

Presented on: 24 /06 /2026

Published by:

Mr. Messara Yacine

Mr. Touimer Fares

Before the jury commission composed of

Mme. Yassa Nacera	Prof	Univ. Bouira	President
Mr. Mellah Hacene	M.C.A	Univ. Bouira	Supervisor
Mr. Geriche Issam	M.C.A	Univ. Bouira	Examinator

Academic Year: 2025-2026



République Algérienne Démocratique et Populaire
Ministère de l'Enseignement Supérieur et de la Recherche Scientifique
Université de Bouira, Faculté des Sciences et des Sciences Appliquées
Département de Génie électrique



Bouira le :15 juin 2026

Autorisation de soutenance d'un mémoire de Master

Je soussigné(e), l'enseignant (e) : H. MELLAH

Encadreur des étudiants (es) :

1 MESSARA YACINE

2 TOUIMER Fares

Spécialité : ER

Les autorise à soutenir leur **mémoire** de Master intitulé :

*Design and sizing of a hybrid agricultural microgrid incorporating
water pumping and optimized energy management*

Signature du rapporteur

Dedication

At this very end of my educational journey, this work has been the fruit of years of education, hard work, and patience. And i can finally say that I'm proud to dedicate this work to my beloved family, to my father whose been always a compass that guides me and illuminates for me the road of knowledge and learning, to my most priceless treasure, my mom. It was for her that I endured my master's journey; to mend her heart and honor her sacrifices, and to my lovely sister who was my joy and my support in every single moment.

I would like to dedicate this work for my big brother, for his unwavering guidance and steadfast belief in me.

Also, to my big brother's wife and my sister's husband and friend for being part of the family that surrounds me.

Special thanks to Zimba and Pitchou and all our cats for being such a joyful companions and demanding attention and food even at critical moments.

Finally, i would like to thank the head of the department, whose administration was nothing short of excellent.

This is for all of you, Thank you.

Messara Yacine

Dedication

First and foremost, I thank Allah Almighty for granting me the strength, patience, and guidance to complete this work successfully, I would like to express my deepest gratitude to my beloved parents, especially my late father, may Allah rest his soul in peace, whose sacrifices, support, and encouragement were the foundation of my success despite all difficulties, My sincere appreciation goes to my dear mother for her endless love, prayers, and unwavering support throughout my academic journey, also to my professors for their valuable knowledge, guidance, and dedication, Special thanks are extended to the Head of the Department for her support, guidance, and efforts in creating a productive academic environment, I would like to thank my friends for their companionship, and assistance during my studies, Finally, I express my heartfelt gratitude to everyone who contributed to the successful completion of this thesis.

Touimer fares

Acknowledgements

This work was conducted within the Department of Electrical Engineering, Faculty of Applied Sciences, at the University of Bouira.

First and foremost, we would like to express our deepest gratitude to Dr. Mellah Hacene, the supervisor of this thesis, for their invaluable guidance, insightful advice, and continuous support throughout the realization of this work. Their expertise and encouragement were essential to the successful completion of this study.

We would also like to extend our sincere thanks to the members of the jury for the honor they have given us by accepting to evaluate this work and for the interest they have shown in it:

Prof. Yassa Nacera.

Dr. Mellah Hacene.

Dr. Geriche Issam.

We are equally grateful to all the professors and staff of the Department of Electrical Engineering for the quality of education and support provided throughout our academic journey.

Finally, we would like to express our heartfelt appreciation to our classmates and everyone who contributed, directly or indirectly, to the completion of this work.

Résumé

Dans ce travail on a fait l'étude et le dimensionnement d'un microréseau agricole hybride afin d'alimenter en électricité une exploitation agricole située dans une zone isolée à Adrar (sud de l'Algérie).

Le système hybride est composé de différents éléments, notamment un générateur photovoltaïque, une batterie de stockage et un groupe électrogène diesel, afin d'assurer la continuité et la stabilité de la production électrique pour répondre aux besoins énergétiques de l'exploitation (pompage d'eau, culture sous serre, culture en plein champ, et chambre froide).

Cette étude est menée à partir des besoins énergétiques de l'exploitation et de l'analyse de la zone ciblée (Adrar), dans le but d'apporter une solution énergétique fiable, durable et économiquement viable, adaptée aux conditions climatiques désertiques.

Le dimensionnement et la simulation du système photovoltaïque ont été réalisés à l'aide du logiciel *Pvsyst*, tandis que l'optimisation technico-économique du système hybride.

L'objectif principal est d'identifier la configuration optimale du système, de réduire les coûts de production et installations, de minimiser l'impact environnemental et d'améliorer l'autonomie énergétique de l'exploitation.

Mots clés: *Pvsyst, système hybride, pompage solaire, énergies renouvelables, Batteries.*

Abstract

In this work, we focused on the study and sizing of a hybrid agricultural microgrid to supply electricity to a farm in an isolated location in Adrar (southern Algeria).

The hybrid system is composed of various components; including a photovoltaic generator, a battery storage bank, and a diesel generator to ensure continuity and stability of the generated electricity to cover the farm's energy requirements (water pumping, greenhouse cultivation, open-field crops, and cold storage unit.)

This study is conducted based on the farm's energy requirements, the analysis of the targeted area of Adrar, to ensure a reliable, sustainable and economically viable energy solution adapted to desert climatic conditions, sizing and simulation of the photovoltaic system was done using *Pvsyst*, and the techno-economic optimization of the hybrid system.

The main objective is to identify the optimal system configuration, reduce production costs and installation, minimize environmental impact, and improve the farm's energy autonomy

Keywords: *Pvsyst, Hybrid system, Water pumping, Renewable energies, Batteries.*

الملخص

في هذه المذكرة قمنا بدراسة وتصميم شبكة صغيرة زراعية هجينة بهدف تزويد مزرعة في منطقة نائية بأدوار (جنوب الجزائر) بالطاقة الكهربائية.

يتكون النظام الهجين من عدة مكونات، منها مولّد كهروضوئي، وبنك لبطاريات التخزين، ومولّد يعمل بالديزل، وذلك لضمان استمرارية واستقرار الطاقة الكهربائية المنتجة لتلبية احتياجات المزرعة (ضخ المياه، الزراعة تحت البيوت البلاستيكية، الزراعة في الحقول المفتوحة، ووحدة تبريد).

أُجريت هذه الدراسة بناءً على الاحتياجات الكهربائية للمزرعة وتحليل المنطقة المستهدفة (أدرار)، بهدف توفير حل طاقي موثوق ومستدام وقابل للتطبيق اقتصاديًا، ويتناسب مع الظروف المناخية الصحراوية.

تم تصميم ومحاكاة النظام الكهروضوئي باستخدام برنامج *Pvsyst*، وأجراء التحسين التقني والاقتصادي للنظام الهجين.

الهدف الرئيسي هو تحديد التركيبة المثلى للنظام، وتقليل تكاليف التركيب والاستهلاك، وتقليل الأثر البيئي، وتحسين الاستقلالية الطاقية للمزرعة.

كلمات مفتاحية: *Pvsyst* نظام هجين، ضخ المياه، طاقات متجددة، البطاريات .

Table of Contents

General introduction.....	1
Chapter I: Generalities on renewable energies and agricultural electrification	
1.1 Generalities on Renewable	4
1.1.2 Relevance of renewable energy for the study site.....	12
1.2 Solar Photovoltaic energy.....	13
1.3.1 Photovoltaic Generator	24
1.3.1.1 Structure of a photovoltaic generator.....	24
1.3.1.2 Series and parallel connections.....	25
1.3.2 Charge controller and power conditioning unit	26
1.3.2.1 Role of charge controller in photovoltaic systems.....	27
1.3.3 Types of charge controller.....	27
1.3.3.1 PWM (Pulse Width Modulation) charge controller	27
1.3.3.2 MPPT (MAXIMUM POWER POINT TRACKING) controller	28
1.3.3.1 Current–Voltage and Power–Voltage Characteristics	29
1.3.4 Comparison between different methods of MPPT commands.....	30
1.3.6 DC-DC converter	31
1.3.6.1 Types of DC-DC converters.....	32
1.3.7 Inverter 32	
1.3.8.2 Main characteristics of battery.....	34
1.3.8.3 Types of solar batteries	35
1.3.8.4 Comparison between different batteries technologies	38
1.3.9 Protection and monitoring devices.....	39
1.4 Types of Photovoltaic systems	39
1.4.1 Grid-Connected systems.....	39
1.4.2 Off-grid systems	40
1.4.3 Hybrid photovoltaic systems	41
1.4.3.1 Classification of Hybrid Systems.....	41
1.4.3.2 By operating mode.....	42
1.4.3.3 By system configuration	42
1.4.4 Photovoltaic system combined with a conventional source.....	42
1.4.4.1 Series-type configuration	43
1.4.4.1.1 Advantages and limitations.....	44
1.4.4.2 Switched PV/Diesel arrangment.....	44
1.4.4.1.2 Advantages and Limitations	45
1.4.4.3 Parallel configuration.....	45
1.4.4.3.1 Advantages and Limitations	46
1.4.5 Choice of configuration for the application site	46
1.5 Generator set.....	46
1.5.1 Principle operation.....	47
1.5.2 Types of generator sets.....	47

1.5.3 Comparison of generator set energy sources.....	49
1.5.4 Choice of generator set for the application site.....	49
1.6 Solar pumping systems.....	50
1.6.1 Main components of a solar pumping system	50
1.6.2 Classification of solar pumping systems	50
1.6.3 Types of pumps used in solar pumping	52
1.6.4 Advantages and limitations of water pumps technologies.....	53
1.6.5 Agricultural Electrification	54
1.6.6 Energy requirements in Agriculture.....	54
1.6.7 Agricultural greenhouses.....	54
1.6.8 Barley cultivation and fodder production	55
Chapter I Conclusion.....	53

Chapter II: Study site, load assessment and system sizing

2.1.1 Presentation of the study area.....	57
2.1.2 Climatic conditions.....	57
2.1.2.1.1 Solar potential of Adrar.....	58
2.1.2.1.2 Water resources in adrar.....	58
2.2 General organization of the farm.....	59
2.3 Water tank sizing.....	61
2.4 Water-pump sizing.....	62
2.5 Cold storage room.....	66
2.6 Storage hangar and residential building.....	67
2.7 Total Electrical Loads.....	68
2.8 Photovoltaic system sizing.....	69
2.8.1 System sizing method.....	69
2.8.2 PV array sizing using the annual average method.....	69
2.8.3 Choice of photovoltaic modules	70
2.8.4 Determination of number of modules	71
2.8.5 Selecting the hybrid inverter	71
2.8.6 Photovoltaic array configuration	72
2.8.7 Battery bank sizing.....	73
2.8.8 Generator-set sizing	74
2.9 Cable section and protection sizing.....	75
ChapterII conclusion.....	64

ChapterIII: PVsyst implementation, and technico-economic optimization

III. Overview of the PVSYST Software.....	83
---	----

III.2 Project Description.....	84
III.2.1 Geographic Data.....	84
III.2.2 Meteorological Data.....	85
III.3 Project Design.....	86
III.3.1 Steps in Designing an Autonomous PV System.....	87
III.3.2 Horizon profile defining.....	87
III.3.3 PV module orientation.....	88
III.3.4 Definition of User Load Requirements.....	89
III.3.5 Preliminary sizing conditions.....	91
III.3.6 Selection and Sizing of the Storage System.....	92
III.3.7 Selection and Sizing of the PV Array.....	92
III.3.8 Selection and Sizing of the Battery Charge Controller and Control Strategy.....	93
III.3.9 Selection and Sizing of the Backup Generator.....	94
III.3.10 Multi-Source System Diagram.....	94
III.3.11 Economic Evaluation of the Multi-Source System.....	95
III.3.12 Impact of Near Shading.....	95
III.3.13 Simulation results and discussion.....	96
III.3.14 PV array & battery system specifications.....	98
GENERAL	
CONCLUSION.....	89

List of figures

Fig. 1.1.	Renewable energy illustration.....	4
Fig. 1.2.	Solar thermal energy scheme	5
Fig. 1.3.	(I) Grid connected PV system, (II) Off-grid PV system	6
Fig. 1.4.	HAWT generator Structure.....	7
Fig. 1.5.	VAWT generator structure.	7
Fig. 1.6.	Hydroelectric Dam (powerplant).	8
Fig. 1.7.	Run-of-river hydropower	9
Fig. 1.8.	Pumped storage hydropower.....	9
Fig. 1.9.	Biomass energy production.	10
Fig. 1.10.	Geothermal energy system.....	11
Fig. 1.11.	Map of Adrar with mean annual sum of global horizontal irradiation (kWh/m ² /year).	12
	13	
Fig. 1.12.	Spectral analyses of solar radiation.....	13
Fig. 1.13.	Solar specter to different mass air values.....	15
Fig. 1.14.	Cartesian geocentric coordinates and local coordinates.....	17
Fig. 1.15.	Angles on an inclined plane.....	18
Fig. 1.16.	Solar cell diagram.	19
Fig. 1.17.	Equivalent circuit of a PV Cell.....	19
Fig. 1.18.	I-V characteristics curve of a PV cell	19
Fig. 1.19.	I) I-V characteristics vs Temperature, II) I-V characteristics vs irradiance.	20
Fig. 1.20.	Silicium mono-crystalline cell	21
Fig. 1.21.	Poly-crystalline silicium cell.....	22
Fig. 1.22.	Amorphous silicon cell	23
Fig. 1.23.	Structure of a photovoltaic generator.....	25
Fig. 1.24.	PV series connection.....	26
Fig. 1.25.	PV parallel connection.....	26
Fig. 1.26.	PWM SOLAR CHARGE CONTROLLER	28
Fig. 1.27.	MPPT P-V curve	29
Fig. 1.28.	Hybrid SOLAR INVERTER-CHARGER 3000VA.....	33
Fig. 1.29.	Electrochemical accumulator.....	34

Fig. 1.30.	Liquid lead-acid battery	36
Fig. 1.31.	Jel battery.....	36
Fig. 1.32.	AGM lead battery	37
Fig. 1.33.	Lithium-ion battery.....	38
Fig. 1.34.	Grid-connected PV system	40
Fig. 1.35.	Off-grid solar system	41
Fig. 1.36.	Classification of Photovoltaic systems	42
Fig. 1.37.	PV/diesel Serie Configuration	43
Fig. 1.38.	Switched pv-diesel arrangement system	44
Fig. 1.39.	Parallel configuration.....	45
Fig. 1.40.	2 KW GASOLINE GENERATOR SET.....	47
Fig. 1.41.	10 kVA diesel generator set.....	48
Fig. 1.42.	Propane gas LPG power generator set	48
Fig. 1.43.	Components of a fuel cell generator set.	49
Fig. 1.44.	Principal diagram of a direct solar pumping system	51
Fig. 1.45.	Battery-coupled pumping system	51
Fig. 1.46.	PV-diesel-eolienne pumping system.....	51
Fig. 1.47.	Surface pump.....	52
Fig. 1.48.	300m Water head stainless steel borehole submersible water pump.....	52
Fig. 1.49.	Centrifugal pump.....	53
Fig. 1.50.	Positive displacement pump	53
Fig. 1.51.	Desert greenhouses	55
Fig. 1.52.	Barley harvest in Adrar.....	55
Fig. 2.1.	Groundwater storage in Algeria.....	59
Fig. 2.2.	Pipe friction table.....	63
Fig. 2.3	Fittings friction losses.....	64
Fig. 2.4.	DAB S4 8 submersible pumps power curves.....	65
Fig. 2.5.	Operating characteristics of DAB S4 8-43 and S4 8-47 65.....	65
Fig. 2.6.	Technical data sheet of CPm 160C	66
Fig. 2.7.	Ja solar module Data sheet. 70	70
Fig. 2.8.	Sun-40K-SG01HP3 Datasheet 71.....	71
Fig. 2.9.	LitooARV lithium-ion battery data sheet 74.....	74

Figure III.1.	Geographic location and coordinates of the Kbertène site, Wilaya of Adrar, Algeria	85
Figure III.2.	Climatic parameters of Kabertene (Adrar, Algeria).....	86
Figure III.3.	Design of the standalone PV system with battery storage.....	87
Figure III.4.	Horizon profile of Kabertene (Adrar, Algeria).....	88
Figure III.5.	Fixed tilt plane orientation.....	89
Figure III.6.	Load profile.....	90
Figure III.7.	Operating time schedule.....	90
Figure III.8.	Parameters of the standalone system.....	91
Figure III. 9.	Selecting the battery bank.....	92
Figure III.10.	PV array parameters.....	93
Figure III.11.	Selection of the battery charge controller and control strategy.....	93
Figure III.12.	Selection and sizing of the backup generator.....	94
Figure III.13.	Multi-source system diagram provided by PVSYST.....	94
Figure III.14.	Economic evaluation of the multi-source system.....	95
Figure III.15.	Near shading configuration interface.....	96
Figure III.16.	report summarizing project and system results.....	97
Figure III.17.	General parameters and PV array characteristics.....	99
Figure III.18.	Array losses table.....	100
Figure III.19.	Near shading parameters.....	101
Figure III.20.	Detailed user needs during seasons.....	102
Figure III.21.	Main results of system production.....	104
Figure III.22.	Loss diagram.....	105
Figure III.23.	Daily input /output diagram.....	107
Figure III.24.	Cost of the system.....	108

List of tables

Table 1: Azimuth values according to direction faced.....	17
Table 2: Summary of MPPT methods, operating principles, advantages and limitations	30
Table 3: Main characteristics of solar battery	35
Table 4: Comparison of battery technologies: operational characteristics, functions, and maintenance requirements	38
Table 5: Advantages and limitations of PV series configuration.....	44
Table 6: Advantages and limitations of switched PV-diesel configuration	45
Table 7: Advantages and limitations of parallel configuration	46
Table 8: Comparison of gun-set technologies, application use, advantage and limitations.....	49
Table 9: Advantages and limitations of water pump technologies	53
Table 10: Data source: NASA-SSE / PVsyst Unit: kWh/m ² /day.....	58
Table 11: Daily water requirements of the farm during growing season.....	61
Table 12: Daily Water Requirements of the farm during harvesting season	61
Table 13: Pipe parameters	63
Table 14: Velocity parameters	63
Table 15: Friction losses of chosen fittings.....	64
Table 16: Total dynamic head determination.....	64
Table 17: Farm's electrical loads during barley growing season.....	68
Table 18: Farm's electrical loads during barley harvest season.....	68
Table 19: Panels strings connections to MPPTS.....	73
Table 20: Distances between electrical components of the installation.....	75

List of acronyms and symbols

• Acronyms

PV	Photovoltaic
DC	Direct current
AC	Alternating current
MPPT	Maximum power point tracking
PWM	Pulse Width Modulation
BMS	Battery management system
ATS	Automatic transfer switch
DOD	Depth of discharge
STC	Standard test conditions
Voc	Open-circuit voltage

• Symboles

α	Azimuth angle
β	Tilt angle
λ	Longitude
kWp	Kilowatt-peak
β	Tilt angle
λ	Longitude
kVa	Kilovolt-ampere
°C	Degrees celsius
MW	megawatt

General Introduction

Modern agriculture requires the availability of energy; it has a massive role in agri-food systems, from seed plantation and farm cultivation, all the way to transport and refrigeration [1].

As modern activities such as irrigation, greenhouse equipment, refrigeration units, and other auxiliary loads, require electricity to maintain productivity, and ensure food security [1], [2]; in fact, the quality and reliability of the energy supply not only influence the technical functioning of the farm, but also its economic efficiency and its capacity to maintain its continuity of service. However, its availability faces serious challenges throughout the globe in isolated or remote areas, where access to the conventional electrical grid is often limited, unstable, or economically difficult to extend [1],[2],[4]., in many cases, agricultural operators frequently rely on diesel generators to satisfy their electrical needs, particularly for irrigation pumping and refrigeration applications, although diesel prices may be affordable in some fossil fuel dependent countries like Algeria, and its fairly easy to get access to this solution, it is fair to say it remains an outdated source of energy full of disadvantages both on the economic side and the ecological [7] , including high emissions of carbon dioxide, frequent maintenance requirements, cost of fuel transportation, and high operating costs. [7]; one of the available solutions to this matter is renewable energy, who gained significant importance in rural and off-grid applications, due to its ability to exploit locally available natural resources while reducing dependency on conventional fuels [4], [8]; several sources of renewable energy can be produced such as solar radiation, biomass, wind, hydro resources, and geothermal, each of which has specific characteristics and application domains [8],[9], in agricultural environments, the choice of renewable energy source depends heavily on local climatic conditions, type of loads to be supplied, and the required level of system autonomy; In the case of arid and desertic regions, solar energy appears to be the appropriate renewable source, this is due to the abundance of solar irradiation, the long duration of sunshine, and the increasing development of photovoltaic technologies[8],[10]; isolated applications prefer photovoltaic systems due to their direct conversion of solar radiation to electricity, high reliability, and limited maintenance compared with conventional generation systems [10], [11], However, photovoltaic systems still have some difficulties despite their advantages, they are not always sufficient to ensure a continuous energy supply under all conditions, due to their dependency on solar availability and are subject to daily and seasonal variations [12], in applications where the loads must be maintained independently of climatic conditions, this is particularly true in agricultural exploitation where certain loads like water pumping or cold storage may require regular or strategically timed operation.

For this reason, the integration of hybrid energy systems has become an increasingly adopted solution in isolated applications; A hybrid system combines more than one source of energy and often

includes an energy storage unit to improve supply continuity, flexibility, and overall system performance [12], [13]; in many cases, the most suitable architecture for agricultural electrification consists of a photovoltaic generator associated with a battery storage system and, when necessary, a diesel generator used as backup [13]; such a configuration makes it possible to exploit solar energy as the principal source while maintaining operational continuity during periods of low irradiation or elevated demand. From an engineering point of view, this type of system generally offers a more balanced compromise between energy autonomy, reliability, and operating cost; Such a configuration makes it possible to exploit solar energy as the principal source while maintaining operational continuity during periods of low irradiation or elevated demand; this type of system generally offers a more balanced compromise between energy autonomy, reliability, and operating cost. This approach is particularly relevant in southern Algeria, where climatic conditions are highly favorable to solar energy exploitation, the Saharan regions of the country, and especially the region of **Adrar**, are characterized by high solar potential and by the growing importance of agricultural development based on groundwater resources and irrigated cultivation [8],[14]; in these areas, agricultural production often depends on electrically driven pumping systems and may also require greenhouse installations, storage facilities, and auxiliary equipment, as a result, the question of energy supply becomes central to the technical and economic viability of the exploitation, although several renewable energy sources can be used for rural electrification, including wind energy, their suitability and usefulness depends on local conditions and application limitations, in the region of Adrar, wind resources are present and have been identified as technically exploitable in previous studies [18], [19], however, compared to solar energy, wind energy remains more variable and less predictable, and its integration requires more complex mechanical installations and maintenance conditions. For micro-grid agricultural applications, where energy demand is closely linked to daytime operation, photovoltaic systems generally offer a more practical and reliable solution, for this reason, the present work focuses on a photovoltaic-based hybrid system adapted to the characteristics of the study site; In this perspective, the design of a photovoltaic-hybrid system must be based on a structured engineering methodology involving several stages.

First, the energy demand of the site must be evaluated through the identification of all electrical and hydraulic loads.

Second, the local solar resource must be analyzed to estimate the production potential of the photovoltaic subsystem.

Third, the different components of the system must be dimensioned according to technical and operational criteria.

Finally, the complete system must be simulated and optimized to determine the most suitable configuration from both technical and economic points of view [13], [15], [16].

Specialized software tools are used to realize this study, in photovoltaic system design, *PVsys* is widely used for pre-dimensioning, performance simulation, and analysis of energy production and system losses [16]; it allows the designer to evaluate the expected behavior of the photovoltaic field under realistic climatic and operating conditions; The problem addressed in this thesis may therefore be expressed as follows:

How can a photovoltaic-hybrid energy system be properly dimensioned and optimized to ensure the reliable electrification of an isolated agricultural exploitation in the region of Adrar?

Based on this problem, the main objective of this thesis is to design and evaluate an optimal hybrid energy system capable of meeting the electrical needs of an isolated agricultural farm through an efficient integration of photovoltaic production, storage, and backup generation.

The selected site represents a relevant case of agricultural electrification in a Saharan environment, where the abundance of solar energy contrasts with the practical difficulties of conventional power supply.

The remainder of this manuscript is organized as follows:

- **Chapter I** presents the general theoretical concepts related to renewable energies, photovoltaic systems, MPPT, hybrid systems, storage technologies, and the role of energy in agriculture.
- **Chapter II** is devoted to the presentation of the study site and the evaluation of the energy needs and system sizing.
- **Chapter III** concerns the dimensioning, simulation, optimization and discussion of the proposed hybrid system using *PVsys*, and evaluation of energy management on the technical, economic, and environmental aspects of the selected system.
- Finally, a **general conclusion** summarizes the main results of the work and presents possible perspectives for future development.

Generalities on Renewable Energy Systems and Agricultural Electrification

1.1 Generalities on Renewable Energies

The concept of renewable energy refers to energy obtained from natural processes that are continuously replenished on a human time scale.

Unlike fossil fuels, which are finite and subject to depletion, renewable energy sources are derived from naturally recurring phenomena such as solar radiation, atmospheric circulation, water cycles, and biological processes [4], [8].

These sources are considered sustainable because their exploitation does not significantly reduce their availability over time when managed appropriately.



Fig. 1.1. Renewable energy illustration

1.1.1 Definitions and Classifications

Renewable energy systems can be classified according to several criteria, the most common being the **type of primary energy source** and the **method of energy conversion**. Based on the nature of the resource

-
- **Solar energy** which comes from sunlight and can be turned into electricity with photovoltaic systems or heat with solar collectors [9], [10].,

Broadly speaking, solar energy falls into two categories:

a) Solar thermal energy

Solar thermal energy is a type of renewable energy that converts sunlight into heat instead of electricity using solar collectors that catch incoming radiation and move the heat generated to a working fluid, usually water or air [8], [10], collected thermal energy can then be used right away for a number of purposes, especially house applications, farm and factories.

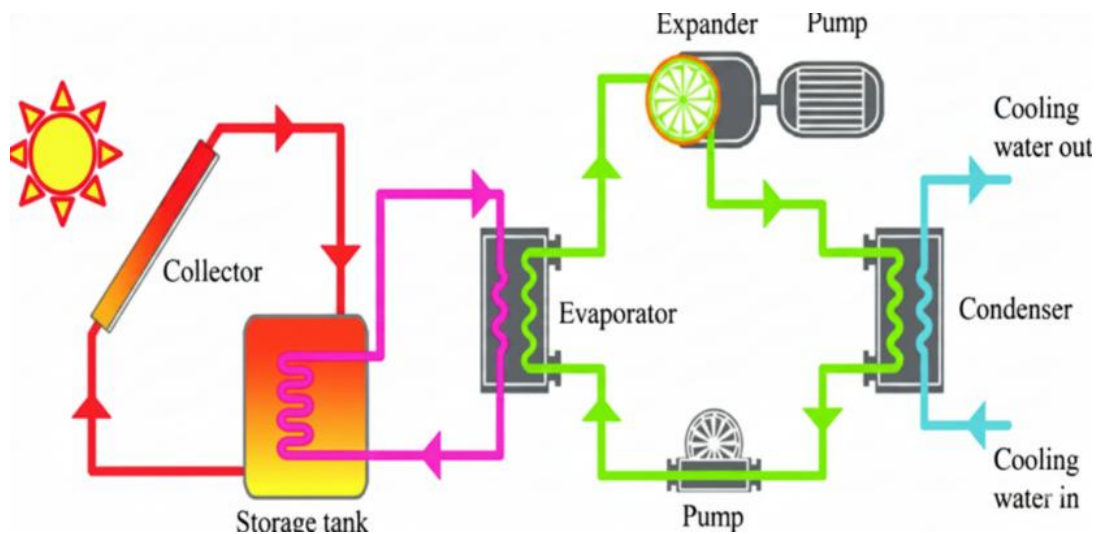


Fig. 1.2. Solar thermal energy scheme

- Advantages:**
- High efficiency for heat production
 - No greenhouse gas emissions during use
- Limitations:**
- Application limited to thermal uses
 - Performance depends strongly on solar availability

b) Photovoltaic solar energy

Photovoltaic energy is a form of solar energy that enables the direct conversion of solar radiation into electrical energy through semiconductor devices known as photovoltaic cells, this conversion is based on the photovoltaic effect, where incident photons generate charge carriers within a semiconductor material, resulting in an electric current when the circuit is closed [9], [10], PV systems are widely used in both grid-connected and off-grid configurations, particularly in rural and isolated areas where access to conventional electricity networks is

limited, their modular structure allows flexible installation and scalability, making them well adapted to applications such as water pumping, lighting, refrigeration, and agricultural electrification [9], [10].

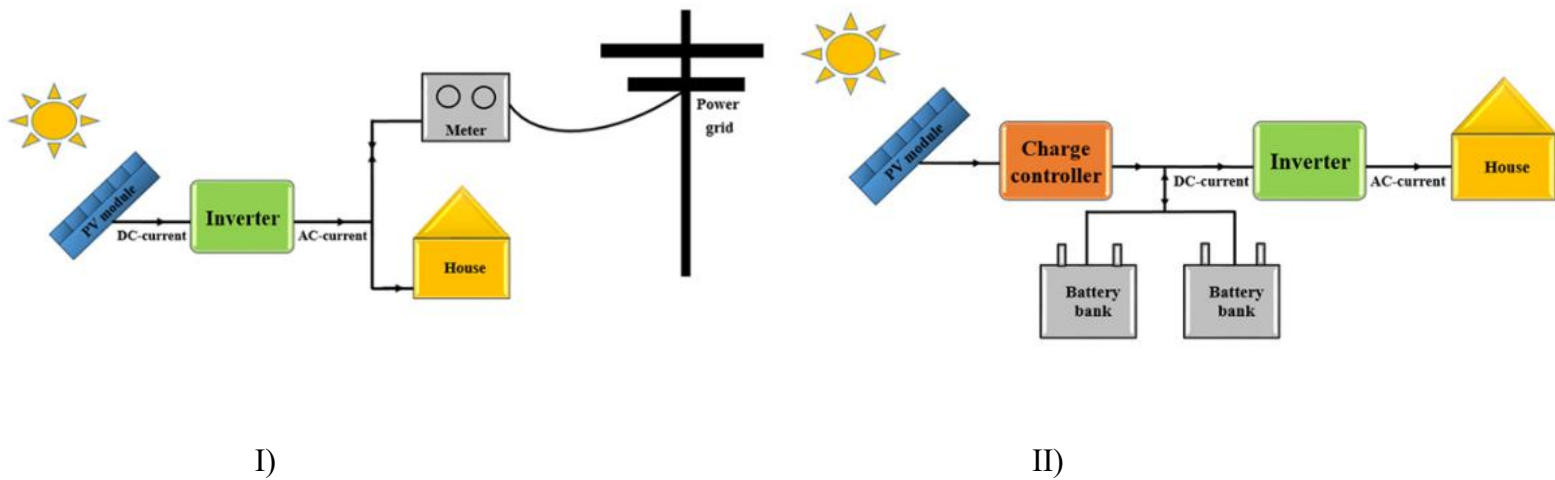


Fig. 1.3.(I) Grid connected PV system, (II) Off-grid PV system

- Advantages:
- Produce electricity directly.
 - Low maintenance and operating costs with no ghg emissions.
- Limitations:
- Production depends on solar availability and seasons.
 - Efficiency affected by heat and environmental conditions.

Wind energy is a clean renewable energy source that uses wind turbines to turn the kinetic energy of moving air masses into electricity, wind flow makes the turbine blades turn, which turns a generator that makes electricity [8]. Wind energy systems can be used in a variety of ways, from small, stand-alone turbines for rural areas to large wind farms that are connected to the electrical grid, wind turbines are classified according to:

-Horizontal axis wind turbines (HAWT): these are the most widely used turbines, with the rotor axis parallel to the wind direction, offering high efficiency, making them dominant in both onshore and offshore applications.

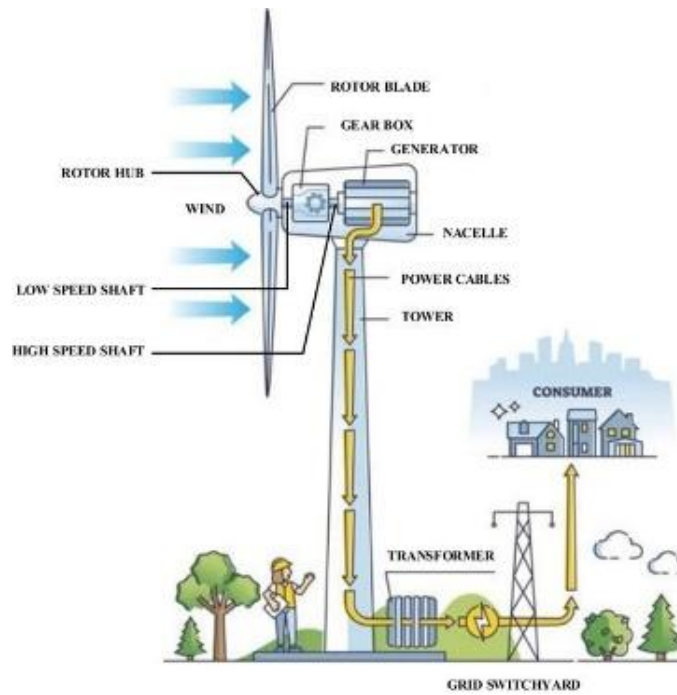


Fig. 1.4.HAWT generator Structure.

