PEOPLE'S DEMOCRATIC REPUBLIC OF ALGERIA
MINISTRY OF HIGHER EDUCATION AND SCIENTIFIC RESEARCH
University Amar Telidji- Laghouat

Faculty: Technology

Department: Electrical Engineering

Domain: Sciences and Technology

Field: Electrical Engineering

Option: Electrical Power System

Master's dissertation

Presented by: Khettab Zakarya
Alla Abdelaziz

Theme

Techno-Economic Analysis and Optimization of Grid-Connected Hybrid Renewable Energy Systems Using Homer Pro

Publicly supported ahead of a jury composed of:

Full name	Grade	Quality
CHETTIH Saliha	Prof	President
ARIF Salem	Prof	Examiner
OUBBATI Youcef	M.C.A	Supervisor
HALMOUS Abdelkader	PhD Student	Co-Supervisor

Academic Year: 2023-2024

الملخص: تناقش هذه المذكرة التحليل الاقتصادي و التقني لتركيب نظام الطاقة المتجددة الهجين، حيث استخدمنا برنامج Homer كأداة لتحسين و إيجاد افضل ظرف و تركيب يمكن ان يحقق الكفاءة الاقتصادية للمستثمر في الطاقة المتجددة، أولا تم اختبار عدة سناريوهات لأسعار الشراء و البيع من و الى الشبكة و لاحظنا ان السعر المدعم للكيلوواط ساعي من طرف الدولة (الدول البترولية) يؤثر على عائدات المستثمرين في الطاقة المتجددة، في المقابل ان سعر الكيلوواط ساعي الغير مدعم يحفز المستثمرين في الطاقات المتجددة بعائدات اكبر و أفضل. ومنه أسعار البيع وشراء الكهرباء تؤثر على قرارات المستثمرين في الطاقات المتجددة، ثانيا مع تثبيت سعر البيع و شراء الكهرباء تم اختبار عدة سناريوهات و تراكيب للطاقات المتجددة و أظهرت النتائج ان افضل نظام يحقق الكفاءة الاقتصادية و الأعلى أرباحا هو التهجين بين طاقة الرياح و الطاقة الشمسية في حالة الاتصال بشبكة كهرباء موثوقة، و هذا يساعد في تقليل انبعاثات الكربون و الحفاظ على البيئة.

الكلمات المفتاحية: نظام طاقة هجين، هومر، الطاقة المتجددة، صافي التكلفة، التحسين.

Abstract: This work discusses the techno-economic analysis of a hybrid renewable energy system using HOMER Pro. We used this tool to optimize and find the optimal conditions and configurations that could achieve economic efficiency for renewable energy investors. First, several scenarios of buying and selling prices to and from the grid were tested. We observed that the subsidized kilowatt-hour price by the government (in petroleum countries) affects the returns of renewable energy investors. On the other hand, the unsubsidized kilowatt-hour price encourages renewable energy investors with higher and better returns. Furthermore, with fixed buying/selling prices, various renewable energy scenarios and configurations were evaluated. The optimal system for maximizing economic efficiency and profitability is the hybridization of wind and solar energy, coupled with a reliable grid connection. This hybrid approach reduces carbon emissions and promotes environmental sustainability.

Keywords: Hybrid power system, HOMER, renewable energy, Net Present Cost, Optimization.

Résumé : Ce travail traite de l'analyse technico-économique d'un système hybride d'énergie renouvelable utilisant HOMER Pro. Nous avons utilisé cet outil pour optimiser et trouver les conditions et configurations optimales pouvant atteindre une efficacité économique pour les investisseurs en énergie renouvelable. Tout d'abord, plusieurs scénarios de prix d'achat et de vente vers et depuis le réseau ont été testés. Nous avons observé que le prix du kilowattheure subventionné par le gouvernement (dans les pays pétroliers) affecte les rendements des investisseurs en énergie renouvelable. En revanche, le prix du kilowattheure non subventionné encourage les investisseurs en énergie renouvelable avec des rendements plus élevés et meilleurs. En outre, avec des prix d'achat/vente fixes, divers scénarios et configurations d'énergie renouvelable ont été évalués. Le système optimal pour maximiser l'efficacité économique et la rentabilité est l'hybridation de l'énergie éolienne et solaire, couplée à une connexion fiable au réseau. Cette approche hybride réduit les émissions de carbone et favorise la durabilité environnementale.

Mots-clés : Système de puissance hybride, HOMER, énergie renouvelable, Coût net actualisé, Optimisation.

Dedication

To my father, who provided me with all the support and encouragement throughout my educational journey, may God prolong his life.

To my mother, may God have mercy on her.

To my aunt, may God protect her.

To my brother, my best friend and greatest supporter.

To my siblings who believed in me and my abilities.

To my esteemed teachers, who generously shared their knowledge and valuable guidance with me.

To my friends and colleagues, who were companions on the difficult path and in challenging situations.

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

Thank you for your support and encouragement.

Zakarya

Dedication

To the soul of my beloved and dear late mother.

You left, oh piece of my heart. May God have mercy on you and grant you the highest place in paradise, God willing.

Here I am today, achieving your dream. But your absence, oh love of my heart, has mixed my sorrows and tears with my joy.

May God envelop you in His mercy, you who supported me with your prayers and supplications.

May God have mercy on you, the strongest woman who ever existed.

To the one with a noble character and enlightened mind,

who played a major role in my reaching higher education (my dear father), may God prolong his life.

To my brothers and sisters, my support in this world, in my strength and weakness, may God keep you in my life.

To all my esteemed teachers who did not hesitate to extend a helping hand to me.

To my friends who were like a support and strength to me in my joys and sorrows.

I dedicate this humble work to you.

Abdelaziz

Acknowledgment

First and foremost, we thank Almighty God for granting us courage, determination, patience, and health throughout all these years of study, and by His grace, we were able to accomplish this work.

We would like to express our deep gratitude to our esteemed supervisors, **Dr. OUBBATI Youcef** and **Dr. HALMOUS Abdelkader**, for their continuous encouragement, supervision, precision, and valuable advice. Without their insight and support, it would have been impossible to complete this work.

We also thank the members of the examination committee **Pr. ARIF Salem** and **Dr. CHETTIH Saliha** who agreed to review and evaluate this work.

We would like to thank the Department of Technology at Amar Telidji University in Laghouat and all the professors throughout the years of study.

We also wish to express our deep gratitude to all the people who significantly contributed to the completion of this final study project, especially our families for their immense moral support and encouragement over the years.

Contents

Chapter II: Modelling of hybrid renewable energy system components 22

List of Figures

List of Tables

Nomenclature

Symbols

P_m	Power from a wind turbine
ρ	Air density
s	The area swept by blades
v	Wind speed
C_p	Wind energy utilization factor or power coefficient
I_b	The direct normal solar radiations
I_d	The direct diffuse solar radiations
R_d	Tilt factors for the diffuse portions of the solar radiations
R_r	Tilt factors for the reflected portions of the solar radiations
T_c	Cell temperature (°C)
T_r	The reference temperature for the cell efficiency
I_T	The total solar radiation
U_L	Coefficient of heat transfer to the surroundings (kW/ m^2)
$\alpha\tau$	Transmittance of the cover over of the PV module
P_f	The packing factor
T_a	The instantaneous ambient temperature
NOCT	Normal operating cell temperature
V_Z	The wind speed at hub
V_i	The wind speed at reference height
Z	The wind speed hub