-Vertical Axis Wind Turbines (VAWT): These turbines have a vertical rotor axis and can capture wind from any direction without orientation systems.

Although simpler design, they generally have lower efficiency and are less commonly used in large-scale applications.



Fig. 1.5.VAWT generator structure.

-
- Advantages:**
- High efficiency under favorable wind conditions and considered one of most mature technologies.
 - Low operating costs and does not require fuel which makes it suitable for decentralized energy production.
- Limitations:**
- Irregular wind resource may be insufficient for reliable energy production
 - Mechanical parts subject to wear, which can increase maintenance requirements, and limit practical implementation for isolated agricultural applications.

Hydropower is based on the conversion of the potential and kinetic energy of water into electricity, typically through hydraulic turbines connected to generators.

It is one of the oldest and most established renewable energy technologies, widely used in large-scale power generation as well as in small-scale installations [2].

Hydroelectric facilities can be divided into three groups:

- **Reservoir** hydropower, also known as storage hydropower, which separates the turbines from the hydro inflows. Dams can employ water storage as a buffer to control or store hydro inputs, decoupling the generating time from the input [2], [13].

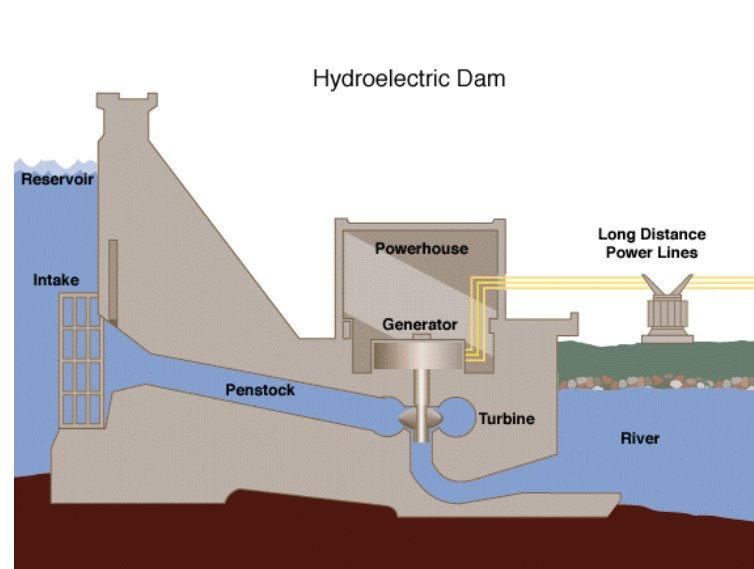


Fig. 1.6. Hydroelectric Dam (powerplant).

-**Run-of-river** hydropower, whose generating output is mostly determined by hydro inflows due to a lack of storage to act as a buffer for the time and magnitude of inflows [2].

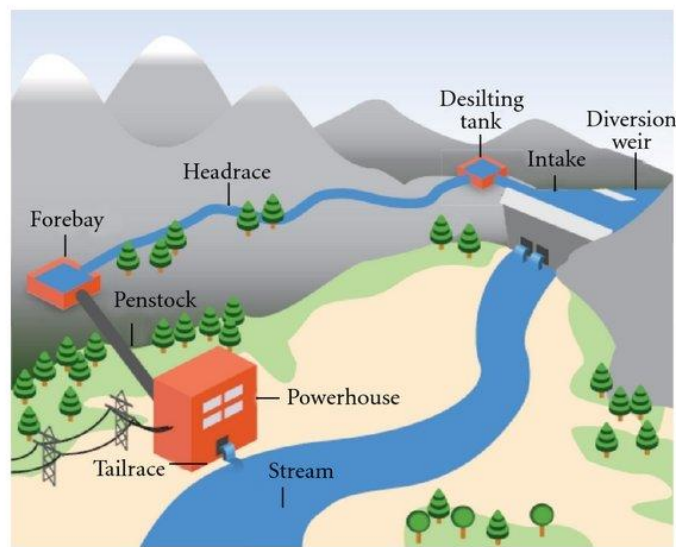


Fig. 1.7. Run-of-river hydropower.

-Pumped **storage** hydropower, which uses reservoirs for higher and lower storage.

Water is pumped from the lower reservoir to the upper reservoir using energy when demand is low, usually during off-peak hours, and released when demand for electricity is high. Peak generating, grid stability, and ancillary services are the main uses for pumped hydro [2].

By storing an abundance of renewable energy that is not required during times of low electricity demand, it can also be utilized to incorporate more variable renewables [2].

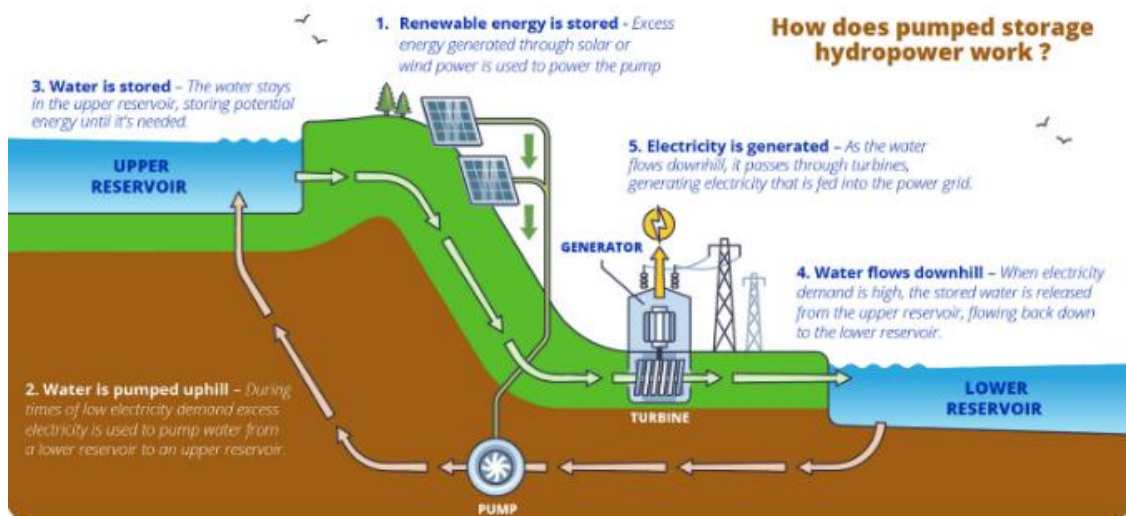


Fig. 1.8. Pumped storage hydropower.

Hydropower can be classified also according to hydraulic head:

High-head systems (>100 m): use Pelton turbines which is suitable for mountainous regions.

Medium-head systems (30–100 m): using Francis turbines offering a balance between efficiency and adaptability.

Low-head systems (<30 m): use Kaplan or propeller turbines and are commonly found in large rivers with low elevation differences.

- Advantages:**
- High efficiency and reliability as water flow can be regulated and controlled thus producing continuous and stable electricity.
 - High conversion rate often exceeds 85%.
 - Long operational life span and low operating costs.
- Limitations:**
- Requires significant infrastructure.
 - Efficiency affected by geographical limitations.

Biomass energy comes from organic materials like animal waste, agricultural waste, wood, and other substances that can break down naturally; Combustion, gasification, or anaerobic digestion can turn these materials into useful energy, which can be used to make heat, electricity, or biofuels [1].

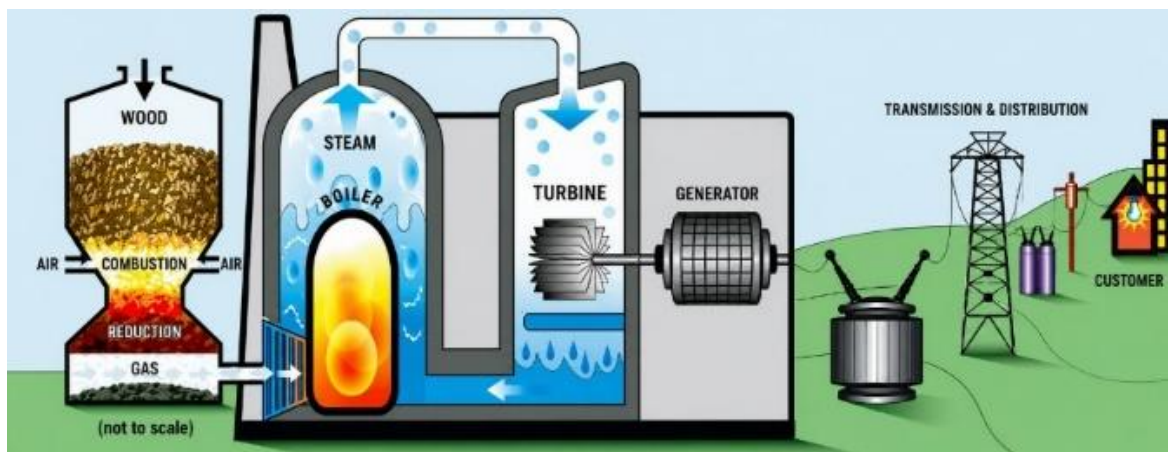


Fig. 1.9.Biomass energy production.

- Advantages:**
- Utilization of agricultural and organic waste.
 - Relatively stable and controllable energy production.
 - Possibility of local resource valorization

-
- Limitations:**
- Requires continuous biomass supply and logistics.
 - Lower conversion efficiency.
 - Emission still present (though reduced compared to fossil fuel).

Geothermal energy exploits heat stored within the Earth's crust for electricity generation or direct thermal use.

This heat is achieved through wells that extract hot water or steam from underground reservoirs, which can then be used to drive turbines or provide heating [8]; Geothermal energy can be classified into 3 main systems:

- Dry steam systems:** use steam directly from underground reservoirs to drive turbines.
- Flash Steam Systems:** by depressurizing high-pressure hot water to produce steam, which turns the turbine.

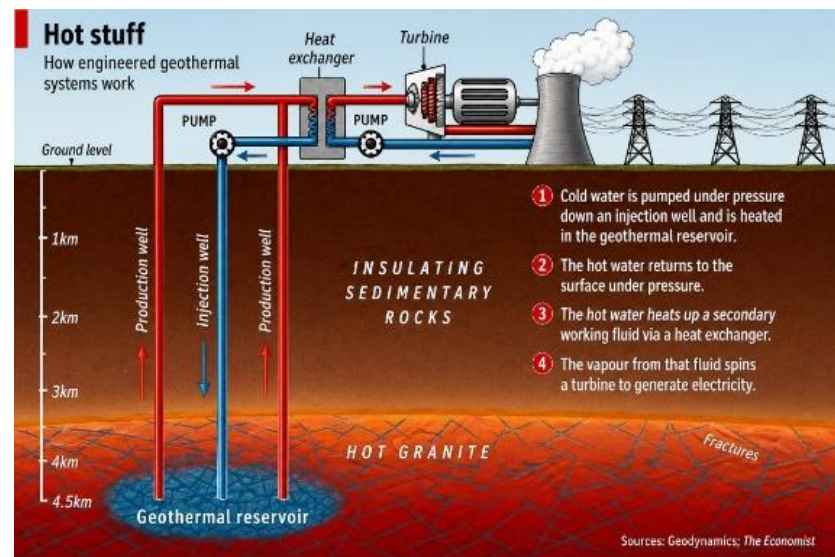


Fig. 1.10. Geothermal energy system.

Binary Cycle Systems: Use moderate-temperature geothermal fluids to heat a secondary working fluid with a lower boiling point, enabling us to make electricity in lower-temperature environments.

- Advantages:**
- Continuous and base-load energy production.
 - Not dependent on weather conditions.
 - High reliability.
- Limitations:**
- Strong geographical dependency.
 - High exploration and drilling costs.
-

1.1.2 Relevance of renewable energy for the study site.

The choice of a suitable renewable energy technology depends not only on its general characteristics but also on its compatibility with the environmental and geographical conditions of the concerned site; this choice is particularly crucial for isolated agricultural exploitations since the energy system has to guarantee reliability, autonomy and adaptation to local constraints, the study area presented in this work is located in a Saharan region of southern Algeria characterized by high solar irradiation, high ambient temperatures and low precipitation levels; these climatic conditions play a significant role in the viability and efficiency of various renewable energy technologies; the region benefits especially from a high solar potential, with numerous hours of sunshine throughout the year, making solar energy one of the most abundant and accessible resources [5], [14].

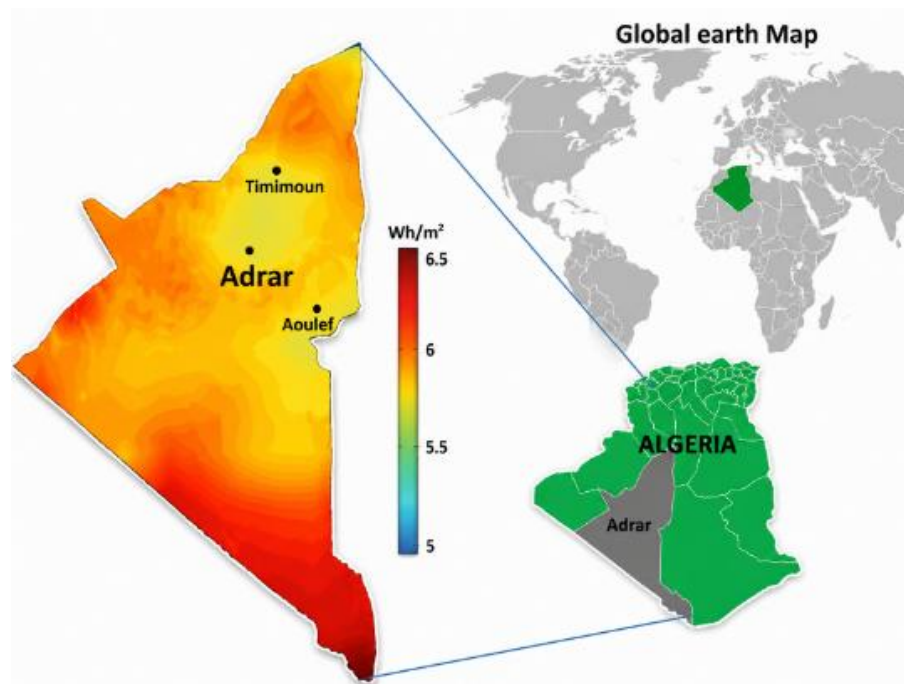


Fig. 1.11. Map of Adrar with mean annual sum of global horizontal irradiation ($\text{kWh/m}^2/\text{year}$).

Other renewable energy sources, on the other hand, do not perform well when evaluated under these circumstances, wind energy is technically feasible but highly dependent on local wind regimes that may be irregular and insufficient to ensure stable and continuous energy supply., hydropower systems (conventional, tidal or hydrokinetic technologies) are not applicable due to the absence of significant water resources and suitable hydraulic conditions.

Similarly, biomass energy relies on organic resources that may be scarce in arid environments, limiting its practicality as a primary energy source, In contrast, geothermal

energy requires geological conditions that are generally not present or economically exploitable in the region under consideration [1],[2],[8], based on this preliminary analysis, solar photovoltaic energy appears to be the most suitable energy source for the electrification of the agricultural site studied, coupled with a hybrid system to ensure continuity in the most unfavorable scenarios, (solar photovoltaic system, batteries, diesel generator).

1.2 Solar Photovoltaic energy

1.2.1 Solar radiation

The sun emits energy in the form of photons covering a broad spectrum, spanning from ultraviolet waves (**0.2 μm**) to far infrared (**2.5 μm**), this energy is distributed across three main spectral bands:

- **9%** in ultraviolet ($< 0.4 \mu\text{m}$)
- **47%** in visible light (0.4 to $0.8 \mu\text{m}$)
- **44%** in infrared ($> 0.8 \mu\text{m}$)

To harness this radiation — whether as heat or electricity — solar collectors must be designed to respond to these specific wavelength ranges, ensuring optimal photon capture.

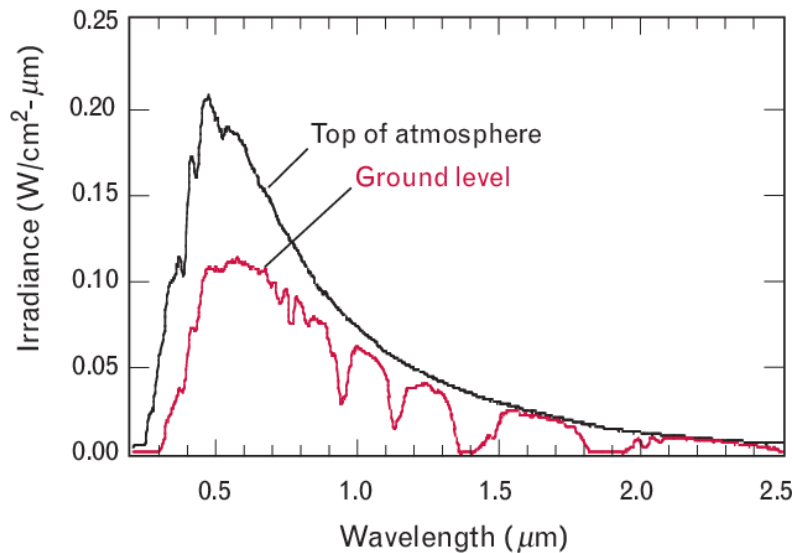


Fig. 1.12. Spectral analyses of solar radiation.

Producing an electric current from solar radiation requires two fundamental conditions to be met, on one hand, the material acting as a sensor must be capable of interacting with incoming photons by absorbing them according to their specific wavelength.

On the other hand, the electrical charges released in this process must be directed and gathered together in order to generate a coherent and usable electric current [18].

1.2.2 Different types of solar radiation

a. Direct Radiation: Direct radiation refers to the portion of solar energy that travels in a essentially straight path from the sun to the Earth's surface without significant deviation. When striking a horizontal surface, it is expressed as:

$$I_h = I \times \sin(h)$$

where **h** represents the solar elevation angle.

b. Diffuse Radiation: Unlike direct radiation, diffuse radiation originates from the entire sky dome rather than the sun itself; it results from the scattering and absorption of sunlight by atmospheric particles, as well as its reflection off clouds; under clear sky conditions, it accounts for roughly 20% of total incoming energy, whereas under overcast conditions, it represents the entirety of radiation reaching the ground

c. Reflected Radiation (Albedo): This component corresponds to solar energy bounced back by ground surfaces or objects present on them; its magnitude depends heavily on the reflective properties of the surface, known as albedo, which tends to be especially high over particularly reflective materials such as water or snow [18].

d. Global Radiation: on a horizontal plane encompasses all solar-origin radiation reaching that surface, combining the vertical component of direct sunlight with diffuse sky radiation, on a tilted surface when the receiving surface is inclined, global radiation becomes the sum of three distinct contributions: direct, diffuse, and reflected radiation [18].

e. Air Mass and STC

The Air Mass (AM) concept describes the ratio between the actual path length traveled by direct sunlight through the atmosphere and the vertical thickness of the atmosphere at that location. It is computed as:

$$AM = 1 / \sin(h) \quad (1.1)$$

For any given site, atmospheric pressure *p* (in millibars) is also factored in. Standard reference conditions are defined as follows: AM0 applies above the atmosphere, AM1 when the sun is directly overhead (zenith), and AM2 at a solar elevation of 30°.

The Air Mass index serves a dual purpose: it quantifies the power carried by incoming solar radiation; approximately 1367 W/m^2 at AM0, dropping to around 833 W/m^2 at AM1.5; and it establishes a reference spectrum for calibrating photovoltaic test cells. Standard qualification conditions for solar cells are set at an AM1.5 spectrum, an incident power of 1000 W/m^2 , and a temperature of 25°C [18].

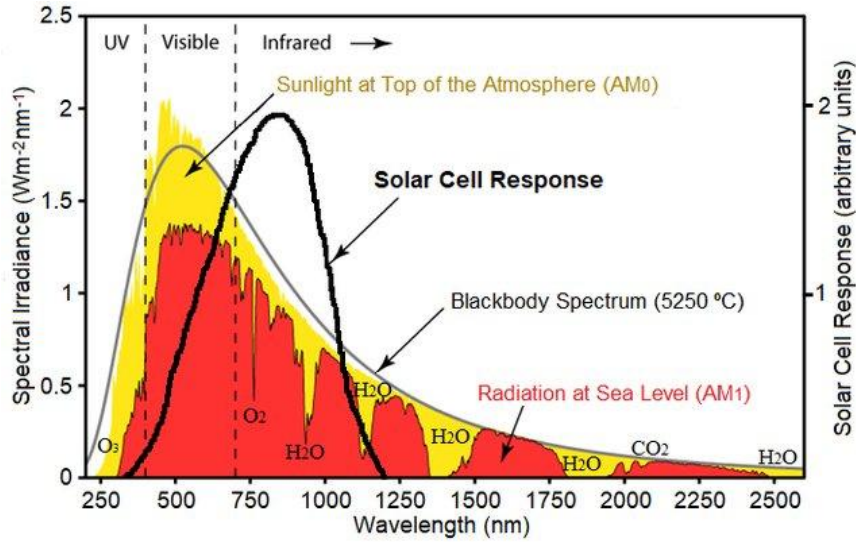


Fig. 1.13. Solar specter to different mass air values

Understanding the Air Mass number requires examining two distinct dimensions, the first it serves as an indicator of the energy intensity carried by solar radiation reaching a given point, this intensity stands at approximately 1367 W/m^2 outside the atmosphere (AM0) and falls around 833 W/m^2 at (AM1.5) due to atmospheric absorption, the second one provides a standardized spectral reference framework used to calibrate benchmark solar cells, which are themselves employed to assess and validate the performance of photovoltaic devices.

In this context, the internationally accepted standard testing conditions for solar cells have been established as follows:

- A reference spectrum corresponding to **AM1.5**.
- An incident irradiance level of **1000 W/m^2** .
- An operating temperature of **25°C** .

Unless explicitly stated otherwise, any performance data or technical specifications provided for a photovoltaic device are assumed to be measured and reported under these standardized conditions which is referred to as STC [18].

1.2.3 Solar geometry and geographical coordinates

Locating any spot on our planet relies on a coordinate system built around three key parameters

1) Longitude: it's a way of measuring how far east or west a place sits relative to a globally agreed-upon starting line, two imaginary vertical planes, both cutting through the earth's polar axis, form an angle between them, one anchored at the Greenwich reference meridian (0°) and the other cuts through the target location, this angle is what we call longitude (λ)

This measurement is covered by some rules:

- a) Value stretch from -180° to $+180^\circ$
- b) Eastward positions carry a positive value, westward ones a negative value
- c) Every single degree of longitudinal separation translates into a 4-minute difference in solar time [19].

2) Altitude: it's how high a location sits above a universally adopted baseline known as average sea level, expressed in meters and reflects the elevation of the point above the theoretical flat reference.

3) Latitude: Latitude (φ) it's about how far north or south is a location from earth's midline, geometrically it is the angle formed at earth's center between the equatorial plane and a line drawn outward to the surface point of interest, and it works as follows:

- The equator sits at 0° , splitting the globe into two halves.
- Moving northward, values climb toward $+90^\circ$ at the north pole.
- Moving southward, values drop to -90° at the south pole.
- Northern Hemisphere locations receive a positive (+) sign, while southern hemisphere ones are given a negative (-) sign [19].

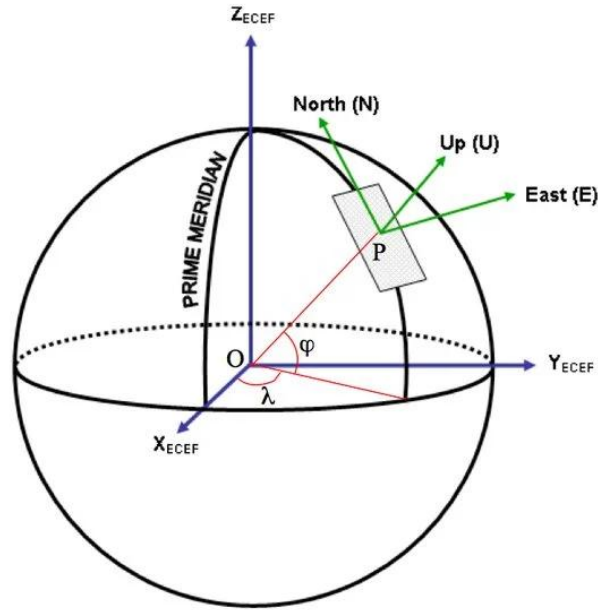


Fig. 1.14. Cartesian geocentric coordinates and local coordinates

1.2.4 Surface orientation and tilt

When studying how much solar energy a surface can capture, two angular parameters become essential, where the surface faces, and how steeply it is angled

1) Azimuth angle (α): the azimuth tells you which compass direction that surface is pointing toward, more precisely, it measures the horizontal angle between the sun's position and due south, the sign convention works as follows:

Direction faced	Azimuth value
East	-90°
South	0°
West	$+90^\circ$
North	$+180^\circ$

Table 1: Azimuth values according to direction faced

A surface pointing due South ($\alpha = 0^\circ$) is generally considered optimal for solar energy collection in the Northern Hemisphere, as it receives the most direct sunlight throughout the day [19].

1) Tilt angle (β): the tilt angle addresses how steeply a surface rises from the ground; it quantifies the deviation between the receiving surface and a perfectly flat horizontal plane:

In practice, most solar installations operate somewhere between 0° and 90° , with the optimal tilt typically matching or approximating the geographic latitude of the installation site.

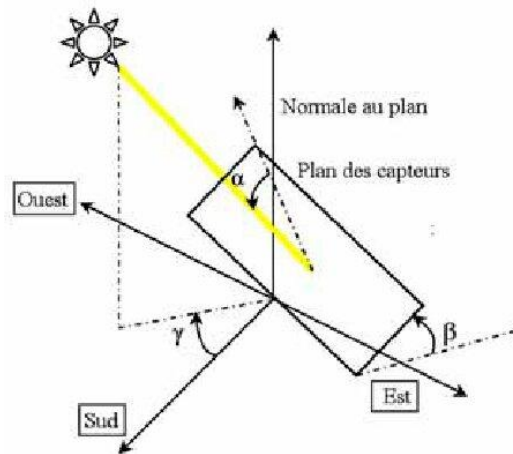


Fig. 1.15. Angles on an inclined plane

1.2.5 Photovoltaic effect

The photovoltaic effect is based on the interaction between incident photons and semiconductor material, leading to the generation of electrical carriers that can be extracted as a usable current; this mechanism represents the core operating principle of photovoltaic technologies and governs their electrical behavior under varying environmental conditions [23].

Photovoltaic conversion occurs within semiconductor materials such as silicon, which are characterized by an energy band structure composed of a valence band and a conduction band separated by an energy gap known as the bandgap, when a photon with energy equal to or greater than the bandgap is absorbed, an electron is excited from the valence band to the conduction band, generating an electron–hole pair [20], [18].

However, the generation of charge carriers alone does not ensure electrical power production, in the absence of an internal electric field, these carriers would recombine without contributing to useful current.

To address this limitation, photovoltaic cells are based on a p–n junction structure, formed by joining p-type and n-type semiconductor materials, the resulting junction creates a depletion region characterized by an internal electric field [20].

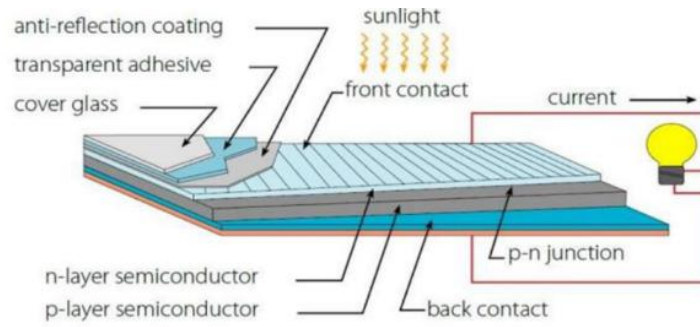


Fig. 1.16. Solar cell diagram.

1.2.6 Photovoltaic cell

A photovoltaic cell—often referred to as a solar cell—is a semiconductor device that transforms light energy directly into electric energy by exploiting a physical phenomenon known as the photovoltaic effect.

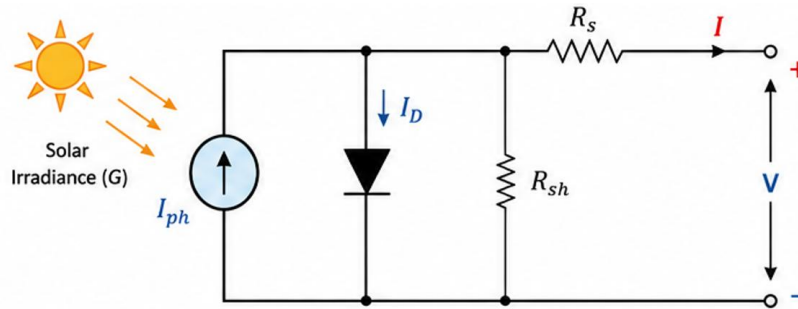


Fig. 1.17. Equivalent circuit of a PV Cell

The electrical behavior of a photovoltaic cell is commonly represented by its current–voltage (I–V) characteristics, which are nonlinear and strongly dependent on irradiance and temperature.

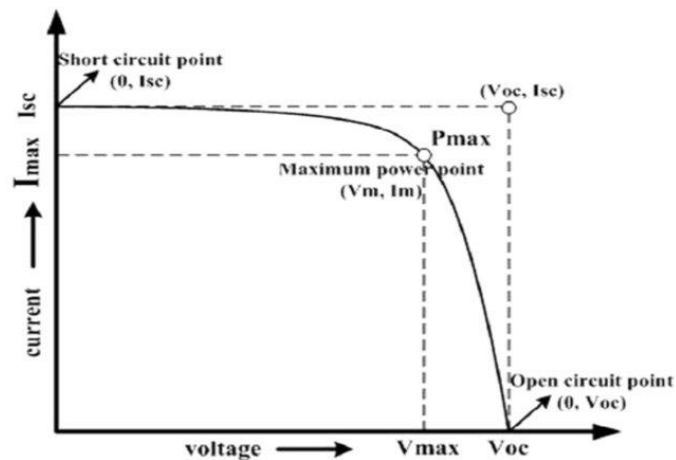


Fig. 1.18. I-V characteristics curve of a PV cell

- V_{oc} = Open-circuit voltage. (maximum voltage output when the current is zero)
- I_{sc} = Short-circuit current. (maximum current output when the voltage is zero)
- P_{max} = Maximum power (at this point, voltage and current reach maximum value)

The photovoltaic energy conversion process can therefore be described in three fundamental stages: photon absorption, generation of electron–hole pairs, and separation of charge carriers under the effect of the internal electric field, the efficiency of this process is influenced by material properties, recombination mechanisms, and thermal effects, which significantly affect the overall performance of photovoltaic systems in real operating conditions [18], [20].

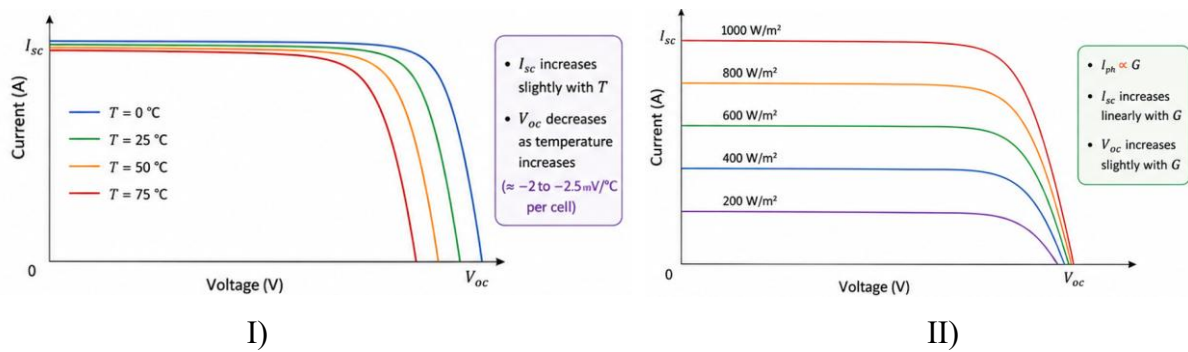


Fig. 1.19. I) I-V characteristics vs Temperature, II) I-V characteristics vs irradiance.

1.2.7 Photovoltaic cell technologies and Semiconductor Materials

The performance of a photovoltaic system depends not only on solar irradiation conditions and system configuration, but also on the semiconductor technology used in the photovoltaic cells. Over the past decades, several photovoltaic technologies have been developed to improve conversion efficiency, reduce manufacturing costs, and adapt photovoltaic systems to different environmental and operational conditions; these technologies mainly differ in their semiconductor materials, fabrication processes, electrical characteristics, and thermal behavior [21].

Silicon remains the dominant semiconductor material in the photovoltaic industry due to its abundance, chemical stability, non-toxicity, and well-established manufacturing technology. Depending on the crystalline structure of the semiconductor material, silicon photovoltaic cells are generally classified into three principal categories: monocrystalline silicon, polycrystalline silicon, and amorphous silicon technologies.

a. Monocrystalline Silicon Cells

Monocrystalline silicon cells are manufactured from a single continuous crystal structure obtained through highly controlled crystallization processes, their uniform crystalline arrangement allows electrons to move more freely within the material, resulting in higher conversion efficiencies compared to other silicon technologies [21].