Z_i	The wind speed reference height
x	Power law exponent
P_r	The rated power
V_{ci}	The cut-in the wind speed
V_{co}	The cut-out the wind speed
V_r	Speed of the wind turbine
A_w	The total swept area
η	Efficiency of wind turbine generator and corresponding converters
$E_{c(Ah)}$	The load in ampere-hours
Ds	The battery autonomy or storage days
DOD_{max}	The maximum battery depth of discharge
η_t	Stands for the temperature correction factor
E_B (t)	The charge level of the battery bank at time t
E_B (t - 1)	The charge level of the battery bank at time $t - 1$
σ	The hourly self-discharge rate
E_{GA} (t)	the total energy generated by the renewable energy source after accounting for losses in the controller
E_L (t)	the load demand at time t
η_{inv}	The efficiency of the inverter
η_{battery}	The charging efficiency of the battery bank
$E_{B_{max}}$	The maximum charge level of the battery
$E_{B_{min}}$	The minimum charge level of the battery

$P_{INV,OUT}$	Inverter output power (kW)
$P_{REC,OUT}$	Rectifier output power (kW)
η_{REC}	Inverter and rectifier efficiency (%)
P_{AC}	AC power (kW)
P_{DC}	DC power (kW)
$\mathrm{C}_{\mathrm{capital}}$	Initial cost
$\mathrm{C}_{\mathrm{replace}}$	Replacement value
$\mathrm{C}_{\mathrm{salvage}}$	Salvage value
$\mathrm{L}_{\mathrm{primAC}}$	The alternating current primary load
$\mathrm{L}_{\mathrm{primeDC}}$	The direct current main load

Acronyms and abbreviations

HRES	Hybrid Renewable Energy Systems
PV	Photovoltaic
WTs	Wind Turbines
A-Si	Amorphous Silicon
CdTe	Cadmium Telluride
CIGS	Copper Indium Gallium Selenide
MPPT	Maximum Power Point Tracking
FL	Fuzzy Logic
ANN	Artificial Neural Networks
NN	Neural Network
MPP	Maximum Power Point

SCIG	Squirrel-Cage Induction Generator
DFIG	Doubly Fed Induction Generator
PMSG	Permanent Magnet Synchronous Generators
HAWTs	Horizontal Axis Wind Turbines
VAWTs	Vertical Axis Wind Turbines
ESS	Energy Storage Systems
SC	Supercapacitors
CAES	Compressed Air Energy Storage
UTES	Underground Thermal Energy Storage
NOCT	Normal Operating Cell Temperature
RESs	Renewable Energy Sources
NOCT	Normal Operating Cell Temperature
BSS	Battery Storage Systems
IHOGA	Improved Hybrid Optimization Genetic Algorithm
RETScreen	Renewable Energy and Energy Efficiency Technology Screen
GUI	Graphical User Interface
CEDRL	CANMET Energy Diversification Research Laboratory
UNEP	United Nations Environment Programme
SAGCHPS	Solar Assisted Ground Coupled Heat Pump System
TRNSYS	Transient System Simulation Tool
VGHEs	Vertical Ground Heat Exchangers
HOMER	Hybrid Optimization Model for Electric Renewable

TNPC	Total Net Present Cost
NASA	National Aeronautics and Space Administration
NREL	National Renewable Energy Laboratory
LCOE	Levelized Cost of Energy
RET	Renewable Energy Technologies
GPP	Grid Power Price
GSP	Grid Sellback Price
Ren frac	Renewable Fraction
CO_2	Carbon dioxide

Electricity plays a crucial role in the sustainable growth and economic prosperity of any country. The population explosion on Earth has led to a continuous increase in the demand for energy, especially electricity. This growing energy demand has contributed to energy scarcity, primarily due to the continuous use of fossil fuels in transportation and power generation.

This master's dissertation examines an issue centered on how to improve grid-connected hybrid renewable energy systems through technical and economic analysis. The issue includes identifying the optimal design to ensure high efficiency and sustainability, applying economic tools to assess financial feasibility, and addressing the challenges of integrating these systems with existing grids. It also focuses on how to improve performance through data analysis and analytical techniques, with an emphasis on environmental and social benefits.