These cells are characterized by:

- high electrical efficiency, typically ranging between 18% and 24%.
- good long-term stability.
- reduced space requirements due to their higher power density.
- relatively high manufacturing costs associated with crystal purification and fabrication processes.



Fig. 1.20. Silicium mono-crystalline cell

Monocrystalline modules are particularly suitable for applications where installation space is limited or where maximizing energy production is essential, their high efficiency makes them attractive for isolated photovoltaic systems operating under strong solar irradiation conditions, such as Saharan regions.

However, their performance remains sensitive to temperature increases, in high-temperature environments, the output voltage decreases, leading to a reduction in overall conversion efficiency [21].

b. Polycrystalline Silicon Cells

Polycrystalline silicon cells are produced using molten silicon that solidifies into multiple crystal grains rather than a single crystal structure; this manufacturing process is simpler and less expensive than that of monocrystalline cells, making polycrystalline technology widely adopted in medium-cost photovoltaic installations [21].

Compared to monocrystalline cells, polycrystalline modules generally present:

- lower manufacturing costs.
- moderate conversion efficiencies, typically between 15% and 19%.
- slightly higher recombination losses due to grain boundaries.
- lower energy production efficiency under identical irradiation conditions.

Despite their lower efficiency, polycrystalline modules offer a good compromise between performance and economic cost, which explains their widespread use in large-scale photovoltaic systems.

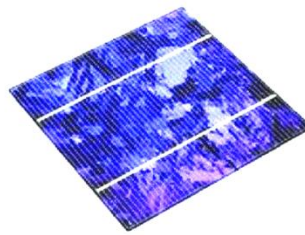


Fig. 1.21. Poly-crystalline silicium cell

c. Amorphous Silicon Cells

Amorphous silicon cells belong to the thin-film photovoltaic technology family, unlike crystalline silicon technologies, amorphous silicon does not possess an ordered crystal structure. Instead, semiconductor material is deposited in thin layers onto substrates such as glass, plastic, or metal surfaces [21].

The main characteristics of amorphous silicon technology include:

- reduced material consumption.
- lightweight and flexible structures.
- lower manufacturing costs.
- better performance under low irradiance conditions.

However, amorphous silicon cells generally exhibit relatively low conversion efficiencies, often below 12%, together with gradual performance degradation over time due to light-induced degradation phenomena.

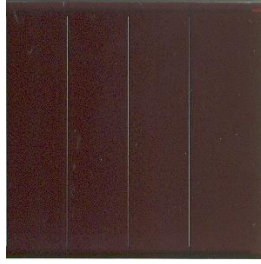


Fig. 1.22. Amorphous silicon cell

d. Thin-Film Photovoltaic Technologies

In addition to silicon-based technologies, several thin-film photovoltaic materials have been developed to reduce manufacturing costs and improve flexibility, the most common thin-film technologies include:

- **Cadmium Telluride (CdTe).**
- **Copper Indium Gallium Selenide (CIGS).**
- **Gallium Arsenide (GaAs).**

Thin-film technologies require smaller quantities of semiconductor materials and can be manufactured on flexible substrates, certain technologies, particularly CIGS, exhibit good thermal behavior under high ambient temperatures, making them potentially attractive for desert environments [21].

Nevertheless, some thin-film technologies remain limited by:

- lower commercial availability.
- reduced long-term stability.
- environmental concerns related to toxic materials such as cadmium.

For isolated agricultural applications in Saharan regions, photovoltaic modules must withstand high solar irradiation, elevated ambient temperatures, dust accumulation, and harsh environmental conditions; under such circumstances, crystalline silicon technologies particularly monocrystalline modules are often preferred due to their high efficiency and operational reliability despite their higher initial cost.

1.3 Components and types of photovoltaic systems

A photovoltaic system is an integrated electrical system designed to convert solar energy into usable electrical power while ensuring energy conditioning, regulation, protection, and

distribution according to the requirements of the application; in practice, photovoltaic installation is not limited to the photovoltaic generator itself but includes several electrical and electronic subsystems operating together to guarantee stable and efficient energy production under varying environmental conditions [22].

The configuration of a photovoltaic system depends mainly on:

- the nature of the electrical load.
- the required autonomy.
- the operating environment.
- and the availability of auxiliary energy sources.

Although photovoltaic system architectures may differ from one application to another, most installations are composed of common fundamental elements including photovoltaic modules, power converters, charge controllers, storage devices, protection systems, and monitoring units.

1.3.1 Photovoltaic Generator

The photovoltaic generator constitutes the primary energy production unit of a photovoltaic system, the electrical energy produced by the photovoltaic generator is delivered in the form of direct current (DC) and subsequently conditioned by power electronic converters to satisfy the requirements of electrical loads or energy storage systems [22], unlike conventional electrical generators, photovoltaic generators do not contain moving mechanical parts and operate solely through the interaction between solar radiation and semiconductor materials, Consequently, their energy production depends directly on environmental conditions, particularly solar irradiance and cell temperature.

1.3.1.1 Structure of a photovoltaic generator

A photovoltaic generator is organized in a layered structure composed of several interconnected elements, the smallest functional unit is the photovoltaic cell, which converts incident solar radiation into electrical energy; individual cells are electrically connected to form a photovoltaic module, commonly referred to as a solar panel; since the electrical power generated by a single module is generally insufficient for practical applications, multiple modules are interconnected to form strings and arrays capable of delivering the required voltage and power levels [23].

layered organization can be summarized as follows:

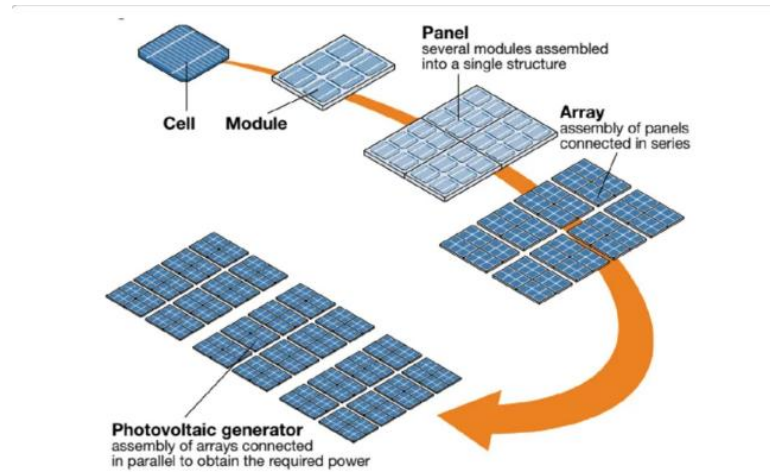


Fig. 1.23. Structure of a photovoltaic generator

Where:

- **Cell:** elementary photovoltaic conversion device.
- **Module :** assembly of interconnected cells encapsulated within a protective structure.
- **String :** group of modules connected in series and /or parallel.

1.3.1.2 Series and parallel connections

The electrical characteristics of a photovoltaic generator are determined by the configuration adopted for module interconnection.

A. Series connection

When photovoltaic modules are connected in series, the positive terminal of one module is connected to the negative terminal of the next module. In this configuration, the output voltage increases while the current remains unchanged [24].

The total voltage is expressed as:

$$V_{total} = N_s V_{module} \quad (1.2)$$

where:

- V_{total} : total generator voltage (V);
- V_{module} : voltage of a single module (V);
- N_s : number of modules connected in series.

Series connections are generally used when high DC voltage levels are required for inverter operation or power transmission.

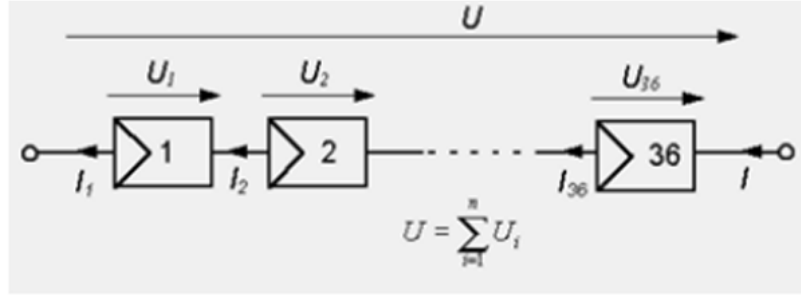


Fig. 1.24. PV series connection

B. Parallel connection

In parallel connections, all positive terminals are connected together, and all negative terminals are connected. This arrangement increases the output current while maintaining approximately the same voltage [24].

The total current is given by:

$$I_{total} = N_p I_{module} \quad (1.3)$$

where:

- I_{total} : total generator current (A);
- I_{module} : module current (A);
- N_p : number of parallel branches.

Parallel connections are commonly employed when large power outputs are required.

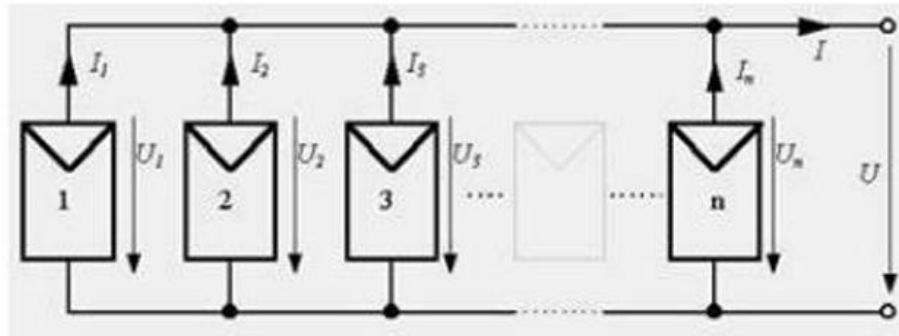


Fig. 1.25. PV parallel connection

1.3.2 Charge controller and power conditioning unit

A photovoltaic generator does not produce constant voltage or power; its electrical output continuously varies according to several factors including:

- Solar irradiance.

-
- Cell temperature.
 - Shading conditions.
 - Load demand.

Therefore, directly connecting a photovoltaic generator to batteries or loads may result in poor energy utilization, battery degradation, unstable operation, reduced system efficiency.

For this reason, photovoltaic systems incorporate a power conditioning stage responsible for regulating energy transfer between the photovoltaic generator, storage units, and electrical loads [22].

1.3.2.1 Role of charge controller in photovoltaic systems

In standalone and hybrid photovoltaic systems, the charge controller represents a critical component responsible for supervising energy transfer from the photovoltaic array to the battery bank while protecting the storage system from potentially damaging operating conditions, beyond its protective role, the charge controller contributes significantly to improving the overall efficiency and reliability of the system by regulating voltage and current levels according to the operating requirements of the batteries and electrical loads [22]; the controller also prevents reverse current flow between the battery and the photovoltaic generator; during periods without solar radiation, photovoltaic modules cease producing electrical energy and may behave as passive electrical loads, without adequate protection, stored energy could flow back into the photovoltaic array, resulting in unnecessary energy losses.

Charge controllers incorporate blocking mechanisms that eliminate this reverse current path and improve overall energy efficiency [22], beyond battery protection, charge controllers are closely associated with power conditioning functions; the electrical output of a photovoltaic generator rarely matches the voltage requirements of the battery bank or electrical loads directly, therefore, voltage adaptation becomes necessary to ensure efficient power transfer under varying operating conditions, this adaptation is achieved through the use of DC/DC converters, which constitute the core of modern photovoltaic charge regulation systems [22].

1.3.3 Types of charge controller

1.3.3.1 PWM (Pulse Width Modulation) charge controller

It adjusts the width of electrical pulses to control the amount of energy sent to the battery, it acts like a fast switch that opens and closes several times per second, the more the battery is charged, the shorter the pulses become, thus reducing the incoming energy

flow, (e.g. if we have a solar panel of 18V, a duty cycle of 75% will allow for a charging voltage of 13.5V for the battery), with this type of device we cannot control the current [22].



Fig. 1.26. PWM SOLAR CHARGE CONTROLLER

1.3.3.2 MPPT (maximum power point tracking) controller

The electrical power generated by a photovoltaic system is not constant, since it depends strongly on environmental conditions such as solar irradiance and cell temperature; under varying operating conditions, the current–voltage (I–V) and power–voltage (P–V) characteristics of photovoltaic modules exhibit a unique operating point at which the extracted power reaches its maximum value; this operating point is known as the Maximum Power Point (MPP), and its location changes continuously throughout the day depending on weather and load conditions; as a result, direct operation of a photovoltaic generator without control leads to suboptimal energy extraction and reduced system efficiency [24].

In order to overcome this limitation, Maximum Power Point Tracking (MPPT) techniques have been developed; MPPT refers to a set of control algorithms implemented within power electronic converters, whose main objective is to continuously adjust the operating voltage and current of the photovoltaic generator so that it remains as close as possible to the MPP under all environmental conditions; these algorithms are typically embedded in DC/DC converters and act by modifying the duty cycle of the switching devices, thereby controlling the electrical operating point of the photovoltaic array [24], [22]. From a physical perspective, the MPPT controller does not directly extract energy from the photovoltaic module; instead, it regulates the impedance seen by the photovoltaic generator. By dynamically matching the load impedance to the optimal operating conditions of the PV array, maximum power transfer is achieved according to the principle of impedance matching, this makes MPPT an essential

component in all modern photovoltaic systems, particularly in standalone and hybrid configurations where energy availability is limited and must be efficiently utilized.

1.3.3.1 Current–Voltage and Power–Voltage Characteristics

The current–voltage characteristic of a photovoltaic module is nonlinear and varies with irradiance and temperature; under standard conditions, the curve is bounded by two extreme points: the short-circuit current, corresponding to zero voltage, and the open-circuit voltage, corresponding to zero current. Between these two limits lies a region where the electrical power varies significantly with voltage [25].

The output power is defined as:

$$P = V \times I \quad (1.4)$$

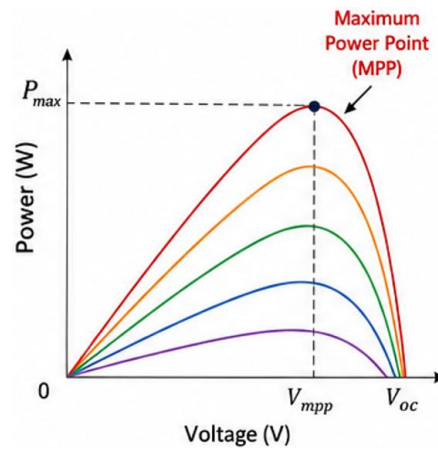


Fig. 1.27. MPPT P-V curve

The corresponding power–voltage curve presents a single maximum point, which defines the optimal operating condition of the photovoltaic generator; this point is characterized by:

- V_{mpp} : voltage at maximum power point
- I_{mpp} : current at maximum power point
- P_{max} : maximum extractable power

$$P_{max} = V_{mpp} \times I_{mpp} \quad (1.5)$$

The condition for maximum power transfer can be mathematically expressed by the derivative of power with respect to voltage:

$$\frac{dP}{dV} = 0 \quad (1.6)$$

Since $P=VI$, the condition becomes:

$$\frac{dP}{dV} = I + \frac{VdI}{dV} \quad (1.7)$$

At the maximum power point:

$$\frac{dI}{dV} = -\frac{I}{V} \quad (1.8)$$

This relationship forms the basis of advanced MPPT techniques, particularly the Incremental Conductance method; it indicates that at the optimal operating point, the incremental conductance is equal and opposite to the instantaneous conductance of the photovoltaic module.

1.3.4 Comparison between different methods of MPPT commands

The following table summarizes the differences between every MPPT method; their operating principles, and their advantages and limitations [24].

Method	Category	Main Principle	Advantages	Limitations
Perturb & Observe (P&O)	Direct	Perturbs PV voltage and observes power variation to approach the MPP.	Simple, low cost, widely used.	Oscillates around MPP, less effective under rapid irradiance changes.
Incremental Conductance (INC)	Direct	Uses the condition $dP/dV = 0$ at MPP to locate the optimal operating point.	High accuracy, reduced oscillations.	More complex calculations and sensitive to measurement noise.
Fractional Open-Circuit Voltage (FOCV)	Indirect	Estimates MPP voltage from the open-circuit voltage.	Very simple and inexpensive.	Requires periodic disconnection of the PV array, causing power loss.
Fractional Short-Circuit Current (FSCC)	Indirect	Estimates MPP current from the short-circuit current.	Fast and simple implementation.	Requires periodic short-circuiting of the PV module.
Fuzzy Logic Control (FLC)	Soft Computing	Uses linguistic rules to determine the optimal operating point.	Robust and efficient under varying weather conditions.	Requires expert knowledge for rule design.
Artificial Neural Network (ANN)	Soft Computing	Learns the relationship between	Very high accuracy and efficiency.	Requires extensive training data and

		environmental conditions and MPP.		high computational resources.
Particle Swarm Optimization (PSO)	Soft Computing	Searches for the global MPP using swarm intelligence.	Excellent under partial shading conditions.	High computational complexity.
Sliding Mode Control (SMC)	Non-linear	Uses robust control laws to force operation toward MPP.	Fast response and strong robustness.	Complex design and chattering phenomenon.
Ripple Correlation Control (RCC)	Direct	Exploits converter switching ripple to locate MPP.	Very fast tracking speed.	Lower steady-state accuracy and noise sensitivity.

Table 2: Summary of MPPT methods, operating principles, advantages and limitations

1.3.5 MPPT IMPLEMENTATION IN A CHARGE CONTROLLER VS INVERTER

The following table summarizes the different roles of MPPT when implemented in a solar charge controller vs hybrid inverter:

Feature	MPPT Charge Controller	MPPT INVERTER
Primary function	Regulates charging to batteries	Converts DC to AC + MPPT tracking
Power Conversion Type	DC to DC	DC to AC
System Role	Battery management	System core (power conversion + optimization)
Typical Use Case	Off-grid systems with batteries	Grid-tied, hybrid, commercial systems
Complexity	Lower	Higher
Cost	Lower upfront	Higher upfront
Scalability	Limited	Highly scalable
Integration	Requires separate inverter	Often all-in-one solution

Table 3 : Comparative analysis of MPPT implementation in charge controller vs hybrid inverter

1.3.6 DC-DC converter

A DC/DC converter is a power electronic device capable of transforming one level of direct voltage into another while maintaining high conversion efficiency; Unlike conventional transformers, which operate with alternating current, DC/DC converters employ high-frequency switching techniques combined with passive components such as inductors and capacitors to regulate energy transfer between the source and the load [31], The operation of

DC/DC converters relies on semiconductor switching devices, typically MOSFETs or IGBTs, which alternate rapidly between conducting and non-conducting states, by controlling the switching sequence and the proportion of time during which the switch remains closed, known as the duty cycle, the converter can regulate its output voltage according to system requirements [22].

1.3.6.1 Types of DC-DC converters

BOOST DC-DC (step-up): A Boost converter (also known as a step-up converter or parallel chopper) is a switched-mode power supply that converts an input DC voltage into a higher value output DC voltage.

In a solar charger, the boost DC-DC converter elevates the PV panel's voltage to match the battery's charging requirements while enabling the MPPT controller to extract maximum power particularly useful when the panel's maximum power point voltage is lower than the battery voltage [22].

BUCK DC-DC CONVERTER (step-down): The Buck converter is commonly used in battery charging applications where the photovoltaic array voltage exceeds the battery charging voltage [22].

1.3.7 Inverter

The inverter is a key element in photovoltaic systems supplying alternating current loads or interacting with an AC distribution network; its primary function is to convert the direct current produced by the photovoltaic generator or the battery storage system into alternating current with appropriate voltage and frequency adapted to the connected loads or the grid.

In modern photovoltaic systems, the role of the inverter extends far beyond simple DC/AC conversion, advances in power electronics and digital control have transformed the inverter into an intelligent energy management device capable of regulating power flows, controlling battery charging and discharging, maintaining electrical stability, and ensuring optimal utilization of renewable energy resources [22]; As a result, the inverter is often regarded as the central control unit of a photovoltaic installation, particularly in standalone and hybrid systems.

- **Operating principle**

The basic operating principle of an inverter relies on the periodic switching of semiconductor devices according to a predefined sequence such as MOSFETs or IGBTs, by controlling the switching frequency and duty cycle, the inverter generates an alternating voltage whose amplitude and frequency can be adjusted to meet load requirements.

Hybrid inverters represent the most advanced category and are particularly relevant for hybrid agricultural microgrids, these devices integrate several functions within a single unit, including photovoltaic energy conversion, battery management, load supply, and coordination with auxiliary generation sources such as diesel generators.

Through advanced control algorithms, hybrid inverters determine the most appropriate energy source according to system conditions, load demand, battery state of charge, and solar resource availability [26], in hybrid photovoltaic systems, the inverter plays a strategic role in the implementation of energy management strategies, during periods of high solar irradiation, photovoltaic production can directly supply electrical loads while simultaneously charging the battery bank, when solar generation becomes insufficient, stored energy may be discharged to maintain supply continuity; if both photovoltaic production and battery reserves are inadequate, the inverter can initiate the operation of the backup generator to guarantee uninterrupted service, this hierarchical management of energy flows contributes significantly to reducing fuel consumption, improving renewable energy penetration, and enhancing system reliability [26].



Fig. 1.28. Hybrid SOLAR INVERTER-CHARGER 3000VA

1.3.8 Storage system

Energy storage systems are integrated into standalone and hybrid photovoltaic installations to ensure continuity of supply during periods of low solar production or nighttime operation [22], [26], batteries therefore play a fundamental role in maintaining system stability, load autonomy, and operational reliability.

1.3.8.1 Batteries composition

An electrochemical storage device consists of two electrodes (a cathode and an anode) connected to an external electrical circuit, both immersed in a compartment containing an electrolyte.

The two electrodes are made of different metallic materials.

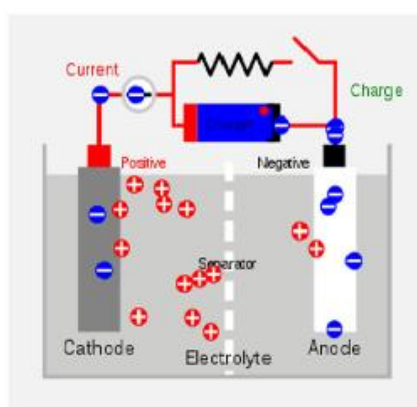


Fig. 1.29. Electrochemical accumulator

The electrolyte acts as an ionic conductive medium, enabling the movement of ions between the electrodes and thereby ensuring the electrochemical operation of the system.

1.3.8.2 Main characteristics of battery

The following table summarizes the key characteristics of battery technologies:

Characteristic	Definition and Role	Typical Design Relevance
Nominal voltage	Rated DC voltage of a single battery or battery block (e.g., 12 V, 24 V, 48 V)	Determines system DC bus level and compatibility with inverters/chargers
Nominal capacity	Stored charge at a given discharge rate (e.g., Ah at C10 or C20)	Used to size autonomy and total usable energy
Usable capacity	Portion of nominal capacity effectively available considering DoD limits	Directly impacts backup duration and risk of load shedding

Depth of discharge (DoD)	Fraction of capacity discharged during a cycle (in %)	Higher DoD increases usable energy but can reduce lifetime
State of charge (SoC)	Instantaneous level of charge relative to full capacity (in %)	Key variable for control, protection, and energy management
Cycle life	Number of charge–discharge cycles before capacity falls below a threshold	Determines replacement frequency and lifecycle cost
Round-trip efficiency	Ratio of discharged energy to charged energy over a full cycle (in %)	Affects overall system efficiency and required PV oversizing
Self-discharge rate	Capacity loss over time when battery is idle	Influences performance in low-usage or seasonal applications
Maximum charge/discharge current	Highest safe current the battery can accept or deliver	Limits pump start-up currents and fast load changes
Operating temperature range	Temperature window ensuring safe and reliable operation	Critical in desert climates; affects lifetime and capacity
Calendar life	Expected lifetime in years under given storage and operating conditions	Complements cycle life for long-term planning
Safety and protections	Built-in or external protections (over-voltage, over-current, thermal, BMS)	Essential for reliability and to prevent thermal runaway or damage
Cost per kWh (installed)	Total installed cost normalized by usable energy	Used in techno-economic optimization and system comparison

Table 3: Main characteristics of solar battery

1.3.8.3 Types of solar batteries

Solar batteries can be classified according to the materials used for their electrodes and the type of electrolyte employed [22], [26].

The most commonly used technologies in photovoltaic systems include lead-acid batteries (flooded, gel, and AGM types) and lithium batteries.

- **Flooded Lead-Acid Batteries**

Flooded lead-acid batteries are the oldest and most widely used battery technology due to their low cost, they employ a liquid electrolyte consisting of sulfuric acid diluted with water. The positive plates are generally made of lead dioxide (PbO_2), while the negative plates consist of sponge lead (Pb).

These batteries require regular maintenance, including monitoring the electrolyte level and adding distilled water to compensate for evaporation losses.

Although they are reliable and economical, their maintenance requirements remain a significant drawback [22], [26].



Fig. 1.30. Liquid lead-acid battery

- **Gel Batteries**

Gel batteries operate on the same electrochemical principle as flooded lead-acid batteries. However, silica is added to the electrolyte to transform it into a gel-like substance.

This design enhances safety by preventing leakage and allows operation in various orientations. Gel batteries also offer good resistance to deep discharges and require minimal maintenance, making them suitable for standalone photovoltaic applications [22], [26].

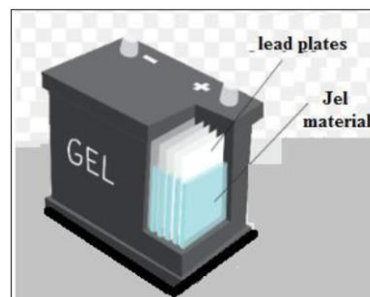


Fig. 1.31. Gel battery

- **AGM battery**

In AGM batteries, the electrolyte is absorbed into fiberglass separators positioned between the electrodes.

This configuration prevents electrolyte leakage and significantly reduces gas emissions during operation.

AGM batteries feature low internal resistance, excellent deep-cycle performance, and a longer service life compared with conventional flooded batteries.

They are also virtually maintenance-free [22], [26].



Fig. 1.32. AGM lead battery

- **Lithium Batteries**

Lithium batteries are currently among the most efficient technologies for solar energy storage. The anode is typically made of graphite because of its low cost, chemical stability, and ability to host lithium ions.

Recent developments have introduced silicon-based, alloy-based, and metal-oxide anodes to improve energy density and battery lifespan ,[13],[22],[26].

The cathode is commonly manufactured from lithium-containing compounds such as lithium cobalt oxide (LiCoO_2) and lithium iron phosphate (LiFePO_4); battery performance varies considerably depending on the cathode material employed, The electrolyte may be liquid, semi-solid, or solid.

Liquid electrolytes generally consist of lithium salts dissolved in organic carbonate solvents. Semi-solid and solid polymer electrolytes provide enhanced safety and greater stability, making them promising candidates for next-generation lithium-ion battery technologies [22], [26].

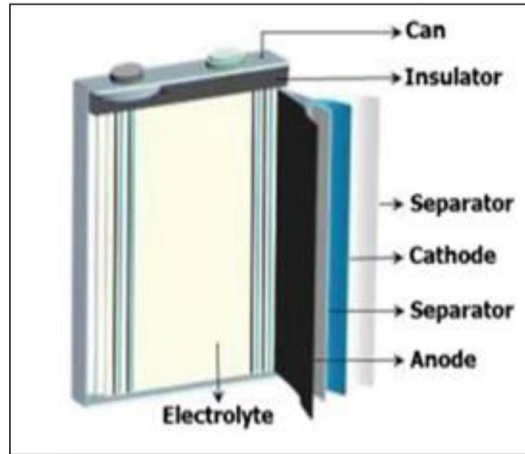


Fig. 1.33. Lithium-ion battery

1.3.8.4 Comparison between different batteries technologies

Different batteries technologies have their own specifications and application fields, the following table summarizes the differences between each of them, and specifies their characteristics:

Characteristics	Flooded Lead-Acid	Gel-AGM Lead acid	Lithium-ion
Typical energy density	Low–medium ($\approx 30\text{--}50 \text{ Wh/kg}$)	Low–medium (similar to flooded)	Medium–high ($\approx 80\text{--}200 \text{ Wh/kg}$)
Round-trip efficiency	$\approx 75\text{--}85\%$	$\approx 80\text{--}90\%$	$\approx 90\text{--}95\%$
Typical cycle life	$\approx 500\text{--}1500$ cycles (at moderate DoD)	$\approx 800\text{--}2000$ cycles	$\approx 3000\text{--}8000$ cycles (depending on DoD)
Recommended depth of discharge (DoD)	40–60% (to preserve life)	50–70%	70–90% (technology dependent)
Temperature sensitivity	Significant; lifetime drops at high temperature	Similar to flooded; sealed construction improves robustness	High; requires proper thermal management
Maintenance	Regular (electrolyte level, ventilation)	Low (sealed, maintenance-reduced)	Very low (electronic BMS handles protection)
Initial investment cost	Low	Low–medium	High
Typical application in PV	Small/medium off-grid, low-cost systems	Off-grid and backup where low maintenance is needed	High-performance hybrid microgrids, demanding cycling profiles

Table 4: Comparison of battery technologies: operational characteristics, functions, and maintenance requirements

1.3.9 Protection and monitoring devices

Photovoltaic systems require various protection and supervision devices to ensure safe and reliable operation. These devices are essential for protecting both equipment and users against electrical faults, overvoltages, and abnormal operating conditions.

Typical protection components include:

- circuit breakers.
- fuses.
- disconnect switches.
- surge protection devices.
- grounding systems.
- overload protection mechanisms.

Monitoring systems are also increasingly integrated into modern photovoltaic installations in order to supervise:

- energy production.
- battery state of charge.
- inverter performance.
- fault detection.
- and overall system efficiency.

These monitoring units facilitate preventive maintenance and improve operational reliability, particularly in remote isolated systems.

1.4 Types of Photovoltaic systems

Depending on their mode of operation and connection configuration, photovoltaic systems are generally classified into three principal categories.

1.4.1 Grid-Connected systems

Grid-connected systems are directly linked to the electrical utility network.

In this configuration, the photovoltaic generator supplies electrical energy to local loads while excess production may be injected into the grid; these systems generally operate without

battery storage and are mainly employed in urban and industrial applications where the electrical grid is continuously available [27].

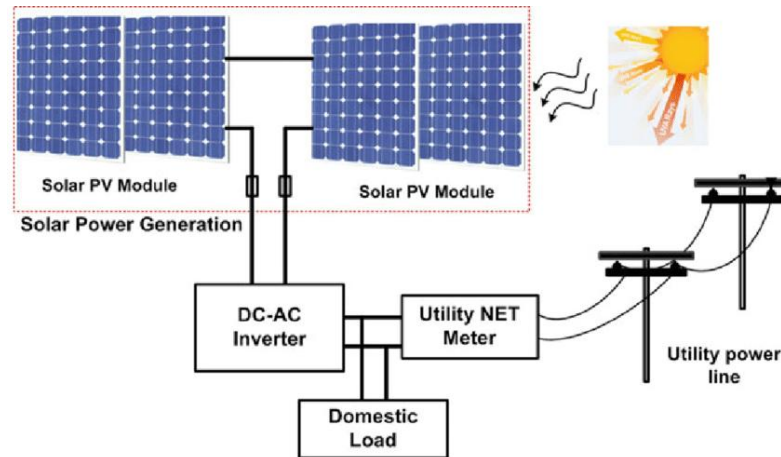


Fig. 1.34. Grid-connected PV system

1.4.2 Off-grid systems

Standalone photovoltaic systems operate independently from the electrical grid and are mainly used in isolated regions where grid access is unavailable or economically impractical [27].

These systems generally include:

- photovoltaic modules.
- battery storage systems.
- charge controllers.
- and power converters.

Standalone systems are widely employed in:

- rural electrification.
- water pumping.
- Telecommunications.
- and isolated agricultural applications.

Their main limitation lies in the intermittency of solar energy and the dependence on storage capacity.

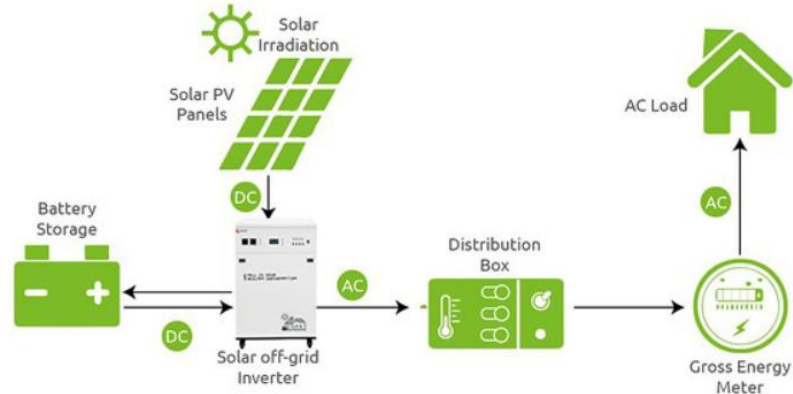


Fig. 1.35. Off-grid solar system

1.4.3 Hybrid photovoltaic systems

Hybrid photovoltaic systems combine solar generation with additional energy sources such as:

- diesel generators.
- wind turbines.
- or battery storage systems.

The objective of hybridization is to improve:

- energy reliability.
- supply continuity.
- operational flexibility.
- and system autonomy.

Hybrid architectures are particularly suitable for isolated agricultural microgrids operating in Saharan regions, where high solar potential can be combined with storage systems and auxiliary generators to ensure continuous power supply despite climatic variability; due to their flexibility and improved reliability, hybrid systems have become one of the most promising solutions for rural electrification and agricultural energy applications in remote areas [28].

1.4.3.1 Classification of Hybrid Systems

There are several ways to classify multi-source hybrid systems; the chosen criterion depends on the particular aspect under consideration [28].

The most common classifications are presented below.

1.4.3.2 By operating mode

- **Grid-connected operation** (in parallel with the existing electricity network).
- **Isolated (stand-alone) operation** (in remote areas with no grid access).

1.4.3.3 By system configuration

This classification is based on several distinct criteria:

- The presence of a conventional (thermal) power source.
- The presence of an energy storage device (batteries..etc).
- Type of renewable energy source(s) used.
- Energy potential which is linked to the area's conditions.
- Energy consumption.

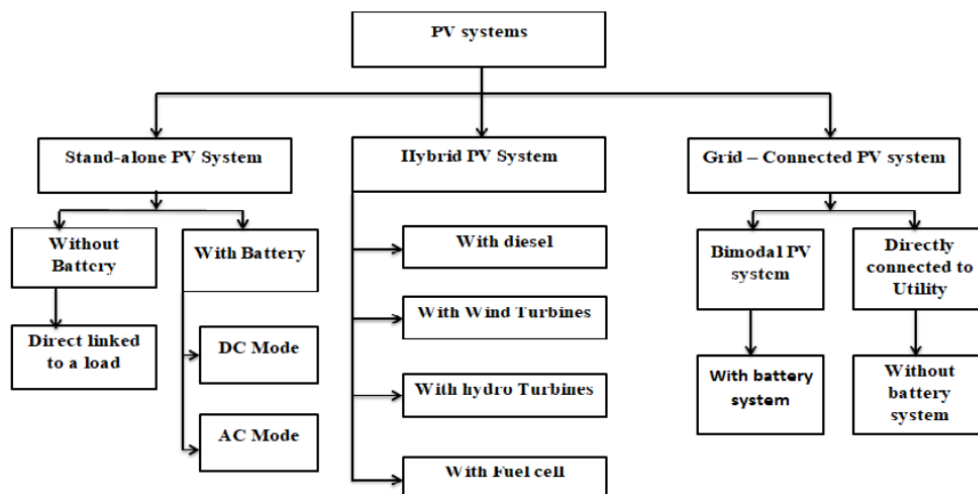


Fig. 1.36. Classification of Photovoltaic systems

1.4.4 Photovoltaic system combined with a conventional source

This type of multi-source system is most deployed in regions with a warm climate and high solar potential, such as Algeria, Saudi Arabia, and similar areas, its main purpose, when operated in standalone mode, is to supply continuous power to a house, a residential or administrative building, or even an entire village [29], standalone configurations generally include batteries as well as other storage devices, the batteries and the photovoltaic array deliver direct current, by contrast, diesel motors can drive generators that deliver either direct or

alternating current, although in most cases the loads require alternating current; Because the PV generator inherently produces direct current while domestic consumption usually relies on alternating current, an inverter must be added to the system in order to convert DC into AC.

In such architectures, the photovoltaic generator can operate in parallel with, or alternately to, the diesel generator; as a result, several configurations of PV/conventional-source hybrid systems can be distinguished, including:

- series-type PV/diesel hybrid systems.
- switched PV/diesel hybrid systems.
- parallel PV/diesel hybrid systems.

1.4.4.1 Series-type configuration

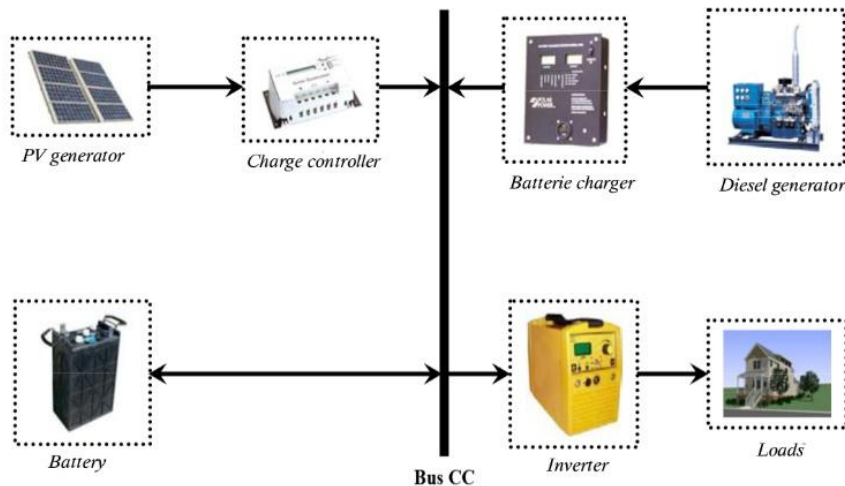


Fig. 1.37. PV/diesel Serie Configuration

Essential characteristics of this design are:

- It is specifically designed for small-scale systems that incorporate a rarely-used Diesel generator.
- Both the Diesel generator and the renewable energy sources are connected to the battery's common DC bus.
- The autonomous inverter functions unidirectionally, maintaining grid voltage, it also facilitates the conversion of all direct current power, whether from the photovoltaic array or the Diesel generator, into alternating current.
- When the photovoltaic system's energy output is insufficient to satisfy the demand, the Diesel generator is disengaged.

1.4.4.1.1 Advantages and limitations

The following table summarizes the advantages and limitations of PV-series configuration

Advantages	Limitations
Easy determination of the appropriate size for the Diesel generator	The inverter cannot operate concurrently with the Diesel generator. Therefore, it must be dimensioned to handle the peak possible load independently.
A simplified electrical circuit, as there's no need for switching mechanisms between AC power sources.	Efficiency is relatively low when an AC Diesel generator is involved, due to the power undergoing two conversions before reaching the consumer.
Starting the Diesel generator does not lead to any interruption in the electricity supply.	Total loss of electrical power in case of inverter fail.
The inverter ensures that the consumer receives a steady power supply with suitable voltage, signal waveform, value, and frequency.	Suitable for only high capacity battery

Table 5 : Advantages and limitations of PV series configuration

1.4.4.2 Switched PV/Diesel arrangement

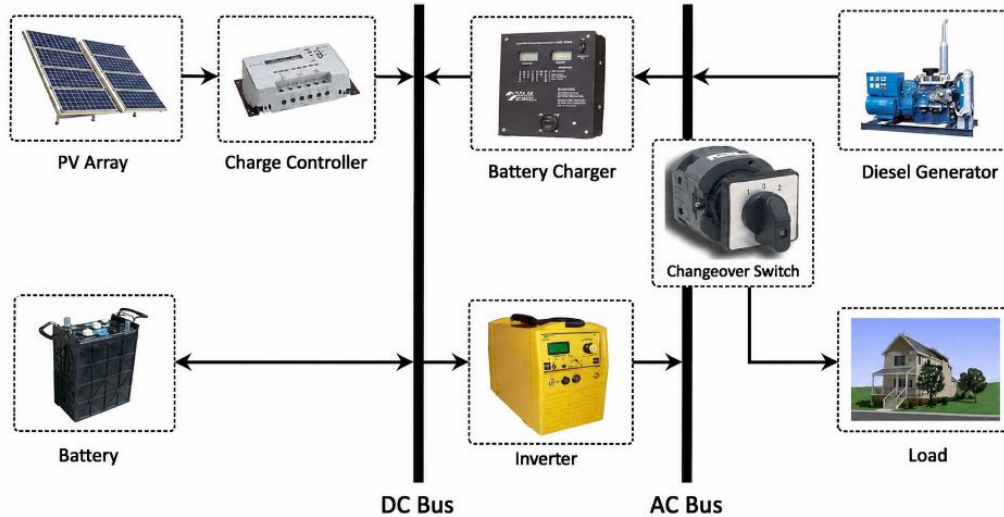


Fig. 1.38. Switched pv-diesel arrangement system

This configuration is widely used even though it presents several drawbacks; in such a system, energy can be supplied either from the conventional grid or from the photovoltaic array combined with the battery through an inverter, but not from both sources at the same time, the diesel generator can also be used to recharge the battery via a rectifier acting as an intermediate

stage, due to the complexity of hybrid systems, their operation requires an automated control and management system [29].

1.4.4.1.2 Advantages and Limitations

The following table summarizes the advantages and limitations of Switched pv diesel arrangement

Advantages	Limitations
Enhanced efficiency because the Diesel generator directly powers the load, leading to reduced fuel usage.	A brief interruption of power occurs when switching between sources.
The inverter can guarantee that the consumer receives power at the specified voltage in terms of both its form and magnitude.	Both the generator and the inverter must be dimensioned for the system's maximum power consumption. Consequently, their efficiency decreases during periods of low demand.
A malfunction of the inverter will not cause a complete power outage, as the Diesel generator can still supply the load.	Complex construction

Table 6: Advantages and limitations of switched PV-diesel configuration.

1.4.4.3 Parallel configuration

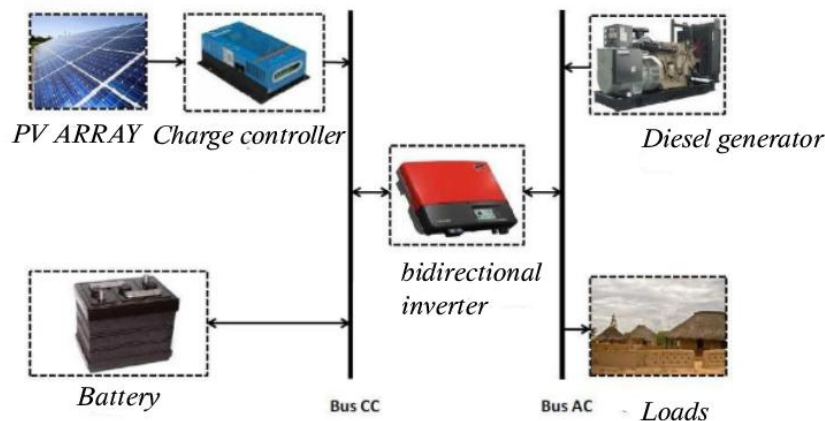


Fig. 1.39. Parallel configuration

In this connection scheme, the diesel generator set is connected to the AC grid, the photovoltaic modules and the battery bank are connected to a separate DC grid [29].

A reversible electronic converter links these two grids together, this device can fulfill two functions: as a rectifier, when the diesel generator supplies the load while also charging the

batteries or as an inverter, when the load (or part of it) is covered by solar energy and/or the batteries.

In this way, the load can draw power from both grids simultaneously.

1.4.4.3.1 Advantages and Limitations

The following table summarizes the advantages and limitations of parallel configuration:

Advantages	Limitations
System components do not need to be sized for the full load, as the consumer can be supplied simultaneously by both energy sources.	An automatic control system is required to ensure proper operation of the overall system.
Higher efficiency is achieved because the sources operate closer to their rated power levels. In addition, there is no energy conversion stage for the diesel generator output.	The power electronic converter must generate a sinusoidal voltage to enable synchronization with the diesel generator.
The number of power electronic converters is reduced, which in turn decreases the required cabling and lowers the initial investment cost of the SMESR system.	Batteries tend to degrade faster due to the absence of an optimized charging system.
A failure in one power electronic converter does not necessarily lead to a loss of power supply to the load.	Skilled personnel are required to operate and maintain the system correctly.

Table 7: Advantages and limitations of parallel configuration

1.4.5 Choice of configuration for the application site

For the studied application, which concerns an isolated agricultural electrification system operating under highly variable solar conditions, the parallel photovoltaic–diesel configuration is identified as the most appropriate solution; its ability to ensure continuous power supply, support dynamic loads such as water pumping systems, and maximize photovoltaic energy utilization makes it particularly suitable for remote Saharan environments where reliability and energy efficiency are critical constraints

1.5 Generator set

A generator set (genset) is an autonomous system designed to produce electrical energy. It generally consists of a thermal engine coupled to an alternator; the system converts mechanical energy from fuel combustion into electrical energy, depending on their design and application, generator sets can range from small portable units weighing a few kilograms to

industrial systems weighing several tons; their power rating is usually expressed in VA or kVA (kilovolt-amperes), which represents the apparent electrical power output[30].



Fig. 1.40. 2 KW GASOLINE GENERATOR SET

1.5.1 Principle operation

Generator sets are mainly used as backup or standalone power sources, the thermal engine converts chemical energy from fuel into mechanical rotational energy, which drives the alternator; the alternator then transforms this mechanical motion into alternating electrical current through electromagnetic induction.

1.5.2 Types of generator sets

Generator sets can operate using different energy sources depending on the design and application [30]:

-Gasoline (petrol): Common in small, portable generators used for domestic purposes, they can be started either manually or using an electric starter, their typical power range is generally between 1.5 kW and 6 kW, making them suitable for household loads and small equipment

They usually provide single-phase output and may include multiple outlets in higher-power models, their engines are typically 2-stroke or 4-stroke, with relatively lower noise levels compared to diesel units.

-Diesel fuel: Widely used in industrial and high-power applications due to its efficiency and durability, they are mainly equipped with 4-stroke diesel engines and can provide single-

phase, or hybrid electrical outputs depending on the configuration, their power capacity can reach several megawatts (MW) in industrial installations, many modern diesel generators include automatic starting systems (ATS) for emergency or standby operation.



Fig. 1.41. 10 kVA diesel generator set

-Natural gas / LPG: cleaner alternatives with lower emissions and reduced operating costs in continuous operation systems



Fig. 1.42. Propane gas LPG power generator set

-Fuel cell systems: Advanced generators that produce electricity through an electrochemical reaction between hydrogen and oxygen without combustion, these systems are highly efficient, quiet, and environmentally friendly, but are still limited by high cost and hydrogen infrastructure requirements [31].



Fig. 1.43. Components of a fuel cell generator set.

1.5.3 Comparison of generator set energy sources

The following table summarizes the differences between generator set energy technologies and their advantages and limitations

Type	Advantages	Limitations	Typical use
Gasoline	Low cost, easy to start, lightweight, low initial investment	High fuel consumption, short lifespan, limited power	Domestic use, small tools, emergency backup.
Diesel	High efficiency, high torque, long lifespan, suitable for heavy loads, reliable for long operations	Noisy, higher emission, higher maintenance, heavier system	Industrial use, backup for remote areas.
Natural gas, LPG	Cleaner emissions, lower operating costs than diesel, quieter operation, good efficiency	Requires gas supply infrastructure, less available in rural areas, higher installation complexity	Urban backup systems, facilities with gas acces
Fuel cell (Hydrogen)	Very high efficiency, silent operation, zero local emissions, low mechanical wear	Very expensive, hydrogen infrastructure issues, still experimental in many regions	Advanced clean energy systems, research, future grids.

Table 8: Comparison of gun-set technologies, application use, advantages and limitations.

1.5.4 Choice of generator set for the application site

for rural and agricultural applications, where energy demand is variable and reliability is essential, diesel generator set offer the most appropriate solution; in particular, the PV–Diesel–Battery hybrid configuration provides an optimal compromise between technical performance

and economic feasibility, this configuration ensures primary energy production during daylight hours, while the battery bank stabilizes the load and improves energy continuity.

The diesel generator acts as a backup source during periods of low solar irradiation or high demand; reducing significantly fuel consumption, operational costs, and it enhances system reliability, which is a critical factor in agricultural applications such as irrigation pumping, where power interruptions can lead to significant losses.

1.6 Solar pumping systems

Water pumping is one of the most important applications of photovoltaic energy in the agricultural sector, particularly in remote and arid regions where access to the electrical grid is limited or nonexistent [32].

Solar water pumping systems utilize photovoltaic energy to power electric pumps responsible for extracting water from groundwater sources, wells, rivers, or reservoirs for agricultural, domestic, and livestock applications.

1.6.1 Main components of a solar pumping system

A photovoltaic pumping system generally consists of the following elements:

- Photovoltaic generators.
- MPPT Controller.
- Inverter.
- Hydraulic pump and motor assembly.
- Water storage tank.
- Monitoring and Protection Devices.
- Battery storage (in hybrid structure).

1.6.2 Classification of solar pumping systems

Solar pumping systems can be classified according to their operating architecture [32].

-Direct-Coupled systems: In direct systems, the photovoltaic generator is directly connected to the pump through a controller

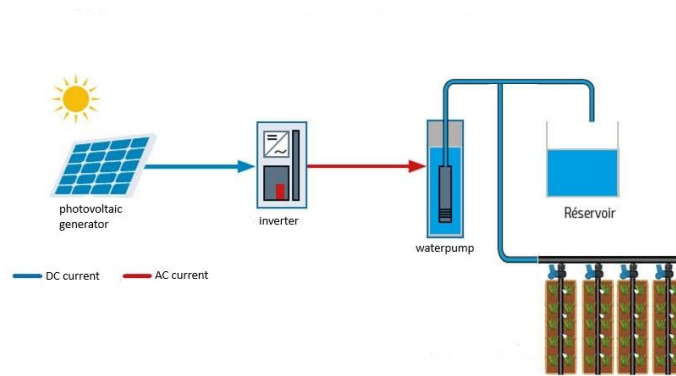


Fig. 1.44. Principal diagram of a direct solar pumping system

-Battery-Coupled Systems: These systems include batteries to store electrical energy.

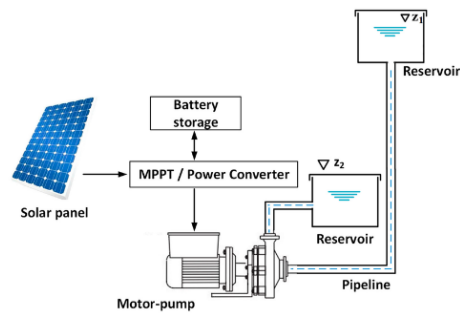


Fig. 1.45. Battery-coupled pumping system

Hybrid Solar Pumping Systems: Hybrid systems combine photovoltaic energy with auxiliary sources such as diesel generators or wind turbines.

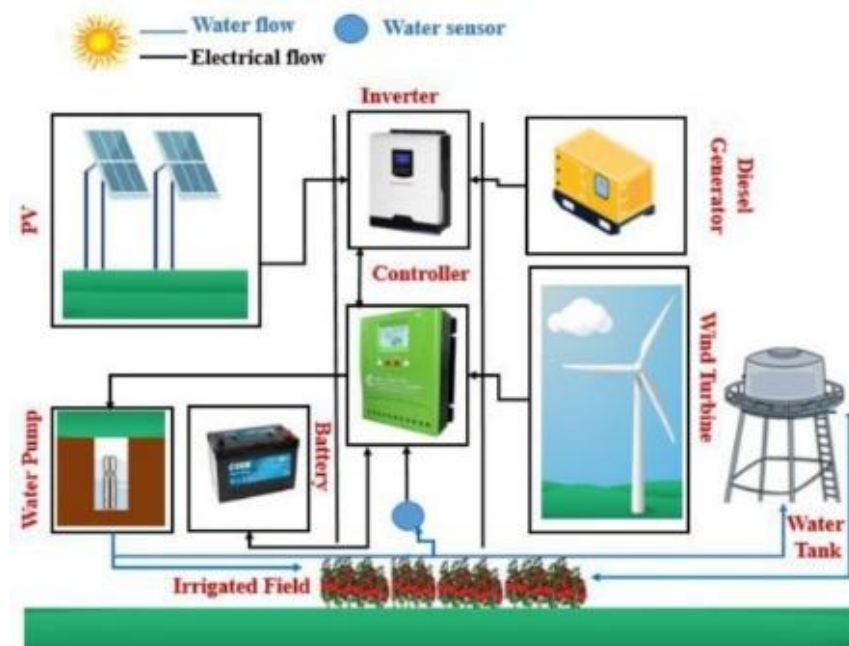


Fig. 1.46. PV-diesel-eolienne pumping system

1.6.3 Types of pumps used in solar pumping

Surface pump: Surface pumps are installed above the water source and are suitable for shallow water levels, generally less than 7–8 meters [32].



Fig. 1.47. Surface pump

-Submersible pump: Submersible pumps operate underwater and are installed directly inside boreholes or wells; its operation depth starts from 15m to 91m, and with specialized modules can go up to 300m.



Fig. 1.48. 300m Water head stainless steel borehole submersible water pump

-Centrifugal pump: Centrifugal pumps use rotating impellers to impart kinetic energy to water, its operating depth can go from 6m to 7m up to 300m.



Fig. 1.49. Centrifugal pump

-Positive displacement pump: These pumps move a fixed volume of water during each cycle, its operating depth depends on its location, its most suitable for moving thick fluids like oil or syrups, for its consistent flow without getting clogged.[32].



Fig. 1.50. Positive displacement pump

1.6.4 Advantages and limitations of water pumps technologies

The following table summarizes the different technologies of water pumps, their advantages and limitations:

Water pump type	Advantages	Limitations
Surface pumps	Easy maintenance, Low installation cost	Limited suction depth
Submersible pumps	High efficiency, Suitable for deep wells, Reduced cavitation risk	Higher installation cost, More difficult maintenance
Centrifugal pumps	High flow rates, Low maintenance	Pressure limits, cavitation risks
Positive displacement pumps	Consistent flow, high pressure, strong suction	Higher maintenance, Overpressure risk, Weaker flow

Table 9: Advantages and limitations of water pump technologies

1.6.5 Agricultural Electrification

Agricultural electrification consists of providing power to equipment and installations such as irrigation systems, water pumps, storage facilities, and greenhouses, it enhances farms productivity and supports the integration of renewable energy technologies in rural areas.

1.6.6 Energy requirements in Agriculture

Energy consumption in agriculture is primarily driven by mechanical, electrical, and thermal needs associated with irrigation, crop processing, storage, and environmental regulation

Unlike industrial loads, agricultural energy demand is highly seasonal and strongly dependent on climatic conditions and cultivation cycles; typical energy requirements include water pumping, refrigeration, ventilation, lighting, and automation systems; these loads may vary significantly during the day, with peak demands often coinciding with irrigation schedules or storage cooling periods, in remote agricultural systems, ensuring a stable and continuous energy supply is a major challenge due to the variability of both energy resources and load demand [1].

The increasing adoption of renewable energy systems, particularly photovoltaic-based solutions, offers a viable alternative to conventional diesel-powered agricultural electrification. These systems reduce operating costs, minimize environmental impact, and improve energy autonomy in rural areas.

1.6.7 Agricultural greenhouses

Greenhouses are controlled agricultural environments designed to optimize crop growth by regulating temperature, humidity, light, and ventilation, these systems require continuous energy input to maintain stable climatic conditions, particularly in regions with extreme temperatures [1] [2].

Energy consumption in greenhouses typically includes ventilation fans, heating systems, irrigation pumps, and artificial lighting; in cold climates, heating represents the dominant load, while in hot and arid climates, ventilation and cooling systems are more significant.

The integration of renewable energy systems, especially photovoltaic and thermal solar technologies, enables partial or full energy autonomy for greenhouse operations, this reduces dependence on conventional energy sources and improves operational sustainability.



Fig. 1.51. Desert greenhouses

1.6.8 Barley cultivation and fodder production

Barley cultivation constitutes an important agricultural activity in arid and semi-arid regions due to its adaptability to harsh climatic conditions and relatively low water requirements compared with other cereal crops. In southern Algeria, particularly in Saharan regions, barley is widely used as animal feed and represents a strategic resource for livestock production.

The successful cultivation of barley depends largely on the availability of water during critical growth stages; consequently, irrigation systems play a central role in maintaining crop productivity, especially in areas characterized by low and irregular rainfall; the extraction and distribution of groundwater generally require electrical pumping systems, making energy availability a key factor in agricultural performance [1].



Fig. 1.52. Barley harvest in Adrar

The adoption of photovoltaic-powered pumping systems has emerged as an attractive solution for barley cultivation in remote regions; the coincidence between high solar irradiance levels and irrigation requirements allows photovoltaic systems to provide a reliable and

sustainable energy source for water pumping operations. This reduces dependence on fossil fuels, lowers operating costs, and contributes to the long-term sustainability of agricultural activities. Furthermore, modern agricultural practices increasingly employ automated irrigation systems, soil moisture sensors, and monitoring equipment to optimize water use efficiency; these technologies require a stable electrical supply, further emphasizing the importance of renewable energy-based agricultural electrification systems.

Conclusion

in this chapter, we presented the general concepts related to renewable energy systems and their applications

We first reviewed the main renewable energy sources, highlighting their operating principles, advantages, limitations, and potential contribution to sustainable agricultural development. Particular attention was given to solar photovoltaic energy, which was identified as the most suitable renewable resource for the study area due to its high solar potential and availability throughout the year, we then examined the fundamental principles of photovoltaic energy conversion, including solar radiation, photovoltaic cell technologies, and the various components of photovoltaic systems. The operation of charge controllers, MPPT techniques, converters, inverters, energy storage systems, and protection devices was also discussed in order to establish a comprehensive understanding of photovoltaic system design and operation.

Furthermore, we analyzed the different types of photovoltaic systems and hybrid architectures, solar pumping with emphasis on photovoltaic–diesel configurations commonly used in isolated applications, finally, we highlighted the energy requirements of the agricultural sector and the importance of reliable energy solutions for applications such as water pumping and agricultural production.

CHAPITRE II:

Study Site, Load Assessment and System Sizing

2.1.1 Presentation of the study area

The study area is the agricultural development perimeter known as Kabertene, located in the Wilaya of Adrar, within the commune of Sebaa Tamentit; this perimeter is part of the ODAS development portfolio dedicated to agricultural valorization in Saharan region; Kabertene is situated approximately 115 km from the wilaya capital (CLW) and around 80 km from the local commune center (CLC); The site is relatively isolated but accessible through a road network located about 15 km away, while the nearest electrical network connection is approximately 16 km from the perimeter, indicating a partially off-grid energy context, Its equipped with a 200m deep artesian well, capable of supplying water with a debit of 30l per second.

The geographical coordinates of the site, as provided in the official ODAS technical fiche, are:

-Longitude (Y): 0.303

-Latitude (X): 28.362

(check appendix 1)

The perimeter covers a total area of approximately 1000 hectares, divided into several spatial agricultural blocks (B01 to B10), as shown in the official cartographic plan of the site

(check appendix 2)

2.1.2 Climatic conditions

The climate of Kabertene, located in the Saharan zone of Adrar, is classified as hot desert climate with very high aridity

The site experiences extreme environmental conditions that strongly influence agricultural planning and irrigation system design such as:

- High aridity throughout the year
- High temperatures
- Strong solar radiation
- Very low humidity

- Strong winds

Due to these conditions, the region requires continuous irrigation support, as natural precipitation is insufficient for crop development

2.1.2.1.1 Solar potential of Adrar

The wilaya of Adrar presents an exceptional solar resource potential, making it one the most suitable regions for photovoltaic energy systems in Algeria; this potential is confirmed by simulation data obtained from PVsyst software, which provides monthly global horizontal irradiation value for the study area

Global Horizontal Irradiation (kWh/m ² /day)													
Site	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Avg.
Adrar	3.68	4.74	5.90	6.84	7.32	7.70	7.45	6.96	5.86	4.60	3.83	3.32	5.69

Table 10: Data source: NASA-SSE / PVsyst | Unit: kWh/m²/day

- Maximum irradiation: 7.70 kWh/m²/day (June)
- Minimum irradiation: 3.32 kWh/m²/day (December)

2.1.2.1.2 Water resources in Adrar

The Wilaya of Adrar relies almost entirely on groundwater resources to meet its water demand for domestic use and agricultural irrigation, due to the absence of permanent surface water sources in the Saharan environment.

Water is generally extracted from significant depths, depending on the aquifer layer:

- Shallow exploitation zones: around 80m
- Deep exploitation zones: up to 200m.

In agricultural perimeters such as Kabertene, groundwater is the only reliable source for irrigation; it is used to supply:

- Open-field crops
- Greenhouse production systems
- Drip and pressurized irrigation networks

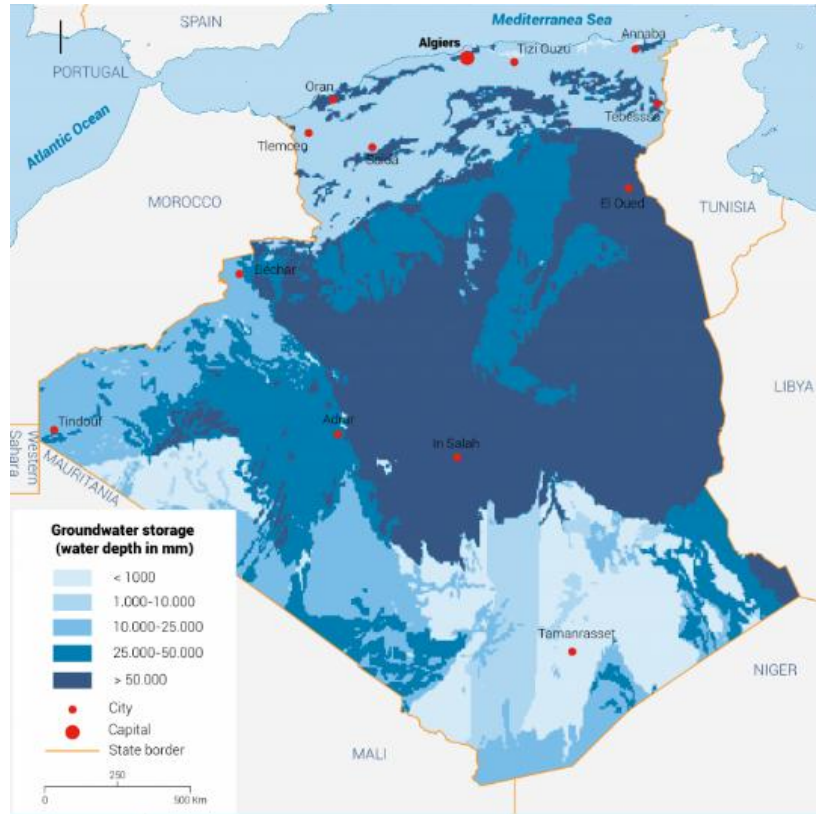


Fig. 2.1. Groundwater storage in Algeria

2.2 General organization of the farm

The proposed organization of the site is designed to combine open-field cultivation and protected agriculture while ensuring efficient water and energy management.

- **Barley cultivation area**

A 1-hectare barley field is planned within the perimeter; the field is organized in a regular rectangular shape to facilitate irrigation network installation, crop management, and machinery access

Barley is selected due to its adaptability to arid environments and its importance as a strategic cereal crop.

- **Greenhouse area**

In addition to the barley field, the project includes twelve modern agricultural greenhouses dedicated to the cultivation of tomatoes and peppers, two high-value crops widely grown under protected agriculture in arid regions.

For the purposes of this study, each greenhouse is assumed to have an area of approximately 500m² (50m x 10m), resulting in a total greenhouse surface of:

$$12 \times 500 = 6000m \quad (2.1)$$

The greenhouses are arranged in parallel rows to optimize land use, facilitate access for agricultural operations, and simplify the installation of irrigation and water distribution systems; their protected environment allows better control of temperature, humidity, and water consumption, leading to higher crop productivity compared with open-field cultivation.

- **Water supply infrastructure**

According to the fact sheet of industrial agriculture development office, the targeted is equipped with a forage of a 200m depth of and an average flow rate of 30 liters per second, ready to be extracted through a hybrid pumping system.

- **Irrigation and water requirements**

Barley is commonly irrigated using sprinklers, in Saharan conditions, it typically requires:

4000-6000 m³/ha per growing season

-For our design we will take a value of 5000m³/ha

Assuming a growing cycle of 120days:

$$\frac{5000}{120} = 41.7m^3/day \quad (2.2)$$

One crop cycle per year: 5000m³/year

Greenhouses (tomatoes and peppers): are irrigated through drip irrigation methods to save **water** and deliver water directly to the root zone.