Using renewable energy instead of fossil fuels aims to achieve a range of environmental, economic, and social benefits. Renewable energies produce clean energy that reduces greenhouse gas emissions and air pollutants caused by burning fossil fuels. Additionally, renewable resources such as sunlight and wind are inexhaustible over time, unlike fossil fuels, which gradually deplete, ensuring a continuous energy supply for future generations. Moreover, investment in renewable energies encourages innovation and the development of new technologies in the energy sector, leading to improved efficiency and cost reduction in the long term. The transition to renewable energies aims to build a cleaner, more sustainable, and secure energy system, offering long-term economic and social benefits.

Hybrid Renewable Energy Systems (HRESs) have emerged as solutions for sustainable and reliable energy. **The chapter 1** provides a comprehensive overview of HRESs, starting with an introduction to their fundamental concepts and discussing their advantages and disadvantages. It covers details of solar energy systems, wind energy systems, the critical role of energy storage systems, and the necessary converters and control mechanisms to optimize HRES performance.

Chapter 2 focuses on modeling components within hybrid renewable energy systems. It emphasizes the importance of accurate component modeling in optimizing system performance and covers detailed models of photovoltaic generators, wind turbine systems, battery storage, and bidirectional converters. Additionally, it explores various methods for optimizing hybrid renewable energy systems, with a specific focus on the HOMER software. The chapter provides a guide to the interfaces of HOMER Pro and instructions on starting a project in HOMER Pro.

Chapter 3 presents the results and discussion of modeling and simulation of hybrid renewable energy systems. It begins with an introduction to site selection and data description, focusing on residential load profiles and various components such as PV systems, wind systems, battery storage, and bidirectional converters. The chapter details the different scenarios tested, with comprehensive analysis and discussion of results for each system configuration, covering both grid-connected and off-grid scenarios and evaluating performance under reliable and unreliable grid conditions.

Finally, we end our master's dissertation with the main conclusions and some prospects for future research.

Objectives of this dissertation

- To see the effect of grid power prices and sellback on the returns of renewable energy sources.
- To analyse the grid connection conditions (off-grid, reliable grid, unreliable grid) on the economic side of the consumers.
- To determine the best configuration that gives a reliable system and best returns.
- To find the best size for every component in the hybrid system.
- To minimize the emissions of CO_2 to the environment.

I.1. Introduction

Hybrid Renewable Energy Systems (HRES) have emerged as a critical solution in the quest for sustainable energy sources, addressing both opportunities and challenges in our power system. In order to provide a stable and dependable energy supply, these systems strategically integrate a variety of renewable energy sources, solar, wind, biomass, and hydropower. This strategy of integration not only guarantees à steady supply of energy but also maximizes resource efficiency and reduces environmental effects.

One of the key aspects is the optimal design and operation of HRES. Operation optimization focuses on efficient energy management and utilization, contributing significantly to the overall performance and cost-effectiveness of HRES. In addition to technical aspects, the role of HRES extends to providing access to electricity in off-grid and remote areas [1,2]

In this chapter we will provide a general idea for each part of hybrid renewable energy systems (Photovoltaic System, Wind Energy Systems, Converters and Energy Storage Systems).

I.2. Pros and Cons of Hybrid Renewable Energy Systems

Hybrid renewable energy systems combine two or more renewable energy sources to generate power. This approach takes advantage of the strengths of different sources to improve energy production and reliability. Here are the pros and cons of HRES [3]:

I.2.1. Pros

Hybrid Renewable Energy Systems offer à multitude of benefits that make them a compelling choice for sustainable energy solutions. These benefits make Hybrid Renewable Energy Systems a Solution for addressing energy challenges, we mention some of them :

Continuous Power Supply: Incorporate diverse renewable energy sources (such as wind, solar, etc.) to ensure a continuous supply of power, considering the variability of each source and balancing them accordingly.

Low Maintenance Cost: to Choose reliable components and technologies with low maintenance requirements, such as durable wind turbines and efficient solar panels with minimal degradation over time.

High Efficiency: utilization advanced converters, control algorithms, and energy storage systems to maximize the overall efficiency of the HRES, optimizing energy conversion and utilization.