-Tomatoes:

A typical annual water requirement of tomatoes ranges between 6000 – 8000 m³/ha/year

-For our design we will take a value of 7000 m³/ha/year

-Assuming 0.3ha of tomatoes: $0.3 \times 7000 = 2100m^3/year$ (2.3)

-Daily demand: $\frac{2100}{365} = 5.75m^3/day$ (2.4)

Peppers:

The annual water requirement of peppers: 5000 – 7000m³/ha/year
For our design we will take a value of 6000m³/ha/year

-Assuming 0.3ha of peppers: $0.3 \times 6000 = 1800m^3/year$ (2.5)

-Daily demand: $\frac{1800}{365} = 4.93m^3/day$ (2.6)

-Total greenhouse demand: $4.93 + 5.75 = 10.7 \text{ m}^3/\text{day}$ (2.7)

During summer, the peak demand may reach 15 - 20 m^3/day

- **Total farm water requirements during Barely growing season:**

The following table summarizes the water requirement during barley growing season:

Crop	Area	Irrigation type	Daily demand	Annual demand
Barley	1 ha	Sprinkler	42 m^3/day	5,000 m^3/year
Tomatoes	0.3 ha	Drip	6 m^3/day	2,100 m^3/year
Peppers	0.3 ha	Drip	5 m^3/day	1,800 m^3/year
Total	1.6 ha	-----	53 m^3/day	8,900 m^3/year

Table 11: daily water requirements of the farm during growing season

- **Total farm water requirements during Barely harvest season**

The following table summarizes the water requirement during barley harvesting season:

Crop	Area	Irrigation type	Daily demand	Annual demand
Barley	1 ha	Sprinkler	0 m^3/day	5,000 m^3/year
Tomatoes	0.3 ha	Drip	6 m^3/day	2,100 m^3/year
Peppers	0.3 ha	Drip	5 m^3/day	1,800 m^3/year
Total	1.6 ha	-----	11 m^3/day	8,900 m^3/year

Table 12: daily water requirements of the farm during harvesting season

2.3 Water tank sizing

The water tank serves as hydraulic storage, allowing the pump to operate when solar energy is available while ensuring irrigation can continue even when solar production decreases

1. **Daily water demand:** from the previous calculations:

$$Qd = 53 \text{ m}^3/\text{day} \quad (2.8)$$

Qd=daily water demand

2. **Tank autonomy**

We going to choose a 2 days autonomy practice to ensure water irrigation in case of solar production is not available.

$$Vt = Qd \times N \quad (2.9)$$

Vt = tank volume (m^3)

Qd = daily demand (m^3/day)

N = number of autonomy days

$$Vt = 53 \times 2 = 106 \text{ m}^3 \quad (2.10)$$

3. Safety factors

To account for:

- Evaporation losses
- Future expansion
- Operational reserve

A safety factor of 10%-20% is usually added

So, the total tank storage capacity:

$$Vt = 106 \times 1.15 = 122m^3$$

2.4 Water-pump sizing

2.4.1 Required flow rate

The required pumping flow rate is determined from the daily irrigation water demand and the selected pumping duration; for a daily water requirement of approximately 53 m³ and an operating period of 6 hours per day, the required flow rate can be calculated through the following formula:

$$Q = \frac{Vd}{t} \quad (2.11)$$

Q = required flow rate (m³/h)

Vd = daily water demand (m³/day)

t = pumping duration (h/day)

Considering water-pump operates 8 hours a day :

$$Q = \frac{53}{8} = 6.62m^3/h \quad (2.12)$$

2.4.2 Total Dynamic Head (TDH)

It's the overall effective vertical distance a pump needs to raise a liquid, considering differences in elevation, resistance caused by pipe wall friction, and the systems required operating pressure.

$$TDH = H_{statique} + H_{friction} + H_{pression} + H_{speed} \quad (2.13)$$

2.4.2.1 Pipe friction losses

Our pipe parameters:

Parameter	Value
Flow rate Q	6.6 m ³ /h
Pipe length (rising main)	200 m (well depth) + 10m surface =210m
Pipe type	HDPE rising main (submersible)

Table 13: Pipe parameters

According to the pipe friction table:

Tuyau		Q m ³ /h	1	3	6	9	12	18	24	30	36	42	48	60	90	120	180	240	300	360	420
		Q l/min	16	50	100	150	200	300	400	500	600	700	800	1000	1500	2000	3000	4000	5000	6000	7000
G 1"	DN 25		2,7	21	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
			0,6	1,7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
G 1" 1/4	DN 32		0,7	5,5	22	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
			0,35	1	2,1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
G 1" 1/2	DN 40		-	1,8	7	14	23	-	-	-	-	-	-	-	-	-	-	-	-	-	-
			-	0,7	1,35	1,9	2,5	-	-	-	-	-	-	-	-	-	-	-	-	-	-
G 2"	DN 50		-	0,5	2,2	4	8	17	28	-	-	-	-	-	-	-	-	-	-	-	-
			-	0,4	0,8	1,25	1,5	2,5	3,2	-	-	-	-	-	-	-	-	-	-	-	-
G 2" 1/2	DN 65	HL	-	-	0,6	1,2	2,1	4,2	8	12	17	22	28	-	-	-	-	-	-	-	-
		v	-	-	0,5	0,75	1	1,4	2	2,5	3	3,4	4	-	-	-	-	-	-	-	-
	DN 80		-	-	-	-	0,8	1,6	2,8	4,2	6,5	7,5	10,5	15	-	-	-	-	-	-	-
			-	-	-	-	0,7	0,95	1,25	1,6	2	2,1	2,6	3,3	-	-	-	-	-	-	-
	DN 100		-	-	-	-	-	0,55	0,9	1,4	2	2,4	3,5	5	11	20	-	-	-	-	-
			-	-	-	-	-	0,6	0,8	1,1	1,25	1,4	1,6	2	3,2	4	-	-	-	-	-
	DN 125	m/100m	-	-	-	-	-	-	-	-	-	0,9	1,2	1,8	4	6,5	15	-	-	-	-
		m/s	-	-	-	-	-	-	-	-	-	0,95	1,1	1,4	2	2,7	4	-	-	-	-
	DN 150		-	-	-	-	-	-	-	-	-	-	0,6	1,5	2,5	5	8	14	-	-	-
			-	-	-	-	-	-	-	-	-	-	0,9	1,4	1,7	2,7	3,5	4,8	-	-	-
	DN 200		-	-	-	-	-	-	-	-	-	-	-	0,4	0,6	1,3	2	3,5	4,6	6,5	-
			-	-	-	-	-	-	-	-	-	-	-	0,8	1	1,6	2	2,6	3	3,5	-
	DN 250		-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,4	0,7	1,1	1,6	2
			-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	1,3	1,6	2	2,3
	DN 300		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,3	0,45	0,7	0,9
			-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,9	1,25	1,4	1,6

Fig. 2.2. Pipe friction table

Looking at Q = 6 m³/h column (closest to 6.6) interpolating between 6 and 9 m³/h:

We choose DN 50 (G2"), the following table summarizes its parameters:

At Q=6.6 m ³ /h	Value
HL	≈ 3.0 m/100m
Velocity v	≈ 0.95 m/s

Table 14: Velocity parameters of DN 50 (G2")

Velocity is in the acceptable range (0.8-1.2m/s recommended for rising mains)

2.4.2.2 Linear friction losses

$$J_L = \frac{HL}{100} \times L = \frac{3.0}{100} \times 210 = 6.3 \text{ m} \quad (2.14)$$

2.4.2.3 Singular (minor) losses from fittings (figure 1.56)

According to the fitting friction loss sheet

Vitesse de l'eau m/sec	Courbes à angle vif α					$\alpha = 90^\circ$ courbes à angle arrondi					Vannes standard	Clapets de pied	Clapets de non retour
	$\alpha = 30^\circ$	$\alpha = 40^\circ$	$\alpha = 60^\circ$	$\alpha = 80^\circ$	$\alpha = 90^\circ$	$\frac{d}{R} = 0,4$	$\frac{d}{R} = 0,6$	$\frac{d}{R} = 0,8$	$\frac{d}{R} = 1,0$	$\frac{d}{R} = 1,5$			
0,4	0,43	0,52	0,71	1,0	1,2	0,11	0,13	0,16	0,23	0,43	0,23	32	31
0,5	0,67	0,81	1,1	1,6	1,9	0,18	0,21	0,26	0,37	0,67	0,37	33	32
0,6	0,97	1,2	1,6	2,3	2,8	0,25	0,29	0,36	0,52	0,97	0,52	34	32
0,7	1,35	1,65	2,2	3,2	3,9	0,34	0,40	0,48	0,70	1,35	0,70	35	32
0,8	1,7	2,1	2,8	4,0	4,8	0,45	0,53	0,64	0,93	1,7	0,95	36	33
0,9	2,2	2,7	3,6	5,2	6,2	0,57	0,67	0,82	1,18	2,2	1,20	37	34
1,0	2,7	3,3	4,5	6,4	7,6	0,7	0,82	1,0	1,45	2,7	1,45	38	35
1,5	6,0	7,3	10	14	17	1,6	1,9	2,3	3,2	6	3,3	47	40
2,0	11	14	18	26	31	2,8	3,3	4,0	5,8	11	5,8	61	48
2,5	17	21	28	40	48	4,4	5,2	6,3	9,1	17	9,1	78	58
3,0	25	30	41	60	70	6,3	7,4	9	13	25	13	100	71
3,5	33	40	55	78	93	8,5	10	12	18	33	18	123	85
4,0	43	52	70	100	120	11	13	16	23	42	23	150	100
4,5	55	67	90	130	160	14	21	26	37	55	37	190	120
5,0	67	82	110	160	190	18	29	36	52	67	52	220	140

Fig. 2.3 Fittings friction losses

According to the friction loss sheet the following table of loss values is presented:

Fittings	Loss (mm WC)	Loss (m)
Check valve	35	0.038 m
Gate valve	38	0.038 m
2× 90° short radius elbow (d/R=0.6)	0.82 x 2	0.0016 m

Table 15: Friction losses of chosen fittings.

According to the data sheet:

$$J_{\text{singular}} \approx 0.035 + 0.038 + 0.002 \approx 0.075 \text{ m} \quad (2.15)$$

Our Total Dynamic Head is summarized in the following table:

Component	Estimate
Static head (well depth)	200 m
Drawdown (dynamic level drop)	+8 m (confined aquifer)
Pipe friction losses (DN50, 210m)	+6.4 m
Pressure at delivery (tank + distribution)	+0 m (Ground level tank)
Total Dynamic Head (TDH)	215 m

Table 16: Total dynamic head depth

2.4.3 Hydraulic power

$$P_{\text{hydraulic}} = \frac{\rho \cdot g \cdot Q \cdot TDH}{3600} = \frac{1000 \times 9.81 \times 6.6 \times 215}{3600} \approx 4 \text{ kW} \quad (2.16)$$

From DAB curve and datasheet:

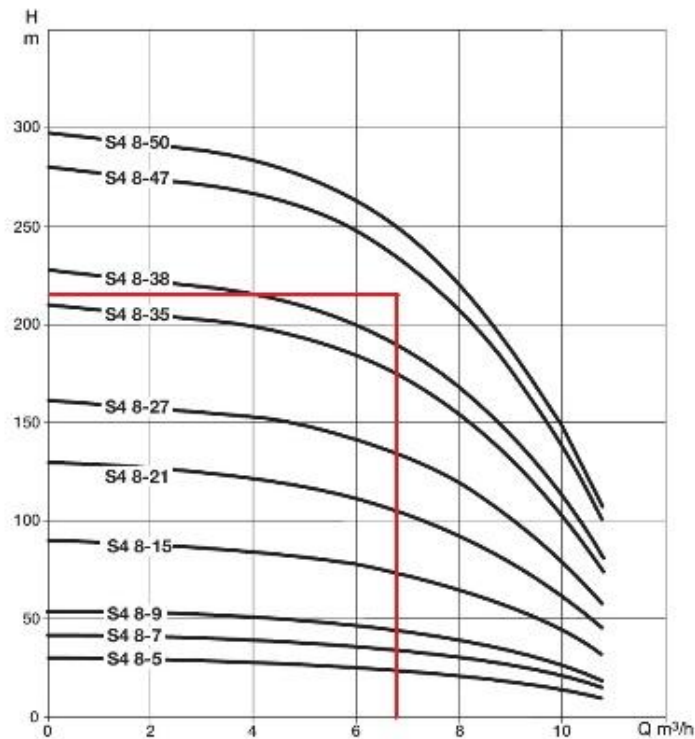


Fig. 2.4. DAB S4 8 submersible pumps power curves

Our (THD,Q) point falls between two submersible pumps which are :

- S4 8-38
- S4 8-47

The selected pump is S4 8-38, 40LT 3x400V

It has a operational depth of 230m, fewer stages to wear, and lower nominal power, also its made of stainless steel to account for salty groundwater in Saharan region of algeria.



MODEL	ELECTRICAL DATA					Ø mm	H mm	DNM	PACKING DIMENSIONS			VOLUME m³	WEIGHT kg
	MOTOR	POWER INPUT 50 Hz	P2 NOMINAL		In A				L/A	L/B	H		
S4 8/47	40LT	3 x 230 V ~	7.5	10	29.2	99	2883	2"	280	230	3380	0.198	71.9
	40LT	3 x 400 V ~	7.5	10	16.9	99	2883	2"	280	230	3380	0.198	71.9
	466T	3 x 230 V ~	7.5	10	30.1	99	2909	2"	280	230	3380	0.198	74.8
	466T	3 x 400 V ~	7.5	10	17.4	99	2909	2"	280	230	3380	0.198	74.8
S4 8/38	40LT	3 x 230 V ~	5.5	7.5	22.8	99	2555	2"	280	230	2820	0.182	63.4
	40LT	3 x 400 V ~	5.5	7.5	13.1	99	2555	2"	280	230	2820	0.182	63.4
	466T	3 x 230 V ~	5.5	7.5	24.2	99	2581	2"	280	230	2820	0.182	66.6
	466T	3 x 400 V ~	5.5	7.5	14	99	2581	2"	280	230	2820	0.182	66.6

Fig. 2.5. Operating characteristics of DAB S4 8-43 and S4 8-47

For the booster pump dedicated to irrigation and water suction from the tank a 1.1kW three phase surface pump is largely sufficient in this scenario.

	Câble de référence	5 m (1x)
	Nombre de référence	3+g
	Tension	Triphase 380V / 400V
	Fréquence	50 Hz
	Puissance	1,1 kW
	Poids	21 kg

Fig. 2.6. Technical data sheet of CPM 160C

2.5 Cold storage room

The cold room runs 24h a day, the compressor cycles on and off but must maintain temperature continuously

Barley is usually stored in silos or warehouses, not cold rooms.

So our refrigeration unit sizing is only determined by greenhouse production.

Tomatoes and peppers yield typically range between 20 and 25 kg /m².

Taking that into account, the annual production of the greenhouse area can be estimated as:

$$M_p = A_g \times Y \quad (2.17)$$

- M_p = annual production (kg),
- A_g = greenhouse area (m²),
- Y = average yield (kg/m²).

For a greenhouse area of 6000m², the annual production becomes:

$$M_p = 6000 \times 25 = 150000 \text{ kg} \quad (2.18)$$

Or 150t /year

In practice, agricultural cold storage facilities are not designed to store the entire annual production simultaneously; a storage capacity corresponding to approximately 10% of annual production is generally sufficient for short-term preservation and market regulation purposes. Therefore, the required storage capacity can be estimated as:

$$M_s = 0.10 \times M_p \quad (2.19)$$

$$M_s = 0.10 \times 150000 = 15000 \text{ kg} \quad (2.20)$$

Assuming an average storage density of **300 kg/m³** for palletized vegetables, the useful storage volume is:

$$V_s = \frac{M_s}{300} \quad (2.21)$$

$$V_s = \frac{15\,000}{300} \quad (2.22)$$

$$V_s = 50 \, m^3$$

To account for circulation aisles, pallets, handling space, and refrigeration equipment, a correction factor is applied. Consequently, the total cold room volume is estimated between **90 and 100 m³**.

A practical configuration may therefore consist of a refrigerated chamber with dimensions of approximately:

$$8 \times 4 \times 3 \, m \quad (2.23)$$

The refrigeration capacity required for fresh vegetable storage at temperatures between 2°C and 8°C can be approximated using a specific cooling load of 70 W/m³:

$$Q_c = V \times q_s \quad (2.24)$$

- Q_c = cooling capacity (W)
- V = Storage volume (m³)
- q_s = specific cooling load (W/m³)

$$Q_c = 96 \times 70 = 6720W \quad (2.25)$$

Assuming a refrigeration system with a coefficient of performance (COP) equal to 2.5, the average electrical power demand becomes:

$$P_e = \frac{Q_c}{COP} = \frac{6.7}{2.5} = 2.68 \, kW \quad (2.26)$$

Considering an average compressor operating cycle of 50%, the daily electrical energy consumption is estimated as

$$E_d = 2.68 \times 24 \times 0.5 = 32kWh/day \quad (2.27)$$

2.6 Storage hangar and residential building

The storage hangar generally presents relatively low electrical demand, mainly associated with lighting, ventilation, security systems, and occasional use of small electrical tools. Considering a medium-sized agricultural hangar with basic services, the average installed power can be estimated at approximately **1 kW**, corresponding to a daily energy consumption of about **5–8 kWh/day**. The residential building constitutes a permanent electrical load and includes lighting, refrigeration, domestic appliances, water supply equipment, communication

devices, and air-conditioning systems; for the purpose of this study, the house is assumed to have an average electrical demand of:

$$P_{\text{house}} = 3 \text{ kW}$$

Assuming an average daily utilization factor of 30–40%, the daily energy consumption can be estimated as:

$$E_{\text{house}} = 3 \times 24 \times 0.35 \quad (2.28)$$

$$E_{\text{house}} = 25.2 \text{ kWh/day}$$

The combined energy demand of the storage hangar and residential building is therefore estimated between:

$$30 \text{ to } 35 \text{ kWh/day}$$

2.7 Total Electrical Loads

The farm's energy loads are divided according to the growing and harvest seasons the following two tables summarizes the electrical loads:

During barley growing season:

Loads	Power	Operation hours/day	Daily Energy
Submersible Pump	5.5 kW	8 h	44 kWh
Booster pump	1.1 kW	7 h	7.7 kWh
Farmer house and storage unit	3.0 kW	12 h	36 kWh
Cold storage unit	2.68 kW	24 h	48 kWh
TOTAL	11.6 kW	-	135.7 kWh/day

Table 17: Farm's electrical loads during barley growing season

During barley harvest season:

Loads	Power	Operation hours/day	Daily Energy
Submersible Pump	5.5 kW	2 h	11 kWh
Booster pump	1.1 kW	2 h	2.2 kWh
Farmer house and storage unit	3.0 kW	12 h	36 kWh
Cold storage unit	2.0 kW	24 h	48 kWh
TOTAL	11.6 kW	-	97.2 kWh/day

Table 18: Farm's electrical loads during barley harvest season

2.8 Photovoltaic system sizing

Photovoltaic system sizing is the process of matching energy needs with available solar resources to determine the correct size of system components; it involves estimating the load demand, evaluating solar potential, and selecting suitable capacities for panels, inverters, and batteries while accounting for losses and system constraints, the goal is to ensure a reliable supply of energy that meets consumption throughout different conditions of the year.

2.8.1 System sizing method

2.8.1.1 *The most unfavorable month method*

In this method, the potential energy yield is calculated for a critical one-month period, referred to as the ‘least favorable month’.

This month corresponds to the period with the lowest solar radiation levels of the year (December in Kabertene Adrar, where radiation is approximately 3.32 kWh/m²/day).

2.8.1.2 *Annual average method*

This method is based on the average solar radiation over the whole year (in Kabertene Adrar region, the average annual radiation is approximately 5.69 kWh/m²/day)

2.8.2 PV array sizing using the annual average method

We adopted the annual average method for calculating the daily energy balance because it provides a representative consumption value for the entire year, avoiding the oversizing that would result from using peak summer values, while ensuring adequate coverage of the system’s actual energy needs.

We can calculate the necessary peak power to guarantee the proper operation of the PV system using the following formula

$$P_c \geq \frac{(E_{needs} \times P_i)}{E_i \times PR} \quad (2.29)$$

P_c = Peak power of the PV array (kWp)

E_{needs} = Daily energy consumed (kWh/day)

E_i = Daily solar energy (kWh/m²/day)

P_i = Power output under STC conditions (1kW/m²)

PR= Performance ratio

- We evaluate the power ratio PR=0.60 due to the site conditions (dust, high temperature); and E_i =5.69 (Table 10)

So for December we have a IGP of 3.32 kWh/m²/day, the peak power is determined as:

$$\frac{136 \times 1}{5.69 \times 0.60} \quad (2.30)$$

$$P_c \approx 40 \text{ kWp}$$

We conclude that a peak-power of 40 kWc is sufficient to ensure the proper functioning of our farm covering most of the year.

The diesel generator is therefore considered as a backup source intended for worst scenarios, such as prolonged periods of adverse weather conditions, maintenance operations, or system failures.

2.8.3 Choice of photovoltaic modules

For this hybrid system, we selected the module **JA SOLAR 585 Wp N-type bifacial monocrystalline solar panel**

We have chosen this module for its high power rating, allowing a reduction in the number of panels required and therefore minimizing installation area, its silicone N-type monocrystalline technology, which allows higher efficiency and lower degradation overtime, Another important factor which is Bifacial technology, that enable additional energy production from reflected sunlight especially in high-albedo environments such as desert areas, And lastly, because of its availability in the Algerian market.

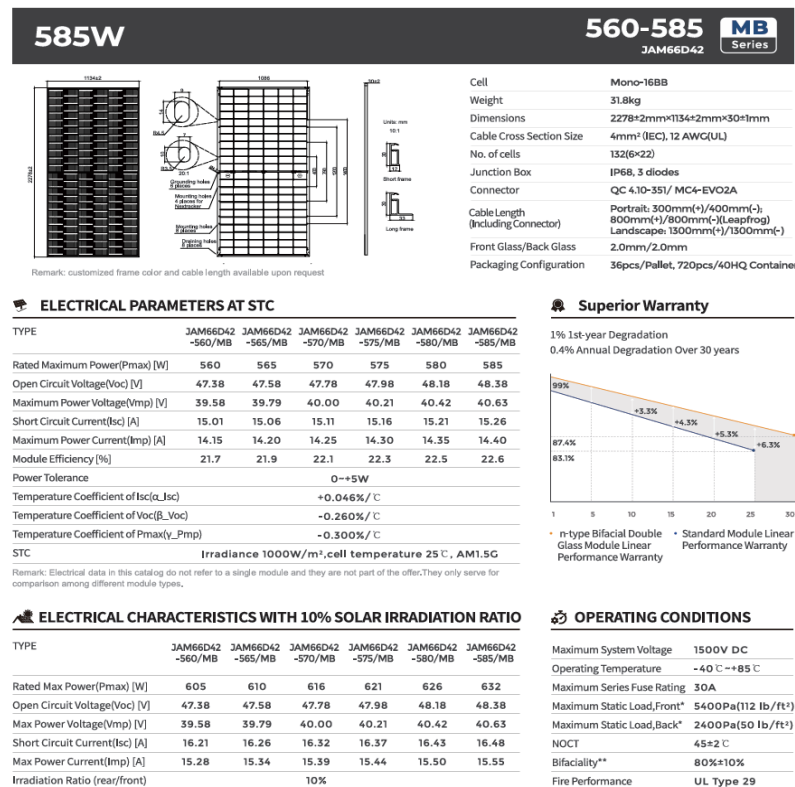


Fig. 2.7. Ja solar module Data sheet.

And lastly, because its availability in the Algerian market.

2.8.4 Determination of number of modules

$$P_{total} = 40kW_c = 40\,000\,W_c$$

$$P_{module} = 585\,W_c$$

$$Nbre\ of\ modules = \frac{40000}{585} \approx 69\ modules$$

2.8.5 Selecting the hybrid inverter

We chose the **Sun-40K-SG01HP3 three-phase hybrid inverter**, a device designed to manage photovoltaic energy, battery storage, and AC loads within a single integrated system; it is a hybrid inverter equipped with 4 MPPT trackers, high efficiency power conversion, and compatibility with lithium battery and Lead acid storage systems.

We also chose a **three-phase configuration** because the irrigation pump is driven by a three-phase asynchronous motor; this ensures balanced voltage supply, higher operational efficiency, improved starting torque, and stable performance under variable hydraulic loads, which is essential for continuous agricultural pumping applications.

Model	SUN-29.9K-SG01HP3 -EU-BM3	SUN-30K-SG01HP3 -EU-BM3	SUN-35K-SG01HP3 -EU-BM3	SUN-40K-SG01HP3 -EU-BM4	SUN-50K-SG01HP3 -EU-BM4
Battery Input Data					
Battery Type	Lithium-Ion				
Battery Voltage Range (V)	160-800				
Max. Charging Current (A)	50+50				
Max. Discharging Current (A)	50+50				
Number of Battery Input	2				
Charging Strategy for Li-Ion Battery	Self-adaption to BMS				
PV String Input Data					
Max. DC Input Power (W)	38870	39000	45500	52000	65000
Max. DC Input Voltage (V)	1000				
Start-up Voltage (V)	180				
MPPT Range (V)	150-850				
Full Load DC Voltage Range (V)	360-850	360-850	420-850	360-850	450-850
Rated DC Input Voltage (V)	600				
PV Input Current (A)	36+36+36	36+36+36	36+36+36	36+36+36+36	
Max. PV I _{sc} (A)	55+55+55	55+55+55	55+55+55	55+55+55+55	
No.of MPP Trackers	3			4	
No.of Strings per MPP Tracker	2+2+2			2+2+2+2	
AC Output Data					
Rated AC Output Active Power (W)	29900	30000	35000	40000	50000
Max. AC Output Active Power (W)	29900	30000	38500	44000	55000
AC Output Rated Current (A)	45.4/43.4	45.5/43.5	53.1/50.8	60.7/58	75.8/72.5
Max. AC Output Current (A)	45.4/43.4	50/47.8	58.4/55.8	66.7/63.8	83.4/79.7
Max. Three-phase Unbalanced Output Current (A)	60	60	60	70	83.3
Max. Continuous AC Passthrough (A)	200				
Peak Power (Off Grid)	1.5 time of rated power, 10 S				
Generator Input/Smart Load /AC Couple Current (A)	45.4 / 200 / 45.4	45.5 / 200 / 45.5	53.1 / 200 / 53.1	60.7 / 200 / 60.7	75.8 / 200 / 75.8
Power Factor Adjustment Range	0.8 leading to 0.8 lagging				
Output Frequency and Voltage	50/60Hz; 3L/N/PE 220/380, 230/400Vac				
Grid Type	Three Phase				
Total Harmonics Current Distortion (THDi)	< 3% (of nominal power)				
DC Current Injection	< 0.5% I _n				
Efficiency					
Max. Efficiency	97.60%				
Euro Efficiency	97.00%				
MPPT Efficiency	99.90%				
Protection					
Integrated	Anti-islanding Protection, PV String Input Reverse Polarity Protection, Insulation Resistor Detection, Residual Current Monitoring Unit, Output Over Current Protection, Output Shorted Protection, Surge Protection, Arc Fault Circuit Interruption (AFCI optional)				
Over Voltage Category	DC Type II/AC Type III				
Certifications and Standards					
Grid Regulation	IEC 61727, IEC 62116, CEI 0-21, EN 50549, NRS 097, RD 140, UNE 217002, OVE-Richtlinie R25, G99, VDE-AR-N 4105				
Safety EMC / Standard	IEC/EN 61000-6-1/2/3/4, IEC/EN 62109-1, IEC/EN 62109-2				

Fig. 2.8. Sun-40K-SG01HP3 Datasheet

We also chose a **three-phase configuration** because the irrigation pump is driven by a three-phase asynchronous motor; this ensures balanced voltage supply, higher operational

efficiency, improved starting torque, and stable performance under variable hydraulic loads, which is essential for continuous agricultural pumping applications.

2.8.6 Photovoltaic array configuration

According to the solar module electrical characteristics:

$V_{oc} = 48.38 \text{ V}$, $V_{mp} = 40.63 \text{ V}$, $I_{sc} = 15.26 \text{ A}$ and $I_{mp} = 14.40 \text{ A}$

The number of modules connected in series is determined according to the maximum DC voltage allowed by the inverter (Max input voltage=1000V):

$$N_s = \frac{V_{imax}}{V_{oc}} = \frac{1000}{48.38} = 20.66 \approx 20 \text{ modules} \quad (2.31)$$

Solar panels open-circuit voltage increases during cold weather so we must apply a cold temperature correction, temperature in winter mornings in Adrar can drop up to 6 degrees Celsius.

$$(2.32) \quad V_{oc}(cold) = V_{oc} \times (1 + (25 - t_{min}) \times 0.0025)$$

$$(2.33) \quad V_{oc}(cold) = 48.38 \times (1 + (25 - 6) \times 0.0025)$$

$$V_{oc}(cold) = 50.67 \text{ V}$$

$$N_s(new) = \frac{V_{imax}}{V_{oc_cold}} = \frac{1000}{50.67} = 19.75 \approx 19 \text{ modules} \quad (2.34)$$

The number of parallel strings is determined by the maximum current accepted by each MPPT tracker, which is 36A, since the operating current of string is $I_{mp,string} = 14.40 \text{ A}$,

$$\frac{36}{14.40} \approx 2.5 = 2 \text{ parallel strings per MPPT}. \quad (2.35)$$

The total number of modules connected in series and parallel must not exceed the maximum DC voltage allowed by the inverter which is 19 modules.

The inverter handles roughly 40 kW of max dc power, our total 69 panels produce 40kWp power at STC conditions, therefore they are fully compatible.

The following table summarizes the panels strings configuration with the inverter's MPPTs:

String	Panels	MPPT
String 1	17	MPPT 1
String 2	17	MPPT 2
String 3	18	MPPT 3
String 4	17	MPPT 4
TOTAL	69	-

Table 19: Panels strings connections to MPPTS

2.8.7 Battery bank sizing

Choosing the battery bank voltage depends on the inverter's operating range specified for it, which ranges from 160 to 600V.

Battery pack voltage chosen: 307V .

Using the following formula, we can determine the battery capacity to store the required energy harvested by the PV or generator set system:

$$C_{td} = \frac{N_d \times E_{needs}}{V_{sys} \times DoD \times n_{bat} \times n_{invt}}$$

V_{sys} = System's voltage.

N_d = Autonomy days.

E_{needs} = daily power consumption (kWhr /day).

DoD = Depth of discharge.

n_{invt} = inverter's efficiency rate.

n_{bat} = Battery's efficiency rate.

We are considering a battery autonomy of 1 day and a maximum discharge depth of 80%

Calculating the battery's nominal capacity by simply applying the following formula:

$$C_{10} = \frac{1 \times 137 \times 1000}{307 \times 0.80 \times 0.92 \times 0.98} \approx 618 \text{ Ah} \quad (2.36)$$

For the selection of the appropriate battery, we selected the Smart BMS 51.2V 200AH LiFePO4 battery.



Application	Solar Energy Storage Systems, Power Tools, Uninterruptible Power Supplies, Electric Power...	Battery Type	Semi-solid state
Cycle Life	6000 cycles	Cathode Materials	LiFePO4
Max Load Quantity(cells)	16	Operating Temperature(°C)	-25-60
Model Number	LH-BSE551200	Place of Origin	Jiangsu, China
Brand Name	Litharv	Dimension (L*W*H)	441x480x155mm
Weight	47.5kg	Nominal Voltage	48V/51.2V
Capacity	100Ah/200Ah	Cell Type	LiFePO4 Battery/LFP
Maximum Charging Current	100A	Maximum Discharging Current	100A
BMS	Built-in	Cycle Life	6000 cycles @80% DOD, 0.5C
Warranty	10 Years	Certification	MSDS, UN38.3, ROHS, IEC62619, CE

Fig. 2.9. LitooARV lithium-ion battery data sheet

We selected this specific batterie due to its superior overall performance in terms of lifetime, efficiency , and reliability under harsh operating conditions; compared to AGM and Gel technologies, which were excluded because of their limited cycle life, (500-1000), depth of discharge (50%) which will require bank replacement every 1-2 years; therefore, despite their higher initial cost, they represent the most economical, reliable, and technically appropriate energy storage solution over the system's lifetime.

- Number of batteries in series

$$N_s = \frac{\text{System voltage}}{\text{Battery voltage}} \quad (2.37)$$

$$N_s = \frac{307}{51.2} = 6 \text{ batteries} \quad (2.38)$$

- Number of Parallel strings

$$N_p = \frac{\text{Bank capacity}}{\text{Battery capacity}} \quad (2.39)$$

$$N_p = \frac{618}{200} = 3 \text{ strings} \quad (2.40)$$

That gives us a total of 18 batteries, composed of 6 series-connected modules and 3 parallel strings, forming a nominal voltage of 307 V, strings are connected in parallel to the inverter, since it has 2 batteries input slots, 2 strings are connected to Bat1, and the third string is connected to Bat2, (another configuration includes DC busbar is recommended by IEC).

2.8.8 Generator-set sizing

- Daily energy demand:

$$E = 137Kwh/day$$

$$= 11.6kW$$

The sizing is based on the maximum simultaneous energy consumption of the installation Applying a 25% design margin (considering a power factor of 0.8); the genset must handle its peak load during daytime when powering the pump and nighttime loads simultaneously:

$$P_{apparent} = \frac{P_{total}}{\eta \times Pf} = \frac{11.6}{0.8 \times 0.8} = 18.1 \text{ kVA} \quad (2.41)$$

Applying a safety factor of 1.25:

$$P_{gunset} = 22.6 \text{ kVA}$$

For our installation, a 25 kVA diesel generator is suitable to ensure production continuity in case of an emergency, coupled with a soft starter to reduce inrush current caused by the generator itself and the submersible pump.

2.9 Cable section and protection sizing

For the cable section and protection devices selection, we provide a table that summarizes the critical cable distances between the installation of electrical components, to ensure accurate voltage drop calculations, cable section selection, and sizing proper protection devices

#	Circuit	Start Point	End Point	Route Description	Distance
1a	PV strings → Inverter	PV array (4 strings)	Inverter	Along ground, conduit	40 m
2a	Inverter → AC busbar	Inverter	AC busbar panel	Inside electrical room	3 m
3	Genset → inverter	Genset hangar	Electrical room	Underground conduit	5 m
4a	Battery string → inverter	Battery rack	inverter	Inside electrical room	2 m
5	AC busbar → Borehole pump	Electrical room	Well (200m deep)	Underground 10m + rising main 200m + 10m surface	220 m
6	AC busbar → Booster pump	Electrical room	Tank area	Underground conduit	30 m
7	AC busbar → House	Electrical room	Farmer's house	Underground conduit	20 m
8	AC busbar → Cold room	Electrical room	Cold storage room	Underground conduit	15 m

Table 20: Distances between electrical components of the installation.

Using the following formula, we can determine cable section through voltage drop

$$SDC/3\phi = \frac{\sqrt{3} \times 2 \times \rho \times L \times I}{\Delta V_{max}}; SDC/1\phi = \frac{2 \times \rho \times L \times I}{\Delta V_{max}} \quad (2.42)$$

S_{DC} = DC cable section (mm²).

ρ_{copper} = 0.0225 (Ω.mm²/m).

L = Cable length (m).

I = single string current (A).

ΔV_{DCmax} = 1%

$$\Delta V_{ACmain} \max = 3\%$$

$$\Delta V_{ACdistribution} \max = 5\%$$

Voltage drop alone is not sufficient to determine the proper cable section, as it does not take into consideration heat, short-circuit, and standard norms.

So the cable section is chosen following this formula and according to IEC 60364/ IS 732:

$$S_{max}(S_{thermal}, S_{voltage\ drop}, S_{shortcircuit},) \quad (2.43)$$

$$, S_{thermal} = I_b \leq I_z \quad (2.44)$$

I_b = current generated by load.

I_z = the permissible current from tables.

$$S_{shortcircuit} = S \geq \frac{I_{sc}\sqrt{t}}{k} \quad (2.45)$$

I_{sc} = is the short-circuit current,

t = the protection disconnection time

k = material constant (Cu=115-143 depending on insulation)

- **Cable 1a — PV strings→inverter**

$$V_{total} = 18 \times 48.63 = 875,34V \text{ DC}$$

$$I_{sc} = 15.26A \text{ (single string)}$$

$$\Delta V_{max} = 1\% \times 875,34V = 8.75V$$

$$S_{voltage_drop} = \frac{2 \times 0.0225 \times 40 \times 15.26}{8.75} = 3.1392mm^2 \quad (2.46)$$

$$S_{voltage_drop} = 4mm^2$$

$$S_{shortcircuit} = S \geq \frac{15.26\sqrt{1}}{115} = 0.13mm^2 \quad (2.47)$$

$$, S_{thermal} = 1.25 \times 15.26 = 19.07A \quad (2.48)$$

$$, S_{thermal} = 2.5mm^2 \quad (2.49)$$

$$S_{PV} = \max(2.5, 4, 0.13) = 4mm^2$$

$$\text{Fuse selection : } I_{fuse} \geq 1.25 \times I_{string} = 1.25 \times 15.26 = 19A$$

Fuse : 20A gPV fuse per string

Dc isolator selection:

$$V_{total} : 875.34V$$

DC isolator : 1000V DC, 32A per string

- **Cable 2 — Inverter → AC Busbar (3-phase)**

$$I_b = \frac{P}{\sqrt{3} \times V \times Pf} = \frac{40000}{\sqrt{3} \times 400 \times 0.8} = 72.2A \quad (2.50)$$

This is the theoretical current value, we will take the inverter's maximum output AC current which is 66.7A

$$I_{thermal} = 1.25 \times 66.7A = 83.375A \quad (2.51)$$

$$S_{thermal} = 25mm^2$$

$$\Delta V_{max} = 3\% \times 400 = 12V.$$

$$S_{voltage_drop} = \frac{\sqrt{3} \times 0.0225 \times 3 \times 72.2}{12} = 7.03mm^2 \quad (2.52)$$

$$S_{voltage_drop} = 10mm^2$$

$$S_{short_circuit} = S \geq \frac{83.375\sqrt{1}}{115} = 0.725mm^2 \quad (2.53)$$

$$S_{inverter} = \max(0.725, 10, 25) = 25mm^2$$

$$\text{Circuit breaker selection : } I_n \geq 1.25 \times I_b = 1.25 \times 72.2 = 90A$$

Selected protection: MCCB 3P 100A AC

- **Cable 3 — Genset → inverter (3-phase)**

$$I = \frac{S_{genset}}{\sqrt{3} \times V} = \frac{25000}{\sqrt{3} \times 400} = 36.1A \quad (2.54)$$

Since we are using the apparent power, there is no need for power factor

$$\Delta V_{max} = 3\% \times 400 = 12V$$

$$S_{voltage_drop} = \frac{\sqrt{3} \times 0.0225 \times 5 \times 36.1}{12} = 0.58mm^2 \quad (2.55)$$

$$I_{thermal} = 1.25 \times 36.1A = 45.1A \quad (2.56)$$

$$S_{thermal} = 10mm^2$$

$$I_{sc} = \frac{I_r}{X_{sc}\%}$$

Xsc% = Short-circuit reactance in %.

According to the Diamond KJT25 diesel generator datasheet, '*an overload capacity equivalent to 300% of the full load impedance can be sustained for 10 seconds at Power Factor =1.*' (check appendix 5).

$$S_{short_{circuit}} = S \geq \frac{36.1 \times 3\sqrt{10}}{115} = 2.97 \text{mm}^2 \quad (2.57)$$

$$S_{gunset} = \max(0.58, 10, 2.97) = 10 \text{mm}^2$$

Circuit breaker selection: $I_n \geq 1.25 \times I_b = 1.25 \times 36.1 = 45.12 \text{A}$

Selected protection : MCCB 3P 63A AC

- **Cable 4 — Battery string → inverter**

Since each Battery port has a maximum charging and discharging current of 50A:

We have 3 parallel strings:

$$\Delta V_{\max} = 1\% \times 307 \text{V} = 3.07 \text{V}$$

$$(2.58) \quad I_{string} = \frac{100}{3} = 33.3 \text{A}$$

$$S_{voltage_{drop}} = \frac{2 \times 0.0225 \times 2 \times 50}{3.07} = 1.46 \text{mm}^2 \quad (2.59)$$

$$I_{thermal} = 1.25 \times 50 \text{A} = 62.5 \text{A} \quad (2.60)$$

$$S_{thermal} = 10 \text{mm}^2 \text{ per battery string}$$

$$S_{short_{circuit}} = S \geq \frac{100\sqrt{1}}{115} = 0.87 \text{mm}^2 \quad (2.61)$$

$$S_{battery_string} = \max(0.87, 10, 1.46) = 10 \text{mm}^2$$

Fuse selection : $I_{fuse} \geq 1.25 \times I_{string} = 1.25 \times 50 = 54.3 \text{A}$

Fuse = 63A DC / 600V , per string

- **Cable 5 — AC Busbar → Summersible pump (3 phase)**

$$I = \frac{P}{\sqrt{3} \times V \times Pf} = \frac{5500}{\sqrt{3} \times 400 \times 0.8} = 9.93 \text{A}$$

- $\Delta V_{\max} = 3\% \times 400 = 12 \text{V}$

$$S_{voltage_{drop}} = \frac{\sqrt{3} \times 0.0225 \times 220 \times 9.93}{12} = 7.09 \text{mm}^2$$

$$I_{thermal} = 1.25 \times 9.93 \text{A} = 12 \text{A} \quad (2.62)$$

$$S_{thermal}=2.5mm^2$$

Assuming a short-circuit current of 6 x In

$$S_{short\ circuit} = S \geq \frac{59.58\sqrt{I}}{115} = 0,51mm^2 \quad (2.63)$$

$$S_{submersible_pump}=\max(0.51, 2.5, 7.09)= 10mm^2$$

Circuit breaker selection : $I_n \geq 1.25 \times I_b = 1.25 \times 9.93A = 12.41A$

Selected protection: MCCB 3P 16A AC

Additional protection can be added : Soft starter 7.5kW, Thermal relay 10A, 18A contactor, Dry run protection, Phase failure relay.

$I_{soft} \geq 1.25 \times I_b = 1.25 \times 9.93 = 15A$ soft starter (7.5kW)

$I_{relay} \geq 1.05 \times I_b = 1.25 \times 9.93 =$ thermal relay =10A

18A contactor for AC-3 motor duty

- **Cable 6 — AC Busbar→ booster pump (3 phase)**

$$I = \frac{P}{\sqrt{3} \times V \times Pf} = \frac{1100}{\sqrt{3} \times 400 \times 0.8} = 1.99A$$

$\Delta V_{max} = 3\% \times 400 = 12V$

$$S = \frac{\sqrt{3} \times 0.0225 \times 30 \times 1.99}{12} = 0.19mm^2$$

$$S_{selected}=2.5mm^2$$

$$I_{thermal} = 1.25 \times 1.99A = 2.48A \quad (2.64)$$

$$S_{selected}=2.5mm^2$$

$$S_{booster_pump}=\max(0.19, 2.5)= 2.5mm^2$$

Circuit breaker selection : $I_n \geq 1.25 \times I_b = 1.25 \times 1.99A = 2.5A$

Selected protection: MCB 3P 6A AC

- **Cable 7 — AC Busbar→ Farmer house (1 phase)**

$$I = \frac{P}{V \times Pf} = \frac{3000}{200 \times 0.8} = 16.3A$$

$\Delta V_{max} = 5\% \times 230 = 11.5V$

$$S = \frac{2 \times 0.0225 \times 20 \times 16.3}{11.5} = 1.27 \text{ mm}^2$$

$$S_{\text{selected}} = 2.5 \text{ mm}^2$$

Circuit breaker selection : $I_n \geq 1.25 \times I_b = 1.25 \times 16.3 \text{ A} = 20.3 \text{ A}$

Selected protection: MCB 3P 20A AC

Another electrical diagram can be sized depending on house's loads.

- Cable 8 — AC Busbar → Cold room (1 phase)

$$I = \frac{P}{V \times P_f} = \frac{2000}{230 \times 0.8} = 10.87 \text{ A}$$

$$\Delta V_{\text{max}} = 5\% \times 230 = 11.5 \text{ V}$$

$$S = \frac{2 \times 0.0225 \times 15 \times 10.87}{11.5} = 0.64 \text{ mm}^2$$

$$S_{\text{selected}} = 2.5 \text{ mm}^2$$

Circuit breaker selection : $I_n \geq 1.25 \times I_b = 1.25 \times 10.87 \text{ A} = 13.5 \text{ A}$

Selected protection: MCB 16A C-curve

Additional protection devices can be linked to specific cables using the international norm IEC 61643

PV array : Type II SPD 1000VDC

Battery bank : Type II DC SPD

AC main busbar : Type II AC SPD 400V

Generator : Voltage, frequency and overcurrent protection

Remark. The inverter's datasheet already specifies and integrates most of the protection functions that we independently calculated

However, our calculations were still performed as design verification step to ensure proper coordination with external components (cables, breakers...etc), as well to account for future system evolution and site-specific operating conditions.

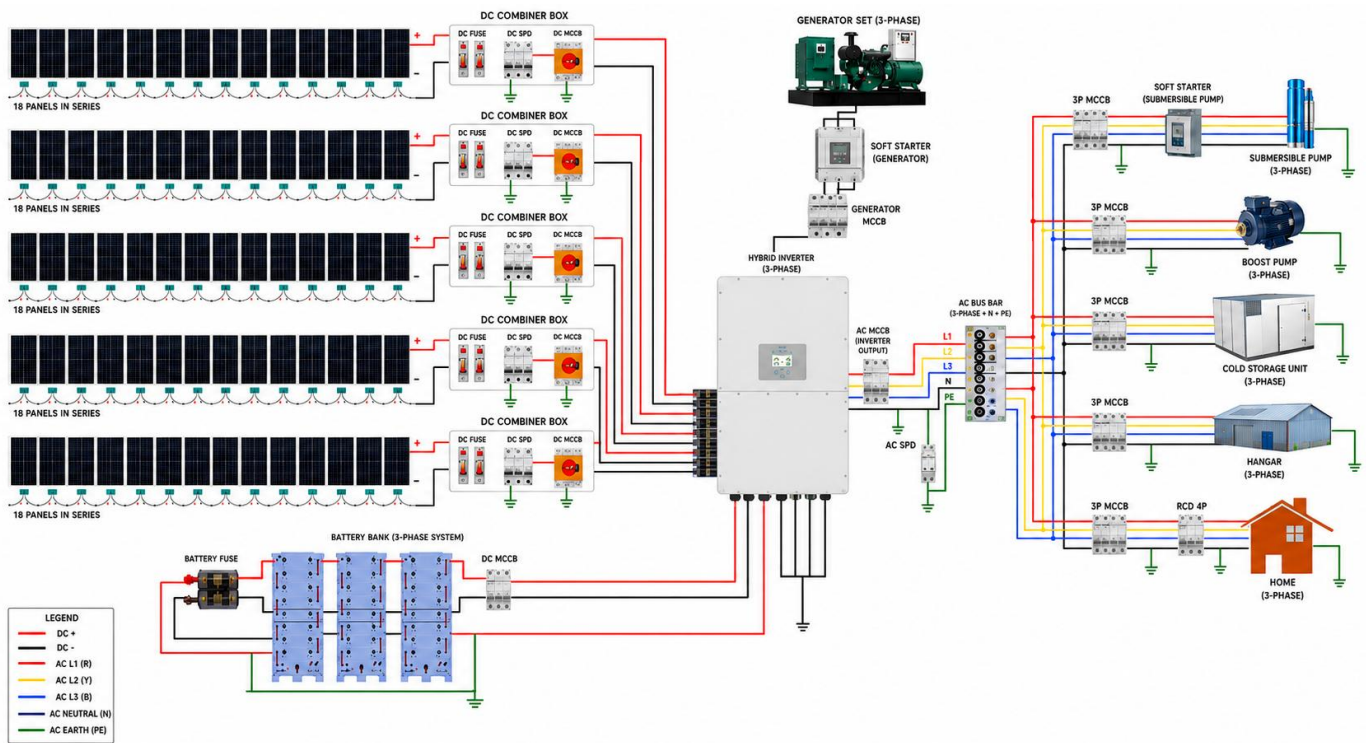


Fig. 2.10. System electrical diagram of the farm.

Conclusion

This chapter presented a complete load assessment and system sizing for the agricultural perimeter of Kabertene in the Wilaya of Adrar, a remote Saharan site characterized by extreme climatic conditions and full reliance on groundwater and solar resources. The study area analysis highlighted the strategic importance of combining irrigation agriculture with decentralized renewable energy production to ensure sustainable development in an off-grid environment.

The load assessment covered all critical components of the farm, including the submersible irrigation pump, booster pump, greenhouse irrigation systems, cold storage unit, residential building, and auxiliary infrastructure. Seasonal variations between Barley growing and harvesting periods were taken into account, leading to a detailed estimation of daily energy consumption, with peak demand reaching approximately 136 kWh/day.

Based on these requirements, the hydraulic system was designed by determining water needs for open-field barley and greenhouse crops, sizing a storage tank with two days autonomy (approximately 122 m³), and selecting a pumping system capable of meeting a total dynamic

head of about 215 m. This led to the selection of an appropriate submersible pump and supporting surface pump, ensuring reliable water supply under deep groundwater conditions.

On the electrical side, a hybrid photovoltaic system was designed using both climatic data and energy demand. The system was sized at approximately 40 kWc, composed of 69 JA Solar 585 Wp modules, connected to a three-phase hybrid inverter compatible with the agricultural pumping load. A lithium battery bank (307 V, 18 units) was integrated to ensure energy continuity, while a 25 kVA diesel generator was included as a backup source for critical or low-solar conditions.

Finally, detailed cable sizing and protection coordination were carried out to ensure safety, efficiency, and compliance with standard electrical design practices. Although most protection functions are already integrated into the inverter system, independent verification was performed to ensure system reliability, scalability, and compatibility with future expansion.

Chapter III :

PVsyst implementation and technico-economic optimization.

III. Overview of the PVSYST Software

III.1 Preliminary Design

The preliminary design stage represents the initial phase of a project, commonly referred to as the pre-sizing process. It is intended for a quick and straightforward assessment of a photovoltaic system. At this stage, the user specifies the project location and the type of system, after which the software estimates key sizing parameters and generates several outputs, including annual energy production graphs, monthly solar irradiation profiles, summary tables, and a preliminary economic analysis. For standalone PV systems, this tool assists in determining the required photovoltaic array power and battery storage capacity based on the load profile and the desired level of system reliability. Reliability is generally evaluated using the Loss of Load Probability (LOLP), which represents the likelihood that the system will fail to meet the load demand, or alternatively through the desired solar fraction.

III.1.1 Detailed Project Design

The project design module is intended for comprehensive system development through detailed hourly simulations. Within a project environment, users can perform multiple simulation scenarios and compare their performance to identify the most suitable system configuration; The software requires the definition of the array orientation, with options for fixed installations, tracking systems, or mounting structures such as sheds; Users can also select specific system components, including PV modules, inverters, batteries, and pumps. Furthermore, PVSYST assists in designing the PV array by determining the appropriate number of modules connected in series and parallel according to the selected equipment specifications. In a more advanced stage of the design process, additional parameters can be introduced to achieve a more accurate system analysis; these parameters include thermal behavior, cable losses, module quality, module mismatch effects, incidence-angle losses, horizon shading, and partial shading caused by nearby obstacles, for photovoltaic water-pumping applications,

different system configurations can be simulated and compared in order to evaluate their operational behavior and overall efficiency; The software provides a wide range of simulation outputs that can be displayed on monthly, daily, or hourly bases and can also be exported for further processing in other software tools, one of the most valuable features of PVSYST is the loss diagram, which helps identify the main sources of energy losses and highlights potential weaknesses in the system design. Additionally, an engineering report can be generated for each simulation run, summarizing the input parameters and presenting the key performance results. The software also offers a detailed economic evaluation based on actual component costs, additional expenses, and investment conditions.

III.2 Project Description

In this project, a standalone photovoltaic (PV) system integrated with a diesel generator is proposed to supply electricity to an agricultural farm located in Kabertene, in the Wilaya of Adrar, Algeria, the hybrid system is designed to ensure a reliable power supply for various agricultural loads, including irrigation equipment, water pumping systems, cold storage facilities, lighting, and other farm-related electrical devices; The integration of a diesel generator provides backup power during periods of low solar irradiation or high energy demand, thereby enhancing the overall reliability and continuity of the power supply; The study site is situated in Kbertène, a region characterized by high solar potential, making it particularly suitable for the implementation of photovoltaic energy systems.

III.2.1 Geographic Data

A geographical site is characterized by several essential parameters, including:

- The name of the site, the country, and the region where it is located.
- Geographic coordinates, namely latitude, longitude, altitude above sea level, and the corresponding time zone.
- Monthly meteorological data, including solar irradiation, ambient temperature, and other climatic parameters required for the assessment and simulation of photovoltaic system performance.

This information is fundamental for accurately evaluating the solar energy potential of the selected site and ensuring reliable system design and simulation results.

Figure III.1: Geographic location and coordinates of the Kabertene site, Wilaya of Adrar, Algeria.

In Figure III.1, the geographic coordinates of the selected site located in Kabertene, Adrar, have been presented, the site is situated at a latitude of 28.2995° N, a longitude of 0.1208° E, and an altitude of 307 m above sea level.

III.2.2 Meteorological Data

These data summarize the climatic characteristics of the project site, including solar irradiation, ambient temperature, wind speed, and other relevant weather parameters; The information used in this study was obtained from NASA-SSE satellite data, which provides reliable monthly meteorological records for solar energy system simulation and assessment.

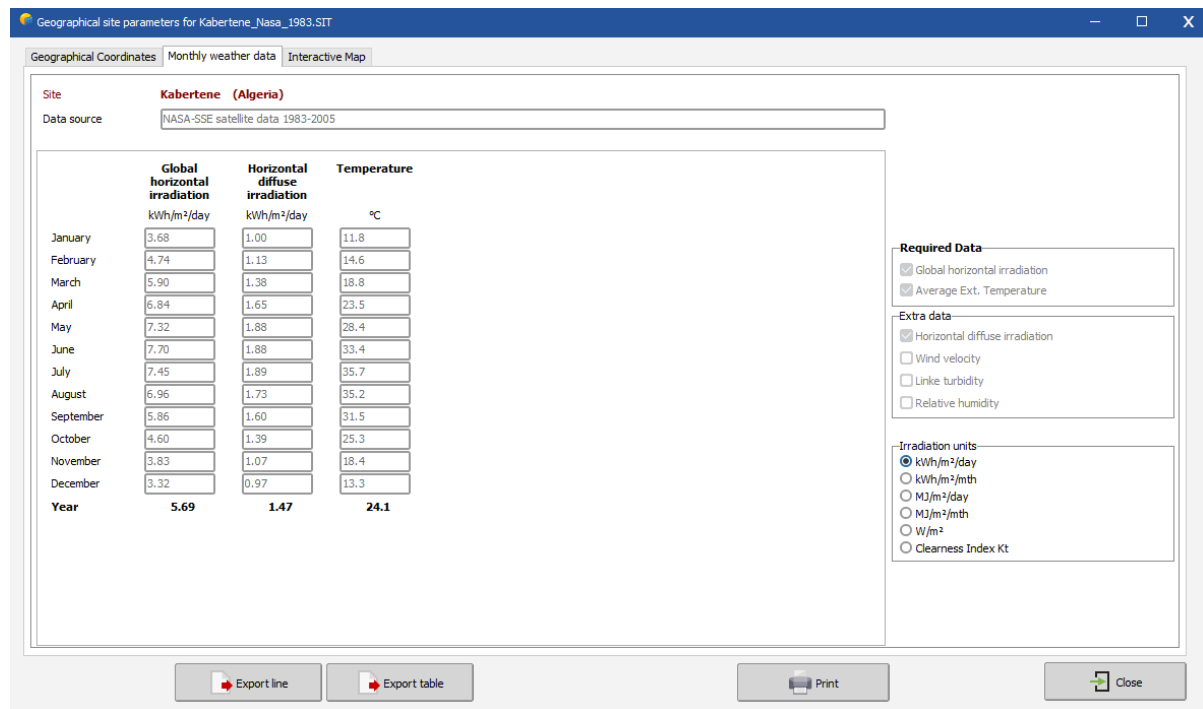


Figure III.2: Climatic parameters of Kbertène (Adrar, Algeria).

III.3 Project Design

In this section, the standalone PV system is modeled in the “off-grid with batteries” configuration, which involves several key design parameters.

The design process is carried out through multiple steps, including selecting the project type and its associated variables, defining the orientation of the PV modules, setting the horizon profile to account for distant shading, modeling near-shading effects, configuring the system components, and finally analyzing the simulation results.

The steps related to distant and near shading are optional, however, when near shading is considered, the precise adjustment of module tilt and azimuth becomes less critical at the early stage, since these parameters can later be refined within the near-shading definition tool.

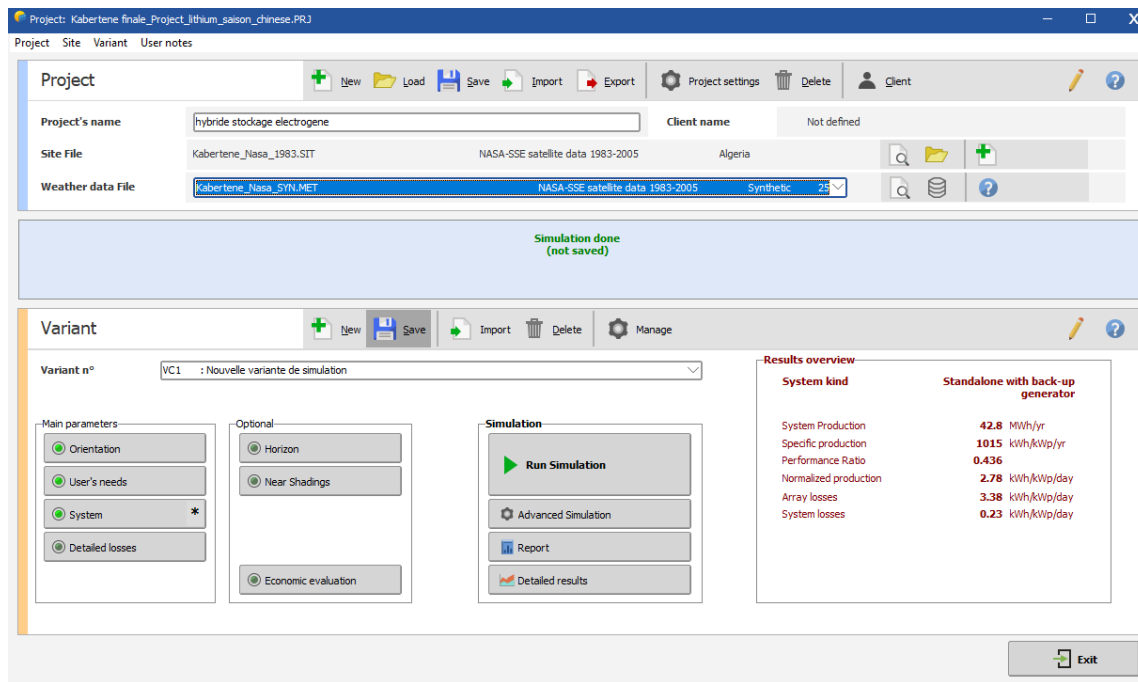


Figure III.3: Design of the standalone PV system with battery storage.

III.3.1 Steps in Designing an Autonomous PV System

This section presents a step-by-step procedure for defining a standalone photovoltaic system in PVSYST:

III.3.2 Horizon profile defining

Defining a horizon profile is a very simple operation with the PVsyst graphical tool; The horizon is a broken line superimposed on the sun path diagram, which can hold any number of height and azimuth points.

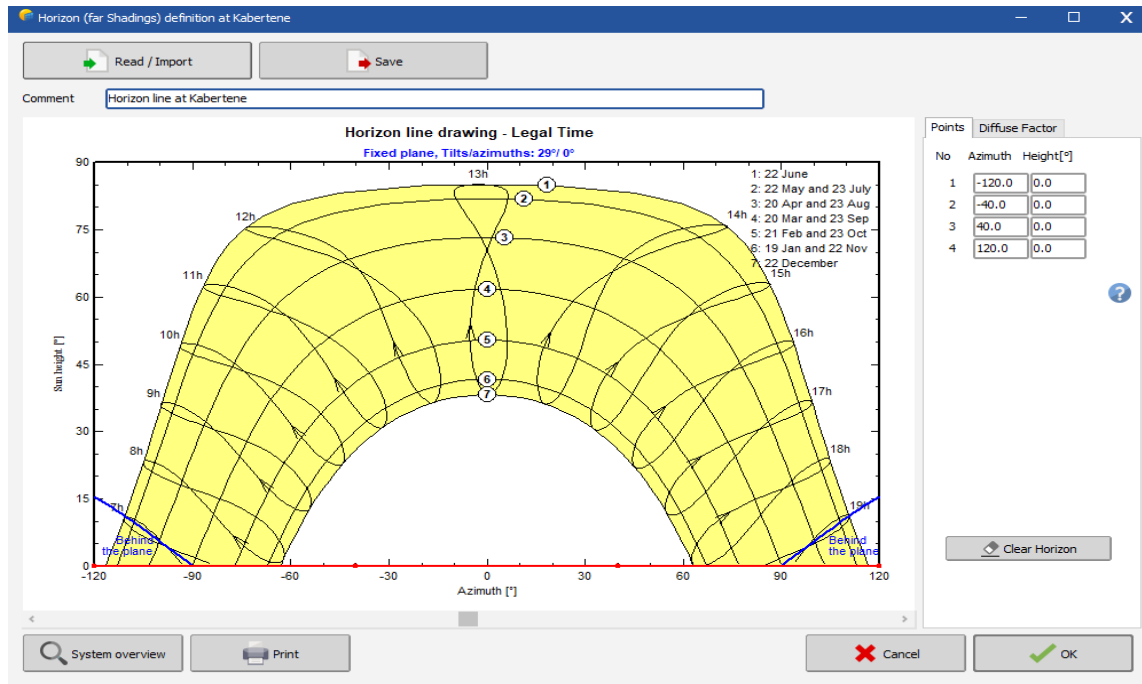


Figure III.4: Horizon profile of Kabertene (Adrar, Algeria).

III.3.3 PV module orientation

To achieve optimal performance of the photovoltaic installation, it is essential to select appropriate tilt and azimuth angles that maximize energy production throughout the year. For the simulation, a fixed tilted plane configuration was adopted with a tilt angle of **29°** and an azimuth angle of **0° (due South)**. These values were selected based on PVsyst's orientation optimization analysis, which indicated that this configuration provides the maximum annual incident irradiation on the collector plane (**2305 kWh/m²**) with a transposition factor of **1.11**.

Furthermore, the selected orientation results in a **0.0% loss with respect to the optimum**, meaning that no additional annual energy losses are incurred due to module orientation. Therefore, the chosen tilt and azimuth angles represent the optimal configuration for maximizing yearly solar energy capture at the project site while ensuring the highest possible energy yield from the photovoltaic array.

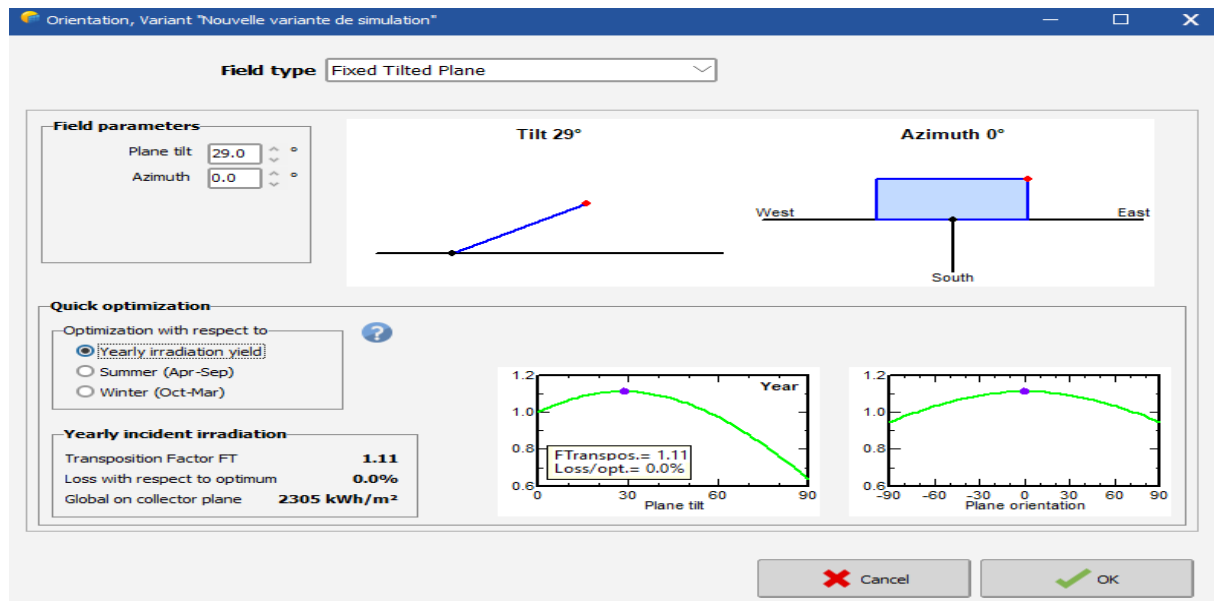


Figure III.5: Fixed tilt plane orientation.

To optimize solar irradiation at the site, the PV array is oriented facing south with a tilt angle of 29°.

III.3.4 Definition of User Load Requirements

The **User Demand window in PVSYST** is used to define the electrical load that the system must supply; it allows the user to specify the energy consumption profile, including daily energy requirements, load power, operating periods, and possible seasonal variations, this information is essential for simulating system performance and for correctly sizing the PV array, storage batteries, and backup systems in standalone configurations.

Comment: Besoins utilisateurs : profils journaliers, Consta

General features | **Daily profile** | Graph

Kind of load profile

- ☐ Unlimited load (grid)
- ☐ Fixed constant consumption
- ☐ Monthly values
- ☒ Daily profiles
- ☐ Probability profiles
- ☐ Household consumers
- ☐ Load values from a CSV hourly/daily file

Daily profiles:

- ☐ Constant over the year
- ☒ Seasonal modulation
- ☐ Monthly normalization
- ☐ Weekly modulation

User's needs: Yearly energy defined

Average power: **4.91 kW**

Yearly energy: **43.0 MWh/yr**

Info system: Defined PV array

Nominal PV Power: **42.1 kWp**

Estimated system yield: **67.1 MWh/yr**

PnomPV / PLoad average: **8.58 Pnom ratio**

PnomPV / PLoad max: **4.90 Pnom ratio**

Model

Load Save

Print Cancel OK

Figure III.6: Load profile.

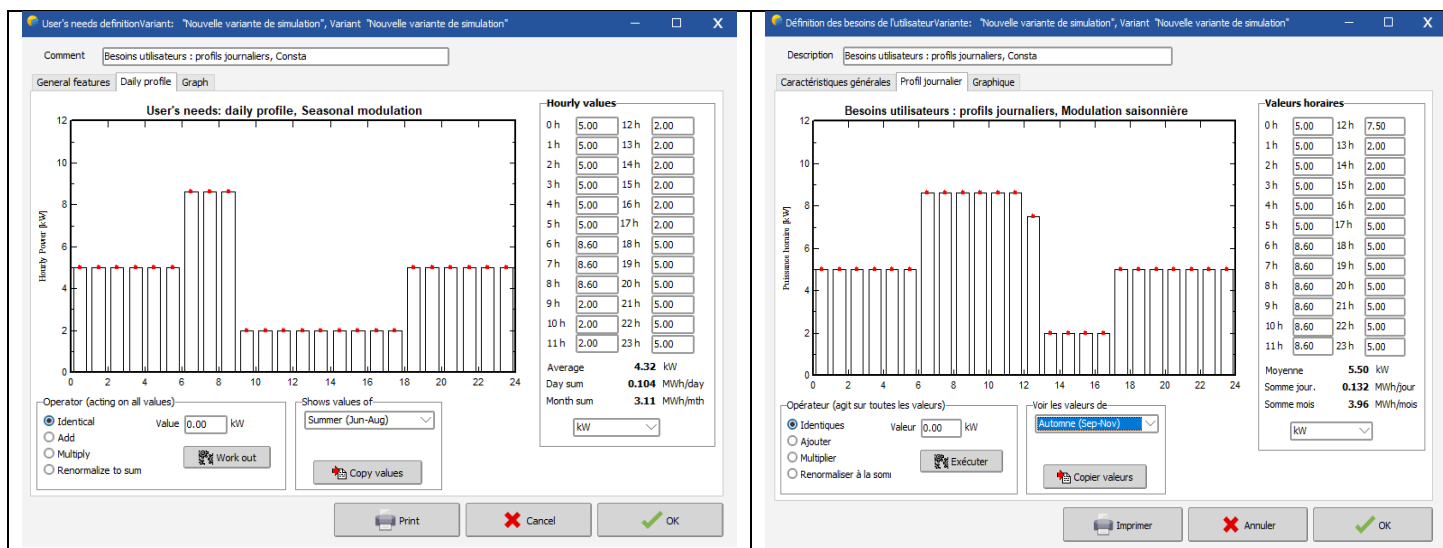


Figure III.7: Operating time schedule.

Two distinct daily load profiles are considered depending on the agricultural season.

During the cultivation period, the energy demand reaches its maximum due to intensive irrigation activities, where the pumping systems operate frequently to support crop growth and field water requirements; In contrast, during the harvest period, barley cultivation is completed, leading to a significant reduction in water demand, at this stage, the load is mainly limited to greenhouse irrigation, resulting in a lower and more stable daily energy consumption compared to the cultivation season.

III.3.5 Preliminary sizing conditions

At this stage, the software provides preliminary sizing suggestions based on the defined load profile, site conditions, and system configuration, these recommendations include an initial estimation of the required PV array power, battery storage capacity, and overall system configuration; The objective is to ensure that the proposed design can meet the energy demand with an acceptable level of reliability, while maintaining system feasibility and efficiency

Figure III.8 shows the window used in the preliminary sizing stage of a standalone PV system design.

The screenshot displays the 'Stand-alone system definition' window with the following sections and parameters:

- Top Bar:** Title 'Stand-alone system definition, Variant: "Nouvelle variante de simulation", Variant: "Nouvelle variante de simulation"'. Buttons for 'Av. daily needs', 'Enter accepted PLOL', 'Requested autonomy', 'Detailed pre-sizing', 'Battery (user) voltage', 'Suggested capacity', and 'Suggested PV power'.
- Inputs:**
 - Av. daily needs: 118 kWh/day
 - Enter accepted PLOL: 2.0 %
 - Requested autonomy: 1.0 day(s)
 - Battery (user) voltage: 307 V
 - Suggested capacity: 506 Ah
 - Suggested PV power: 37277 Wp (nom.)
- Storage:** Tabs for 'Champ PV', 'Back-Up', and 'Simplified sketch'.
 - Sub-array name and Orientation:** Name 'Champ PV', Tilt '29°', Azimuth '0°', Orient. 'Fixed Tilted Plane'.
 - Pre-sizing Help:** Radio buttons for 'No sizing' and 'Planned power' (37.8 kWp). A 'Resize' button and '... or available area' (182 m²) are also present.
- Select the PV module:**
 - Available Now: JA Solar
 - Sort modules: Power (selected), Technology
 - Module: 585 Wp 38V Si-mono JAM78-S30-S85-MR Since 2021
 - Approx. needed modules: 65
 - Sizing voltages: Vmpp (60°C) 38.6 V, Voc (-10°C) 58.6 V
- Select the control mode and the controller:**
 - MPPT power converter
 - Universal controller: _Generic
 - Operating mode: MPPT converter (selected), Direct coupling, DC-DC converter
 - MPPT 1000 W 307 V 15.1 A 28 A Universal controller with MPPT conve
- PV Array design:**
 - Number of modules and strings: Mod. in series 18, Nb. strings 4
 - Operating conditions: Vmpp (60°C) 695 V, Vmpp (20°C) 813 V, Voc (-10°C) 1054 V, Plane irradiance 1000 W/m², Impo (60°C) 53.1 A, Isc (60°C) 56.5 A, Isc (at STC) 56.2 A
 - Max. operating power (at max. irradiance and 50°C): 38.4 kW
 - Array nom. Power (STC): 42.1 kWp
- User's needs summary:**
 - Daily profile: Daily energy 118 kWh, Night ratio 50.6%, 3 in parallel, 307 V
 - Battery pack: Capacity 600 Ah, Autonomy 1.3 day, Stored energy 147 kWh
 - PV Array: 4 str. of 18 modules, Nom. Power 42.1 kWp, PV/PLoad 8.6, Av. daily energy 184 kWh
 - Controller: Universal MPPT, Nom. Power 36.6 kW, PV/PCConv 1.15, Thresholds acc. to SOC
- Buttons:** Cancel, OK

Figure III.8: Parameters of the standalone system.

In the main window, the input parameters required for calculating the number of batteries and sizing the multi-source system are defined as follows:

- The required autonomy, typically set to 1 day.
- The acceptable probability that the load demand is not met by the system (Loss of Load Probability, LOLP), which is set to 2%.
- The nominal voltage of the battery bank, which is defined as 307 V.

This window is divided into four sub-sections, namely:

- The storage system.
- The PV array.
- The backup generator set.
- The system configuration diagram.

III.3.6 Selection and Sizing of the Storage System

The storage system can be selected from the internal database of PVSYST, or alternatively, a custom storage configuration can be defined if the required battery model is not available in the software library.

In this study, the selected battery brand is the same as the one used in the iterative sizing method, as shown in Figure III.9

Specify the Battery set

Sort batteries by: ☒ voltage ☐ capacity ☐ manufacturer

Selected battery: Jiangsu Lihui Technology Co. | 51.2 V | 200 Ah | Li LFP | LH-HSE-R51200 51.2V Since 2023 |

Lithium-ion

The selected battery is a module

Configuration	Value
modules in series	6
modules in parallel	3
Number of modules	18
Number of elements	576

Initial State of Wear (nb. of cycles): 100.0 %

Initial State of Wear (static): 100.0 %

Operating battery temperature

Temper. mode: Fixed (air-conditioned)

Fixed temperature: 30 °C

The battery temperature is important for the aging of the battery.

Parameter	Value
Battery pack voltage	307 V
Global capacity	600 Ah
Stored energy (80% DOD)	147 kWh
Total weight	1620 kg
Nb. cycles at 80% DOD	5000
Total stored energy during the battery life	747 MWh

Figure III. 9. Selecting the battery bank.

Figure III.9 shows the number of batteries obtained (in series, in parallel, and total), as well as the selected battery model, under a fixed operating temperature of 30°C.

1 III.3.7 Selection and Sizing of the PV Array

PV modules can be selected from the internal database of PVSYST, or alternatively, additional modules can be added if the required module brand or model is not available in the software library.

The selected PV module brand is the same as the one used in the iterative sizing method, as shown in Figure III.10.

The screenshot shows the 'Sub-array name and Orientation' section with 'Name' set to 'Champ PV', 'Orient.' set to 'Fixed Tilted Plane', 'Tilt' at 29°, and 'Azimuth' at 0°. The 'Pre-sizing Help' section includes 'Planned power' at 37.8 kWp and '... or available area' at 182 m². The 'Select the PV module' section shows 'Available Now' as a dropdown, 'Sort modules' set to 'Power', and 'JA Solar' as the selected brand. The 'Sizing voltages' section shows 'Vmpp (60°C)' at 38.6 V and 'Voc (-10°C)' at 58.6 V. The 'Approx. needed modules' is 65.

Figure III.10: PV array parameters.

The software determines the number of PV modules to be connected in series and parallel based on several design constraints, these constraints may or may not be considered during system sizing, such as battery voltage, planned system power, and available installation area (see Figures III.9 and III.10).

2 III.3.8 Selection and Sizing of the Battery Charge Controller and Control Strategy

PVSYST allows the selection of a battery charge controller and its proper sizing based on system voltage, output current, and battery power requirements (Figure III.11).

The screenshot shows the 'Select the control mode and the controller' section. The 'Operating mode' section has three options: 'Direct coupling', 'MPPT converter' (selected), and 'DC-DC converter'. The 'MPPT power converter' section shows 'Max. Charging - Discharging current' with values 151 A and 28 A. The 'Universal controller with MPPT conve' dropdown is selected. A note states: 'The operating parameters of the universal controller will automatically be adjusted according to the properties of the system.'

Figure III.11: Selection of the battery charge controller and control strategy.

In addition, PVSYST allows the selection among three battery charging control strategies: direct coupling, coupling using an MPPT charge controller, and coupling using a DC–DC power converter.

3 III.3.9 Selection and Sizing of the Backup Generator

The sizing of the backup generator is taken into account in PVSYST. It is included in the system to compensate for any potential energy shortage that may occur at different times of the year, especially during periods of low solar irradiation or increased demand.

Back-up generator						
☒ Uses back-up genset	StdGenerator3.GEN : Back-up generator - 3 kW [Open]					
Full load capability	Nominal power	25.0 kW	Battery voltage	307 V	Charging Current	81.4 A
Effective operating	Power	20.0 kW	Battery voltage	307 V	Charging Current	65.1 A

Figure III.12: Selection and sizing of the backup generator.

Figure III.12 illustrates the selected generator power used to compensate for the possible power deficit that cannot be met by the PV array.

III.3.10 Multi-Source System Diagram

The multi-source system configuration (PV array, batteries, backup generator, and charge controller) proposed by PVSYST is illustrated in Figure III.13.

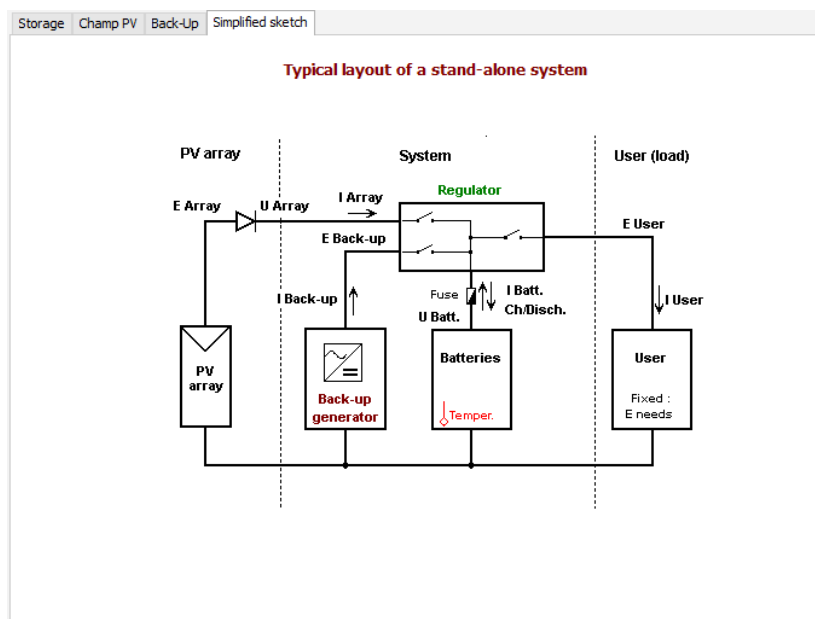
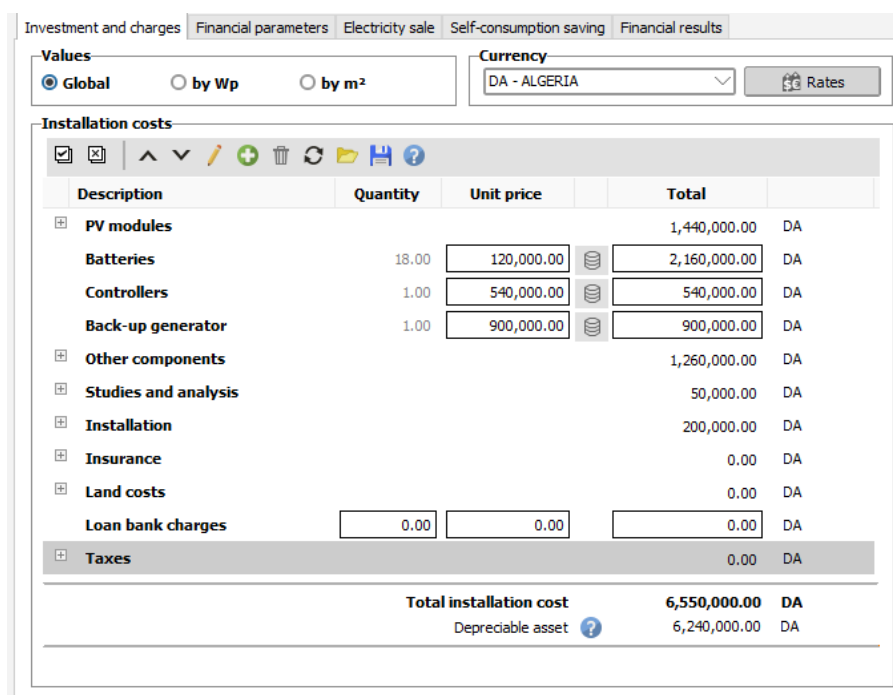


Figure III.13: Multi-source system diagram provided by PVSYST.

III.3.11 Economic Evaluation of the Multi-Source System

Based on the cost analysis of the main system components conducted at the beginning of this study, these values were entered into PVSYST in order to evaluate the total investment cost and estimate the additional expenses associated with the project.



Description	Quantity	Unit price	Total	
PV modules			1,440,000.00	DA
Batteries	18.00	120,000.00	2,160,000.00	DA
Controllers	1.00	540,000.00	540,000.00	DA
Back-up generator	1.00	900,000.00	900,000.00	DA
Other components			1,260,000.00	DA
Studies and analysis			50,000.00	DA
Installation			200,000.00	DA
Insurance			0.00	DA
Land costs			0.00	DA
Loan bank charges	0.00	0.00	0.00	DA
Taxes			0.00	DA
Total installation cost			6,550,000.00	DA
Depreciable asset			6,240,000.00	DA

Figure III.14: Economic evaluation of the multi-source system.

III.3.12 Impact of Near Shading

PVSYST makes it possible to analyze the effect of shading caused by nearby obstacles such as trees, buildings, or walls, as well as self-shading between PV modules within the array.

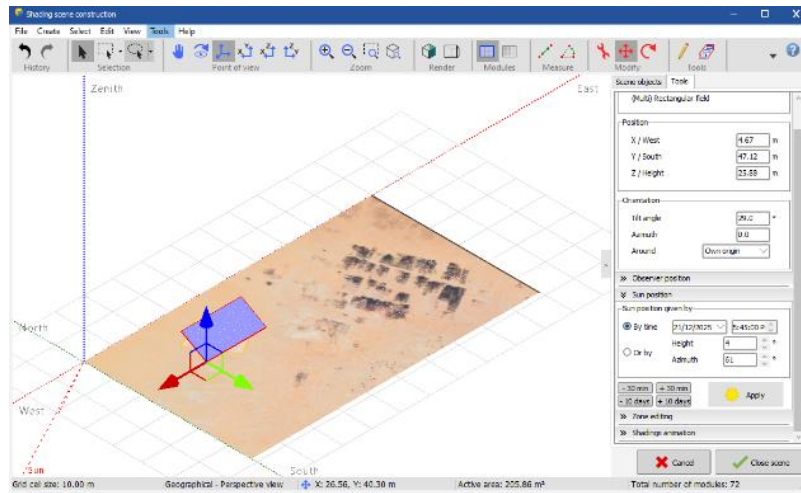


Figure III.15: Near shading configuration interface.

The near shading factor is set to 0 because there are no surrounding objects in the area that could cause shading.

III.3.13 Simulation results and discussion

The simulation was conducted using PVsyst v7.4.7 for a standalone photovoltaic system with backup generator support, located in Kabertene, Algeria (Latitude 28.30°N, Longitude 0.12°E, Altitude 307 m).

The system is designed to cover an average daily load of 118 kWh/day using a 42.1 kWp PV array coupled with a Lithium-Ion (LFP) battery pack rated at 600 Ah / 307 V and backed by a diesel genset.

Key Performance Indicators

- ▶ Annual useful energy from solar: 43,009 kWh/year
- ▶ Available solar energy: 80,768 kWh/year
- ▶ Excess (unused) energy: 36,403 kWh/year — indicating battery oversaturation during high-irradiance periods
- ▶ Performance Ratio (PR): 43.56% Since PR actually measures Y_f/Y_r , where $y_f(\text{Final/specific yeald}) = E_{\text{user}}/P_{\text{nominal}}$, which is the useful energy actually delivered to the load, normalized per kWp

$Y_r(\text{reference yield}) = \text{globEff} / G_{\text{STC}}$ = the theoretical energy the PV array could produce based on the irradiation that fell on it, normalized per kWp

The key point E_{user} includes the generator's contribution = (solar + battery + generator energy), but Y_r is purely calculated from solar irradiance.

- Solar Fraction (SF): 99.45% excellent; the genset is almost never needed

Conclusion

The system achieves an excellent Solar Fraction of 99.45%, meaning that nearly all of the annual load is supplied by the PV-battery subsystem; The diesel generator is configured strictly as an emergency backup source and contributes only a negligible amount of energy during rare periods of low solar availability and low battery state-of-charge; Therefore, the presence of excess solar energy should not be interpreted as a design deficiency. In standalone systems requiring high reliability, some level of unused energy is expected and often

intentionally accepted to guarantee uninterrupted power supply throughout the year



PVsyst V7.4.7
VC1, Simulation date:
06/15/26 04:30
with V7.4.7

Project: hybride stockage electrogene
Variant: Nouvelle variante de simulation

Project summary			
Geographical Site Kabertene Algeria	Situation Latitude 28.30 °N Longitude 0.12 °E Altitude 307 m Time zone UTC+1	Project settings Albedo 0.20	
Weather data Kabertene NASA-SSE satellite data 1983-2005 - Synthetic			

System summary			
Standalone system PV Field Orientation Fixed plane Tilt/Azimuth 29 / 0 °	Standalone with back-up generator Near Shadings Linear shadings : Fast (table)		User's needs Daily profile Seasonal modulation Average 118 kWh/Day
System information PV Array Nb. of modules Pnom total	72 units 42.1 kWp	Battery pack Technology Nb. of units Voltage Capacity	Lithium-ion, LFP 18 units 307 V 600 Ah

Results summary			
Useful energy from solar	43009 kWh/year	Specific production	1015 kWh/kWp/year
Missing Energy	0 kWh/year	Available solar energy	80768 kWh/year
Excess (unused)	36403 kWh/year	Perf. Ratio PR	43.56 %
		Solar Fraction SF	99.45 %

Table of contents	
Project and results summary	2
General parameters, PV Array Characteristics, System losses	3
Near shading definition - Iso-shadings diagram	5
Detailed User's needs	6
Main results	7
Loss diagram	8
Predef. graphs	9
Cost of the system	10

Figure III.16: report summarizing project and system results.

III.3.14 PV array & battery system specifications

The PV array consists of 72 modules of JA Solar JAM78-S30-585-MR (585 Wp each), arranged in 4 strings of 18 modules in series, yielding a nominal STC power of 42.1 kWp. The array is mounted on a fixed plane tilted at 29° facing due South (Azimuth 0°), which is an appropriate tilt angle for the latitude (~28°N) to maximize annual energy capture; Operating at 50°C ambient (typical Saharan field temperature), the array produces 38.4 kWp at MPP — a ~8.8% thermal derating — with $U_{mpp} = 724$ V and $I_{mpp} = 53$ A. This underscores the importance of thermal loss modelling in hot climates.

The battery pack from Jiangsu Lihui Technology comprises 18 LFP units (3 in parallel × 6 in series) with a total nominal capacity of 600 Ah (C10) at 307 V, equating to approximately 147.5 kWh of stored energy, the minimum discharge SOC is set at 20%, with charge/discharge command thresholds of SOC = 0.90/0.75 (charging) and SOC = 0.20/0.45 (discharging). The back-up genset activates at SOC = 0.25 and deactivates at 0.45, The MPPT controller operates with maximum/EURO efficiencies of 97.0%/95.0%, and a temperature coefficient of -5.0 mV/°C/element — well within standard parameters for LFP chemistry.

- **Array Loss Budget**

Thermal losses ($U_c = 20$ W/m²K with no wind correction), DC wiring losses (1.5% at STC), module mismatch (2.0%), and ohmic losses (1.34%) are the primary derating factors. Module quality is modelled with a positive gain of +0.75%, typical for high-grade monocrystalline silicon modules

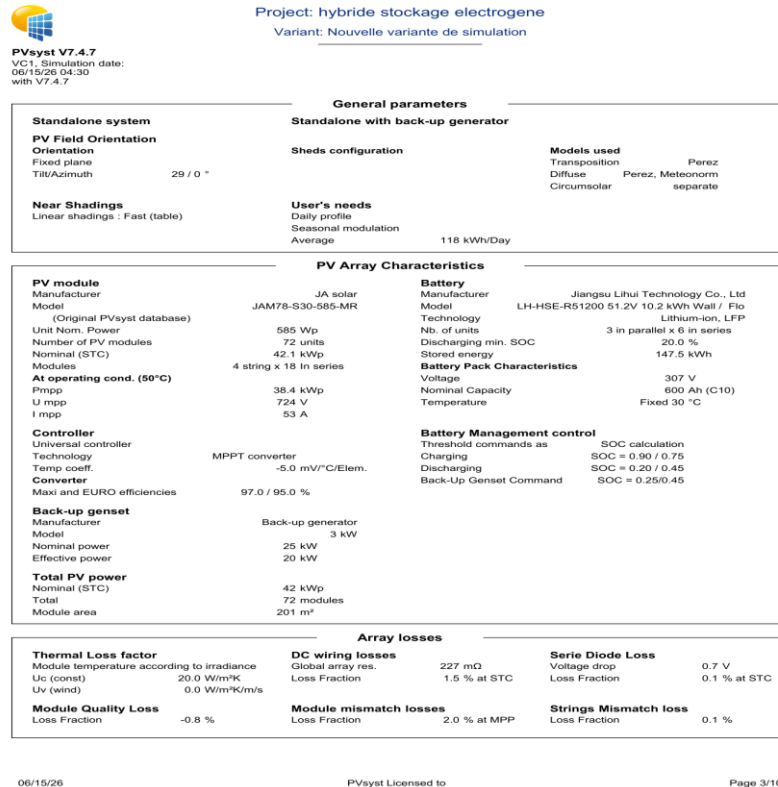


Figure III.17: General parameters and PV array characteristics.

- **Incidence angle modifier (IAM) analysis**

The Incidence Angle Modifier (IAM) accounts for the reduction in transmittance of solar radiation through the module's glass cover as the angle of incidence increases from normal. PVsyst models this using the Fresnel equation for smooth glass with a refractive index $n = 1.526$, which is the standard for low-iron tempered glass used in PV modules.

- **IAM table interpretation**

At normal incidence (0°), $IAM = 1.000$ (no loss). Up to 50° , losses remain minor ($IAM = 0.981$), which covers most daily generation hours for this latitude. Beyond 60° , losses accelerate: at 70° IAM drops to 0.862 (-13.8%), at 80° to 0.636 (-36.4%), and at 90° to 0.000 , these steep-angle losses occur primarily during early morning, late evening, and winter months when the sun is low on the horizon.

For a fixed-plane installation at 29° tilt in Kabertene, the annual IAM-integrated loss (shown as -2.44% in the loss diagram) is quite acceptable and consistent with industry benchmarks for similar latitudes. If bifacial modules or single-axis trackers were employed, the IAM profile would differ and typically yield better annual performance.



PVsyst V7.4.7
VC1, Simulation date:
06/15/26 04:30
with V7.4.7

Project: hybride stockage electrogene

Variant: Nouvelle variante de simulation

Array losses

IAM loss factor

Incidence effect (IAM): Fresnel smooth glass, n = 1.526

0°	30°	50°	60°	70°	75°	80°	85°	90°
1.000	0.998	0.981	0.948	0.862	0.776	0.636	0.403	0.000

Figure III.18: Array losses table.

- **Near shading analysis**

The near-shading scene is displayed in 3D from a perspective of the PV field and its surroundings, the installation is located in a flat, open desert terrain in Kabertene (Saharan Algeria), with minimal obstructions visible to the south and east directions. A single blue rectangle represents the PV array footprint, with no significant near-field obstacles recorded in the model.

- **Iso-shading diagram**

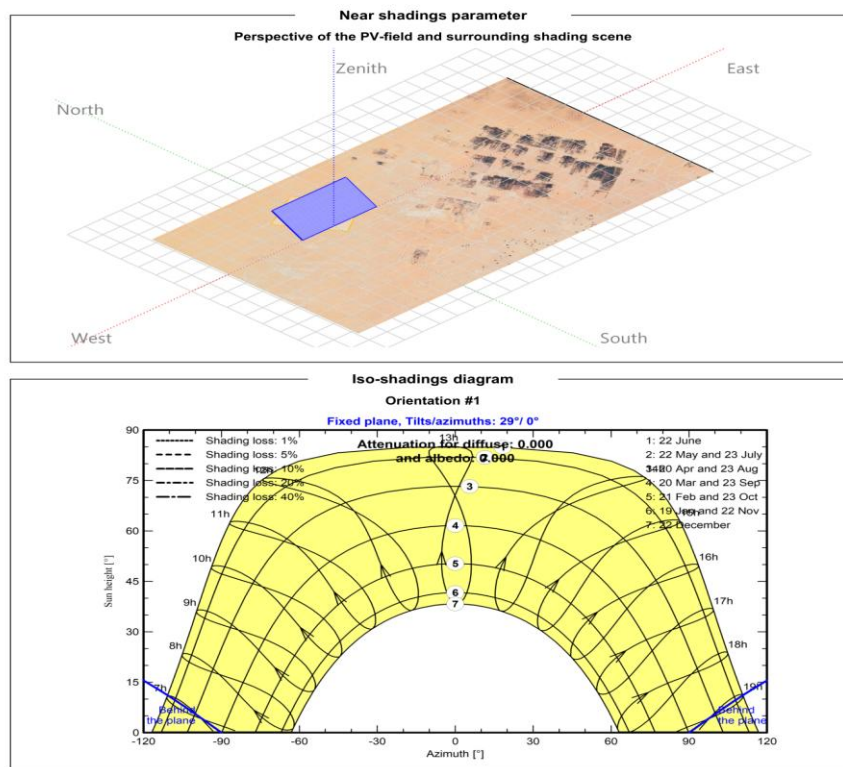
The iso-shadings diagram maps the sun's annual path (sun height vs. azimuth) overlaid with shading loss contour lines (1%, 5%, 10%, 20%, 40%). The yellow zone — which dominates the diagram — represents the region where shading losses are below 1%, confirming that the PV array experiences essentially no near-shading losses (0.00% irradiance loss recorded in the loss diagram).



PVsyst V7.4.7
VC1, Simulation date:
06/15/26 04:30
with V7.4.7

Project: hybride stockage electrogene

Variant: Nouvelle variante de simulation



06/15/26

PVsyst Licensed to

Page 5/10

Figure III.19: Near shading parameters

- **Load profile & seasonal modulation**

The load profile is defined as a daily demand schedule with seasonal modulation across four periods: Summer (Jun–Aug), Autumn (Sep–Nov), Winter (Dec–Feb), and Spring (Mar–May), the overall annual average is 118 kWh/day, with significant seasonal variation.

- **Seasonal load analysis**

Summer & Spring (104 kWh/day): The load profile shows a base load of 5 kW during nighttime hours (00h–05h), a morning peak of 8.6 kW from 06h–08h (irrigation pumping), and a reduced afternoon load of 2 kW before rising again to 5 kW in the evening. The lower daily average reflects reduced heating needs.

Autumn & Winter (132 kWh/day): The same morning peak pattern is observed but extends further into the day (06h–11h at 8.6 kW), and a brief spike of 7.5 kW appears at the 12h mark. This 27% higher winter load compared to summer may reflect longer operational hours, and critically coincides with the period of lowest solar irradiance; creating a seasonal energy balance challenge.

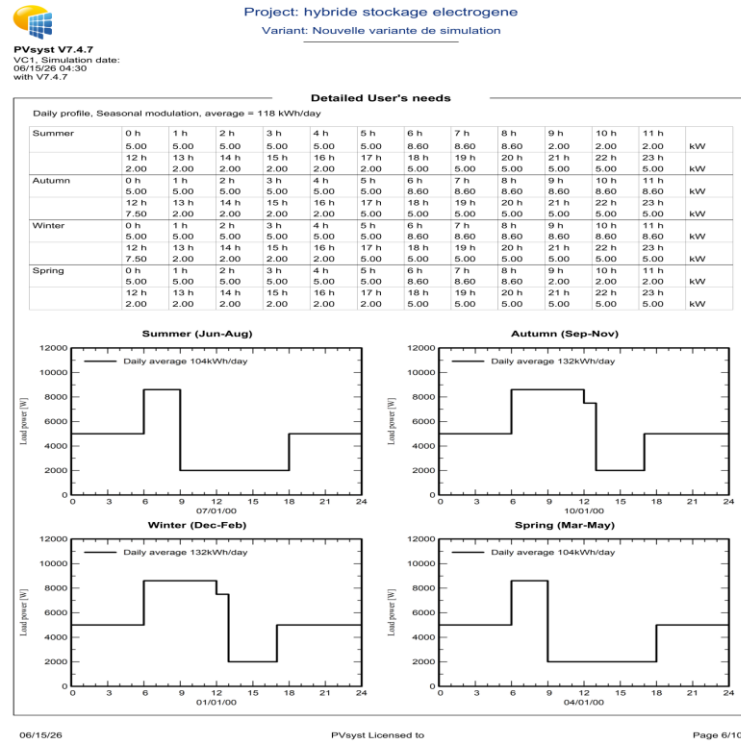


Figure III.20: Detailed user needs during seasons.

- **Main simulation results**

The annual energy balance confirms the system meets user demand with a Solar Fraction of 99.45%, meaning only 244.4 kWh/year (0.55%) is supplied by the back-up diesel generator. This represents an extremely high degree of solar autonomy; a key performance target for remote off-grid installations.

- **Monthly energy balance review**

Peak solar production months are May–August, with available energy ranging from 6,862 kWh (June) to 7,672 kWh (March). However, unused (excess) energy during these months is very high (3,620–4,363 kWh/month), confirming that the battery becomes fully charged and excess generation is wasted; a critical observation for system sizing optimization.

January and December are the critical months: available solar energy drops to 5,999 and 5,390 kWh respectively, while the load remains at 4,095 kWh. The genset provides 107.6 kWh and 136.8 kWh respectively, demonstrating the back-up system's role is minimal but necessary for full reliability.

- **Performance ratio discussion**

The reported Performance Ratio (PR = 43.56%) should be interpreted with caution because this is a standalone hybrid PV-battery system rather than a grid-connected PV plant, in PVsyst, the PR calculation includes energy that cannot be utilized once the battery reaches full charge, which artificially reduces the PR value. Since the diesel generator is configured only as a backup source and contributes approximately 0.55% of the annual load, the low PR does not indicate poor system performance. instead, it reflects the operational strategy adopted to maximize reliability and ensure full load coverage under all seasonal conditions. For isolated systems, Solar Fraction, Loss of Load Probability (LOLP), and energy availability are generally more meaningful performance indicators than PR alone.



PVsyst V7.4.7

VC1, Simulation date:
06/15/26 04:30
with V7.4.7

Project: hybride stockage electrogene

Variant: Nouvelle variante de simulation

Main results

System Production

Useful energy from solar 43009 kWh/year
Available solar energy 80768 kWh/year
Excess (unused) 36403 kWh/year

Back-Up energy from generator

Back-Up energy 244 kWh/year
Fuel Consumption 18 liter/year

Perf. Ratio PR 43.56 %
Solar Fraction SF 99.45 %

Battery aging (State of Wear)

Cycles SOW 96.1 %
Static SOW 85.9 %
Battery lifetime 7.1 years

Economic evaluation

Investment

Global 7,361,340.00 DA
Specific 175 DA/Wp

Yearly cost

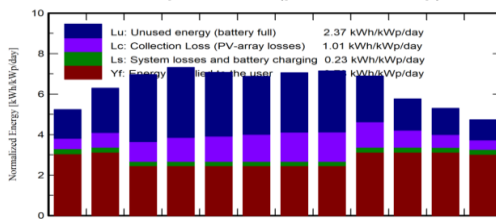
Annuities
Run. costs
Payback period

0.00 DA/yr
21.12 DA/yr
Unprofitable

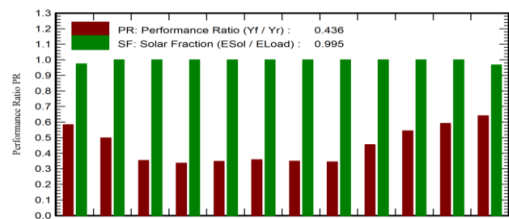
LCOE

Energy cost 0.00 DA/kWh

Normalized productions (per installed kWp)



Performance Ratio PR



Balances and main results

	GlobHor	GlobEff	E_Avail	EUnused	E_BkUp	E_User	E_Load	SolFrac
	kWh/m ²	kWh/m ²	kWh	kWh	kWh	kWh	kWh	ratio
January	109.7	159.0	5999	1851	107.6	4095	4095	0.975
February	131.9	173.1	6407	2583	0.0	3699	3699	1.000
March	184.1	211.2	7672	4318	0.0	3218	3218	1.000
April	213.9	213.8	7606	4363	0.0	3114	3114	1.000
May	236.8	212.8	7459	4109	0.0	3218	3218	1.000
June	232.8	199.8	6862	3620	0.0	3114	3114	1.000
July	242.4	212.2	7183	3833	0.0	3218	3218	1.000
August	225.1	215.5	7287	3936	0.0	3218	3218	1.000
September	185.7	201.9	6940	2850	0.0	3963	3963	1.000
October	141.0	174.9	6238	2008	0.0	4095	4095	1.000
November	111.3	155.9	5726	1635	0.0	3963	3963	1.000
December	97.3	143.8	5390	1296	136.8	4095	4095	0.968
Year	2112.2	2274.0	80768	36403	244.4	43009	43009	0.995

Legends

GlobHor Global horizontal irradiation
GlobEff Effective Global, corr. for IAM and shadings
E_Avail Available Solar Energy
EUnused Unused energy (battery full)
E_Miss Missing energy

E_User Energy supplied to the user
E_Load Energy need of the user (Load)
SolFrac Solar fraction (EUsed / ELoad)

06/15/26

PVsyst Licensed to

Page 7/10

Figure III.21: Main results of system production.

• Energy loss pathway analysis (Sankey diagram)

The loss diagram provides a full energy flow breakdown from incident irradiation to final energy delivered to the user. Starting from 2,112 kWh/m² of global horizontal irradiation, the cascade of losses and gains can be traced through the system:

-Irradiance to array losses

A +10.4% gain is achieved by tilting the array to the collector plane (plane-of-array irradiance benefit). Near shading contributes 0.00% loss. IAM reduces the effective irradiance

by -2.44% , yielding an effective irradiation of $2,274 \text{ kWh/m}^2$ on 201 m^2 of collector area = $457,074 \text{ kWh}$ of irradiation on the array.

-PV conversion losses

With STC efficiency of 20.93% (JA Solar module), the nominal array energy is $95,803 \text{ kWh}$. Key losses: temperature (-11.03%), irradiance level (-0.34%), mismatch (-2.10%), and wiring (-1.34%). A module quality gain of $+0.75\%$ partially offsets these, the largest energy flow identified by PVsyst is the unused energy occurring when the battery reaches full state-of-charge. In this project, this result should not automatically be interpreted as system oversizing. Because the design objective is to achieve very high energy autonomy with only emergency generator support, surplus energy during high-irradiance periods is an expected consequence of maintaining a high level of supply security, the simulation confirms that this design approach successfully achieves a Solar Fraction of 99.45% while maintaining virtually zero unmet load.

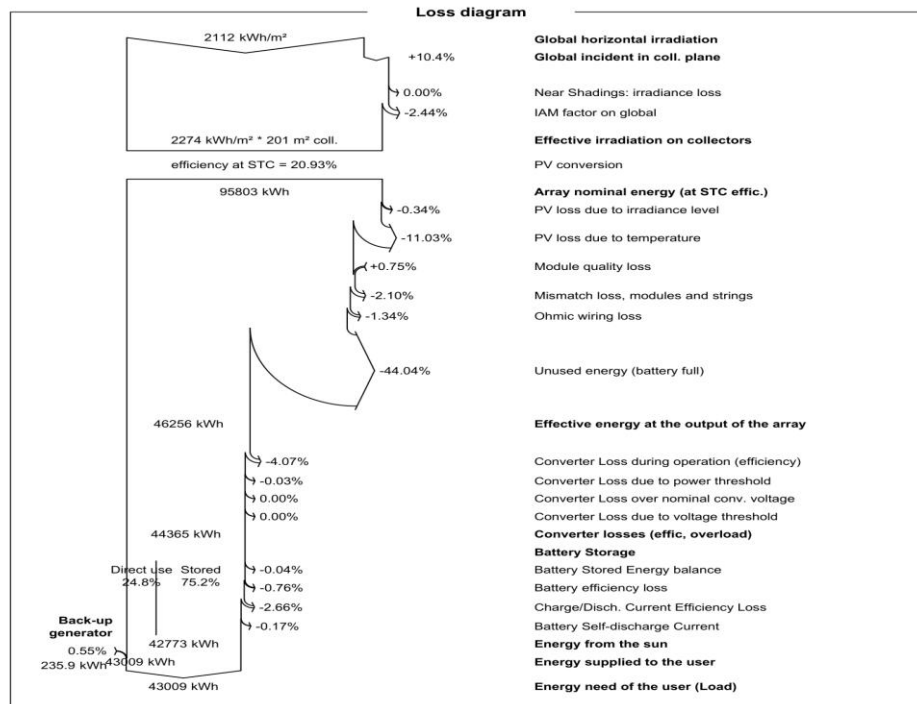
-Converter & battery losses

Converter losses total -4.10% (efficiency + threshold losses). Battery losses include efficiency (-0.76%), charge/discharge current efficiency (-2.66%), and self-discharge (-0.17%). Approximately 75.2% of converter output is stored in the battery while 24.8% is used directly — a healthy direct-use fraction that reduces cycling stress on the batteries.



PVsyst V7.4.7
VC1, Simulation date:
06/15/26 04:30
with V7.4.7

Project: hybride stockage electrogene
Variant: Nouvelle variante de simulation



06/15/26

PVsyst Licensed to

Page 8/10

Figure III.22: Loss diagram

• Daily Input-output diagram analysis

The Daily Input/Output diagram is a scatter plot correlating the global incident irradiation in the collector plane (X-axis, kWh/m²/day) against the useful system output energy (Y-axis, kWh/day). Each data point represents one day of the simulation year.

-Interpretation of the scatter pattern

The diagram reveals two distinct behavioral regions: (1) On days with low-to-moderate irradiation (0–3 kWh/m²/day), the system output varies between ~70–105 kWh/day, maintained by battery discharge to meet load demand even when solar input is insufficient. (2) On high-irradiance days (5–8 kWh/m²/day), the system output clusters tightly around 100–130 kWh/day, corresponding to the full load satisfaction from solar + battery.

The horizontal banding visible at output values near 130 kWh/day (winter load) and 104 kWh/day (summer load) confirms the system's seasonal load modulation. Several isolated low-output days visible at low irradiance correspond to deep winter days when battery charge is depleted and the genset supplements supply.

-Conclusion

The scatter plot's upper cluster at 7–8 kWh/m²/day with output capped at ~130 kWh/day (rather than scaling linearly) reflects battery full-charge limitations and load ceiling; a clear manifestation of the high excess energy fraction noted earlier. An ideal system with matched storage capacity would show a steeper, more linear correlation. This graph is a powerful visual diagnostic tool for identifying battery sizing constraints in standalone systems

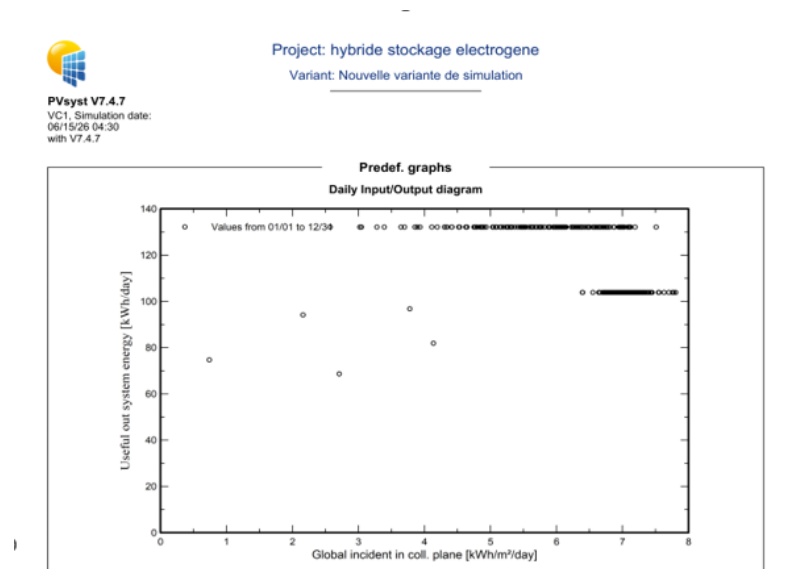


Figure III.23: Daily input /output diagram.

• Economic Evaluation & Cost Breakdown

The total installation cost of the hybrid PV system is 7,361,340 DA (Algerian Dinars), equivalent to 175 DA/Wp at the installed capacity of 42.1 kWp, the annual operating expenditure (OPEX) is minimal at 21.12 DA/year, representing solely the fuel cost for the back-up generator — a testament to the system's high solar fraction.

-Capital cost (CAPEX) breakdown

-Module Mounting Supports: 36,000 DA (0.5%)

- Batteries (18 units × LFP): 1,800,000 DA (24.5%) ;the largest single component cost:

- Controllers (MPPT): 600,000 DA (8.2%)
- Back-up Generator: 900,000 DA (12.2%)
- Accessories & Wiring: 1,300,000 DA (17.7%)
- Engineering: 10,000 DA (0.1%)
- Transport & Installation: 100,000 DA (1.4%)
- VAT: 1,175,340 DA (16.0%)

Project: hybride stockage electrogene
Variant: Nouvelle variante de simulation

PVsynt V7.4.7
VC1: Simulation date:
06/15/26 04:30
with V7.4.7

Cost of the system			
Item	Quantity units	Cost DA	Total DA
PV modules			
JAM78-S30-585-MR	72	20,000.00	1,440,000.00
Supports for modules	72	500.00	36,000.00
Batteries	18	100,000.00	1,800,000.00
Controllers			600,000.00
Back-up generator			900,000.00
Other components			
Accessories, fasteners	1	1,200,000.00	1,200,000.00
Wiring	1	100,000.00	100,000.00
Studies and analysis			
Engineering	1	10,000.00	10,000.00
Installation			
Transport	1	100,000.00	100,000.00
Taxes			
VAT	1	0.00	1,175,340.00
		Total	7,361,340.00
		Depreciable asset	5,976,000.00

Operating costs	
Item	Total DA/year
Fuel for Back-Up generator	21.12
Total (OPEX)	21.12

System summary	
Total installation cost	7,361,340.00 DA
Operating costs	21.12 DA/year
Excess energy (battery full)	36.4 MWh/year
Used solar energy	43.0 MWh/year
Used energy cost	8.5583 DA/kWh

06/15/26

PVsynt Licensed to

Page 10/10

Figure III.24: Cost of the system.

From a purely economic standpoint, the electrification of this desert agricultural farm in Adrar through a hybrid PV-Diesel system represents not merely a technically sound choice, but an overwhelmingly superior economic decision compared to conventional grid extension; The total installation cost of 7,361,340 DA, while significant, must be contextualized against the reality of Adrar's geographical remoteness, extending the Sonelgaz medium voltage network to a desert farm located kilometers from the nearest grid connection point would require infrastructure investments estimated to exceed 16,500,000 DA for the extension alone;more

than double the entire PV-Diesel system cost; without accounting for ongoing subscription fees, energy bills, and the chronic unreliability of grid supply in remote southern Algerian regions.

Furthermore, the simulation demonstrates an exceptionally competitive energy cost of 8.5583 DA/kWh, comparable to or below conventional grid tariffs, achieved with near-complete energy autonomy, the annual operating cost of merely 21.12 DA/year; representing diesel consumption during periods of insufficient solar irradiation; underscores the system's remarkable self-sufficiency; Over a 20-year operational horizon, the hybrid system generates estimated savings exceeding 20 million DA compared to the grid extension alternative, while simultaneously providing the farm operator with complete energy independence; immunity to power cuts, voltage fluctuations, and the administrative constraints associated with Sonelgaz supply contracts, the excess solar production of 36.4 MWh/year; energy generated beyond the system's immediate needs; further highlights the economic opportunity inherent in this design. This surplus could power future farm expansions, additional cold storage capacity, or be redirected toward productive agricultural processes, generating additional revenue without incremental energy cost.

General Conclusion

The work carried out in this thesis was motivated by a fundamental and practical challenge: how to provide reliable, autonomous, and economically viable electrical energy to an isolated agricultural farm in one of the most remote and extreme environments in Algeria, the Saharan region of Adrar.

The answer, as this study has demonstrated, lies in the intelligent combination of solar photovoltaic energy, lithium battery storage, and diesel backup generation; a hybrid architecture that proved to be not only technically capable of meeting every electrical and hydraulic need of the farm, but also overwhelmingly superior to any conventional electrification alternative from an economic standpoint.

Perhaps the most significant achievement of this work is the demonstration that a farm of this scale and complexity; comprising a submersible pump operating at 215 meters of dynamic head, a greenhouse irrigation network, a cold storage facility, and a residential building; can be powered with a total installation cost of **7,361,340 DA** and an annual operating expenditure of barely **21.12 DA/year**, to put this into perspective, simply extending the Sonelgaz medium voltage network to the site would require infrastructure investments exceeding **16,500,000 DA** for the grid connection alone; more than double the cost of the entire hybrid system; without accounting for monthly energy bills, subscription fees, or the chronic unreliability that characterizes grid supply in remote southern Algerian regions. Over a twenty-year operational horizon, the hybrid system generates savings estimated to exceed **20 million DA** compared to the grid extension alternative.

Beyond the economic argument, the simulation results confirmed an exceptional solar fraction of **99.45%**, meaning that the diesel generator; included strictly as an emergency backup; contributes only **0.55%** of the annual energy supply. The farm operates on solar energy for virtually the entire year, achieving a competitive energy cost of **8.5583 DA/kWh** while maintaining complete independence from the national grid, immunity to power cuts, and full operational autonomy even during the most energy-intensive agricultural periods.

The excess solar production of 36.4 MWh/year; energy generated beyond the system's immediate needs during peak irradiation periods; should not be viewed as a design inefficiency

but rather as an untapped economic opportunity. This surplus energy could be redirected toward future farm expansions, additional cold storage capacity, or other productive agricultural processes, generating additional value without any incremental energy cost.

In the broader context of Algerian agricultural development, this study demonstrates that the vast solar-rich desert regions of the south are not an obstacle to agricultural productivity they are, in fact, an energy asset; the hybrid photovoltaic system designed for the Kabertene perimeter represents a replicable and scalable model for sustainable agricultural electrification across the Saharan wilayas of Algeria, where the combination of exceptional solar irradiation, deep groundwater resources, and growing agricultural ambitions creates ideal conditions for the widespread adoption of renewable energy-based farming systems.

Bibliographical references

- [1] Food and Agriculture Organization (FAO), Energy-Smart Food for People and Climate. Rome, Italy: FAO, 2011.
- [2] International Renewable Energy Agency (IRENA), Renewable Power Generation Costs in 2022. Abu Dhabi, UAE: IRENA, 2023.
- [3] United Nations Environment Programme (UNEP), Global Environment Outlook 6. Nairobi, Kenya: UNEP, 2019.
- [4] U.S. Department of Energy, “Energy Efficiency and Renewable Energy,” Office of Energy Efficiency & Renewable Energy, Washington, DC, USA.
- [5] Zhang, Taiping & Stackhouse Jr, Paul & Chandler, William & Hoell, J. & Westberg, D. & Whitlock, C.. (2010). A GLOBAL ASSESSMENT OF SOLAR ENERGY RESOURCES: NASA's Prediction of Worldwide Energy Resources (POWER) Project. AGU Fall Meeting Abstracts..
- [6] Fraunhofer Institute for Solar Energy Systems ISE, Photovoltaics Report. Freiburg, Germany: Fraunhofer ISE, 2025.
- [7] Adam, Muhammad &, Suwarno & Cahyadi, Catra. (2026). Hybrid energy storage systems as a sustainable energy source. International Journal of Advances in Applied Sciences. 15. 219. 10.11591/ijaas. v15.i1.pp219-226.
- [8] European Commission Joint Research Centre, “PVGIS: Photovoltaic Geographical Information System,” European Commission, Brussels, Belgium.
- [9] A. Herez, H. Jaber, H. El-Hage, et al., “A review on the classifications and applications of solar photovoltaic technology,” AIMS Energy, vol. 11, no. 6, pp. 1102–1130, 2023.
- [10] Ahmed, Shoaib & Ali, Dr-Amjad & Ansari, Jamshed & Abdul Qadir, Sikandar & Kumar, Laveet. (2025). A Comprehensive Review of Solar Photovoltaic Systems: Scope, Technologies, Applications, Progress, Challenges and Recommendations. IEEE Access. PP. 1-1. 10.1109/ACCESS.2025.3558539.
- [11] E. Skoplaki and J. A. Palyvos, “On the temperature dependence of photovoltaic module electrical performance,” Solar Energy, vol. 83, no. 5, pp. 614–624, 2009.

-
- [12] Šimić, Zvonimir & Topić, Danijel & Knežević, Goran & Pelin, Denis. (2021). Battery energy storage technologies overview. *International journal of electrical and computer engineering systems*. 12. 53-65. 10.32985/ijeces.12.1.6.
- [13] International Renewable Energy Agency (IRENA), *Electricity Storage and Renewables: Costs and Markets*. Abu Dhabi, UAE: IRENA, 2017.
- [14] Centre de Développement des Énergies Renouvelables (CDER), *Solar Atlas of Algeria*. Algiers, Algeria: CDER.
- [15] Aleyn, Med & ALEY, SIDI & Heyine, Mohamed. (2020). Étude et dimensionnement d'une installation solaire dans un site isolé à Tweimratt (Hodh Gharby). 10.13140/RG.2.2.31102.51526.
- [16] PVsyst SA, *PVsyst Documentation and User Manual*. Satigny, Switzerland: PVsyst SA.
- [17] International Electrotechnical Commission (IEC), *IEC 61400 Wind Turbine Standards*. Geneva, Switzerland: IEC.
- [18] E. Kenu, R. Uhunmwangho, and E. N. C. Okafor, "A Review of Solar Photovoltaic Technologies," *International Journal of Engineering Research & Technology (IJERT)*, vol. 9, no. 7, 2020.
- [19] D. Watson, "Where the sun is: A brief review of solar geometry for architectural designers," in *Passive and Low Energy Architecture*, S. Yannas, Ed., Pergamon, 1983, pp. 471–481, doi: 10.1016/B978-0-08-030581-3.50062-1.
- [20] A. Pan and X. Zhu, "Optoelectronic properties of semiconductor nanowires," in *Semiconductor Nanowires*, J. Arbiol and Q. Xiong, Eds., Woodhead Publishing, 2015, pp. 327–363, doi: 10.1016/B978-1-78242-253-2.00012-8.
- [21] M. S. Ramkumar, R. Felshiya Rajakumari, N. Kannan, R. Premkumar, S. Mohanasundaram, S. Purushotham, D. Ramya, and K. Rajan, "Semiconductor Materials for Solar PV Technology and Challenges towards Electrical Engineering," *Advances in Materials Science and Engineering*, vol. 2022, Art. no. 7272489, pp. 1–14, Aug. 2022.
- [22] M. A. M. Ramli, M. H. Habaebi, S. S. A. Hamid, M. R. Islam, and A. M. Motakabber, "An IoT-Based Smart Monitoring Scheme for Solar PV Applications," in *2021 IEEE 11th IEEE Symposium on Computer Applications & Industrial Electronics (ISCAIE)*, Penang, Malaysia, 2021, pp. 120–125,

-
- [23] B. Đurin, S. Lajqi, L. Plantak, and N. Kranjčić, “Using Solar Photovoltaic Energy for Irrigation: A Review of the Application,” *Advances in Environmental Studies*, vol. 4, no. 2, pp. 358–367, Dec. 2020, doi: 10.36959/742/232.
- [24] M. Alkahtani, Z. Wu, C. S. Kuka, M. S. Alahammad, and K. Ni, “A Novel PV Array Reconfiguration Algorithm Approach to Optimising Power Generation across Non-Uniformly Aged PV Arrays by Merely Repositioning,” *J.*, vol. 3, no. 1, pp. 32–53, Feb. 2020, doi: 10.3390/j3010005
- [25] D. Nnadi, S. E. Oti, and D. C. Ahiabuike, “Mechanical Sun-Tracking Technique Implemented for Maximum Power Point Tracking of a PV System for Effective Energy Supply,” *Nigerian Journal of Technology*, vol. 33, no. 2, pp. 230–237, Apr. 2014, doi: 10.4314/njt.v33i2.13.
- [26] M. H. Alshammari, A. A. S. Mohammed, and A. M. Z. K. Al-Mashhadani, *Hybrid Solar Inverter*, Project Report, Department of Electrical Engineering, Ahsanullah university of science and technology, 2021.
- [27] “Types of photovoltaic systems: characteristics and advantages,” BibLus – ACCA Software, 2025. [Online]. Available: <https://biblus.accasoftware.com/en/types-of-photovoltaic-systems-characteristics-and-advantages/>. [Accessed: Jun. 15, 2026].
- [28] J. A. Assadeg, K. B. Sopian, and A. Fudholi, “Performance of grid-connected solar photovoltaic power plants in the Middle East and North Africa,” *International Journal of Electrical and Computer Engineering*, vol. 9, no. 5, pp. 3375–3383, Oct. 2019,
- [29] L. Stoyanov, G. Notton, and V. D. Lazarov, “Optimisation des systèmes multi-sources de production d’électricité à énergies renouvelables,” *Revue des Energies Renouvelables*, vol. 10, no. 1, pp. 1–18, 2007.
- [30] M. Zellagui, “Chapitre 3 - Les Groupes Électrogènes,” *Cours : Production d’Énergie Électrique*, Département d’Électromécanique, Université de Batna 2, Batna, Algeria, 2024.
- [31] J. Kim and T. Kim, “Compact PEM Fuel Cell System Using Chemical Hydride Hydrogen Source for Portable Power Generators,” *Energy Procedia*, vol. 61, pp. 1992–1995, 2014
- [32] A. S. A. Elmaryami et al., “Design a Solar Water Pump Model to Study the Effect of the Impeller Blades Number on the Pump Performance, Tobruk, Libya,” *Journal of Multidisciplinary Engineering Science and Technology*, vol. 9, no. 1, pp. 15041–15049, 2022.

-
- [33] R. C. Carter, Rural Community Water Supply: Sustainable Services for All. Rugby, U.K.: Practical Action Publishing, 2022.

List of appendices

FICHE DESCRIPTIVE DE PÉRIMÈTRE DE MISE EN VALEUR –4^{ème} PORTEFEUILLE DE L'ODAS

PÉRIMÈTRE : Kabertene 06

SUPERFICIE : 1000 HA

LOCALISATION :

WILAYA : **Adrar**

COMMUNE : **Sebaa - Tamentit**

LIEU DIT : **Kabertene 06**

DISTANCE EN KM/ CLW : **115 km**

DISTANCE EN KM/ CLC : **80 km**

COORDONNÉES GÉOGRAPHIQUES :

Longitude Y : **0,303**

Latitude X : **28,362**

CARACTÉRISTIQUES :

DISTANCE DU RESEAU ÉLECTRIQUE EN KM : **16 km,**

DISTANCE DES VOIES D'ACCÈS EN KM : **15 km par route**

INFRASTRUCTURE DE BASE DISPONIBLE : **néant**

RELIEF DU PÉRIMÈTRE : **plein**

ALTITUDE : \

RESSOURCE HYDRIQUE :

- NAPPE:\

- DÉBIT MOYEN (APPROXIMATIF) : **30 l/s**

- TYPE D'OUVRAGE : **forage**

- PROFONDEUR : **200 m**

RESSOURCE EN SOL :

- TYPE DE SOL : **sablonneux**

- PROFONDEUR DU SOL : **profond**

- APTITUDES CULTURELS : **annuelles et pérennes**

- PRÉVOIR UNE AMÉLIORATION FONCIÈRE : **oui**

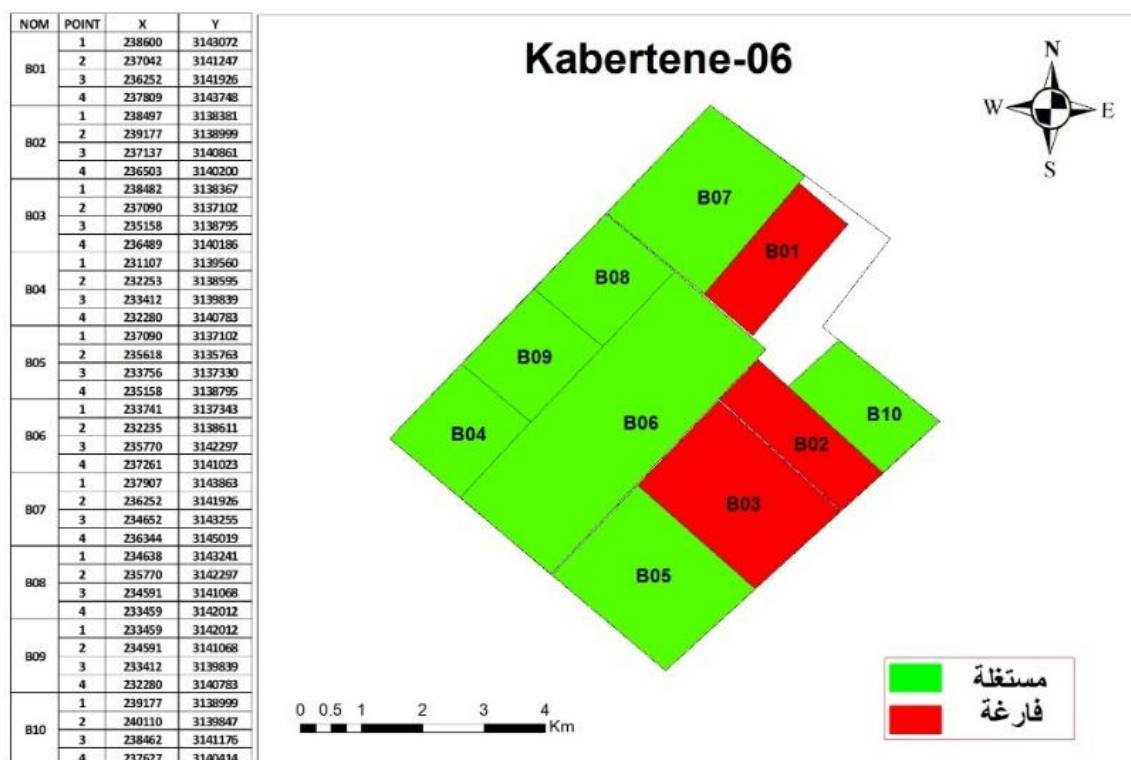
CLIMAT :

- SAHARIEN À TRÈS FORTE ARIDITÉ, À HIVER TEMPÉRÉ.

- SAISON SÈCHE SUR TOUTE L'ANNÉE.

- TEMPÉRATURE ÉLEVÉE, FORTE INSOLATION, HUMIDITÉ QUASIMENT INEXISTANTE, ET DES VENTS FORTS FONT QUE L'ÉVAPOTRANSPIRATION SOIT TROP IMPORTANTE EXIGEANT UN RECOURS CONTINU À L'IRRIGATION.

Appendix 1 : développement perimeter of Kabertene descriptive sheet.



Appendix 2 : Descriptive fact sheet of the perimeter of Kabertene.



STECKER EXPRESS

Current carrying capacity three-phase current

Nominal-cross-section in mm ²	Current-carrying capacity NYY cables	Current-carrying capacity NYCWY cables	Current-carrying capacity NAYY cables	Current-carrying capacity NAYCWY cables
1,5	19,5	19,5	-	-
2,5	25	26	-	-
4	34	34	-	-
6	43	44	-	-
10	59	60	-	-
16	79	80	-	-
25	106	108	82	83
35	129	132	100	101
50	157	160	119	121
70	199	202	152	155
95	246	249	186	189
120	285	289	216	220
150	326	329	246	249
185	374	377	285	287
240	445	443	338	339

We are happy to advise you! Mon - Fri from 8.00 am to 1.00 pm

 Lembergstraße 52
72766 Reutlingen

 00800 / 750 20 20
 0800 / 750 30 30

 info@stex24.com
 www.stex24.com

Appendix 3: Current carrying capacity three-phase current.

Current carrying capacity direct current

Amperes	Power in volts	Cable cross-section for 1 m cable length	Cable cross-section for 3 m cable length	Cable cross-section for 5 m cable length
1 A	12 V	0,75 mm ²	1,5 mm ²	1,5 mm ²
2 A	24 V	0,75 mm ²	2,5 mm ²	4 mm ²
5 A	60 V	1,5 mm ²	6 mm ²	10 mm ²
10 A	120 V	4 mm ²	10 mm ²	16 mm ²
15 A	180 V	6 mm ²	16 mm ²	25 mm ²
20 A	240 V	6 mm ²	25 mm ²	35 mm ²
25 A	300 V	10 mm ²	25 mm ²	50 mm ²
30 A	306 V	10 mm ²	25 mm ²	50 mm ²
35 A	420 V	10 mm ²	35 mm ²	50 mm ²

Appendix 4: Current carrying capacity Direct current.

STANDARD FEATURES

ENGINE

State of the art technology, water cooled, four stroke heavy duty high performance industrial type diesel engine.

COOLING SYSTEM

Made of quality industrial type radiator, expansion tank and cooling fan keeps the engine system at the appropriate temperature of the generator equipment. Radiator and cooling fan, complete with safety guards, designed to cool the engine at high ambient temperatures.

ELECTRICAL SYSTEM

Battery group (12V or 24V), redresser, battery tray and cables are provided with genset. The charging alternator is mounted on the engine and is driven by a belt-pulley. DC starting motor to crank the engine is available mounted on the engine.

FUEL SYSTEM

On Generating Sets up to 1250 kVA, the base-frame design is incorporated with an integral fuel tank with a capacity of approx. 8 hours running at full load. The tank is supplied complete with fill cap breather, fuel level gage, fuel feed and return lines to the engine and drain plug. Higher capacities and double-walled fuel tanks are also available as an option.

LUBRICATION SYSTEM

Our diesel generators feature an efficient oil pump and integrated filtration system, ensuring optimal lubrication and removal of impurities from the engine oil. Equipped with low oil pressure sensors, they automatically trigger an emergency shutdown to protect the engine in critical situations. This advanced oil management system reduces friction among moving parts, extending the engine's lifespan and ensuring reliable performance. With these features, our generators offer superior protection and efficiency, making them an excellent choice for your power needs.

EXHAUST SILENCER

Heavy duty steel industrial type exhaust silencer. Silencer noise reduction level is 10-15 dB(A). Higher capacity silencers also available as residential, critical or hospital types as option.

CUSTOMIZED SOLUTIONS

KJ Power customized power systems, as tailor made production built and

SOUND ATTENUATED CANOPIES

Sound insulated canopies are produced from galvanized sheets in accordance with rust and harsh weather conditions, as modular design canopies are cleaned with a special process and painted with electrostatic powder paint. KJ Power canopies have a modular structure that can be easily disassembled, providing the group with easy service and maintenance and on-site parts replacement. At the same time, the canopies are designed to take into account the cooling performance and power output value of the generator set according to the ambient temperature, and are designed to not cause any power drop during operation. Canopies are produced after prototype tests are carried out for suitability to ambient temperature and sound level.

Container type and super silent canopies are also offered optionally according to customer demand.

ALTERNATOR

Synchronous 4 Poles, 3 phase, self excited, brushless alternators are designed to offer you the best power generation performances. The insulation system is Class H. All windings are impregnated in either a triple dip thermosetting liquid, oil and acid resisting polyester varnish or vacuum pressure impregnated with a special polyester resin. Heavy coating of antitracking varnish provides additional protection against moisture or condensation. The fully sealed Automatic Voltage Regulator (AVR) maintains voltage regulation up to $\pm 1\%$ nominal adjustment by means of a trim pot incorporated on AVR. When the PMG or AREP option is installed, an overload capacity equivalent to **800%** of the full load impedance can be sustained for 10 seconds at Power Factor $\cos\phi = 1$.

FACTORY ACCEPTANCE TESTS

All generator sets manufactured at KJ Power facilities are subjected to load testing before being shipped. Control functions of all protective devices and field load conditions are implemented by simulation.

DOCUMENTATION

Maintenance and user manuals related with engine, generator and controller. Wiring diagram/Electric schematic.

WARRANTY

All our generator sets are covered by a warranty against manufacturing

Appendix 5: KJT25 25KVA DATASHEET.

TYPICAL PV CABLE - CCC				
Electrical Characteristics				
Conductor Size mm ²	Voltage drop factor mV / A.m	Current Rating (exposed) Amps	Insulation Resistance MΩ.km	Conductor Resistance Ω/km @ 20°C
2.5	20.4	21	690	7.98
4	12.6	27	570	4.95
6	8.42	34	490	3.30
10	4.87	48	370	1.91
16	3.09	63	340	1.21



Appendix 6 : PV CABLE-CC voltage drop and current rating.