Economic and Environmental Returns: Conduct cost-benefit analyses and consider the long-term economic and environmental impacts of the HRES, including factors like reduced fuel costs, avoided emissions, and potential revenue from excess energy production.

Reduced Negative Effects of Fossil Fuels: Replace or minimize reliance on fossil fuel-based backup systems by enhancing the reliability and resilience of the HRES through energy storage, grid integration, and backup power options from renewable sources.

Transmission and Distribution Relief: Distribute HRES installations strategically to alleviate congestion on transmission and distribution networks, improving overall system stability and efficiency.

Improved Power Quality: utilization power conditioning equipment and grid integration technologies to maintain high-quality power output, minimizing voltage fluctuations and ensuring compatibility with electrical loads.

I.2.2. Cons

Hybrid Renewable Energy Systems offer significant benefits but also come with certain cons that need to be addressed. These cons can include [3]:

Complex System Design and Integration: Utilization modular design principles, standardized components, and advanced simulation tools to streamline system integration and optimize overall performance.

Weather Dependence: Implement hybrid configurations that combine multiple renewable sources (solar, wind) to mitigate the impact of weather fluctuations, improving system reliability and energy availability.

System Control and Management: Develop advanced control algorithms, predictive analytics, and real-time monitoring systems to optimize system performance, maximize energy yield, and proactively address operational challenges.

Location-Based Performance: Conduct thorough site assessments, feasibility studies, and resource mapping to identify optimal locations for HRES installations, considering environmental factors, grid connectivity, and energy demand patterns.

While these cons exist, ongoing advancements in renewable energy technology, and are addressing many of these concerns, making HRES an increasingly viable and attractive option for sustainable energy solutions.

I.3. Photovoltaic (PV) Systems

Photovoltaic (PV) technology is a method of generating electrical power by converting solar radiation into direct current electricity using semiconducting materials that exhibit the photovoltaic effect. This technology plays a crucial role in the renewable energy sector, particularly in solar power generation. the PV system designer depends on the capacity of a storage battery for reliable extended operation of the system load during hours of darkness and below average solar resource.

PV systems can be off-grid or grid-on, contributing to the generation of clean and sustainable energy [4].

I.3.1. Types of Photovoltaic Systems

a. Monocrystalline Solar Cells:

These cells are made from a single crystal structure of silicon, resulting in a uniform and high-purity material (Figure 1). Monocrystalline cells have high efficiency rates (typically 15-22%) due to their uniformity, making them suitable for applications where space is limited, such as rooftop installations. However, they are more expensive to produce compared to other types [5].

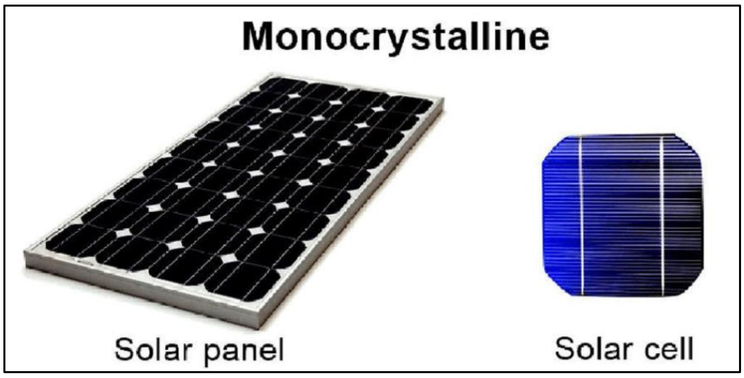


Figure I.1 Monocrystalline Solar Cells [5].

b. Polycrystalline Solar Cells:

Polycrystalline cells are made from multiple silicon crystals, resulting in a lower purity but lower production cost compared to monocrystalline cells (Figure 2). They have slightly lower efficiency rates (typically 13-18%) but offer a cost-effective option for larger installations where space is not a constraint [5].

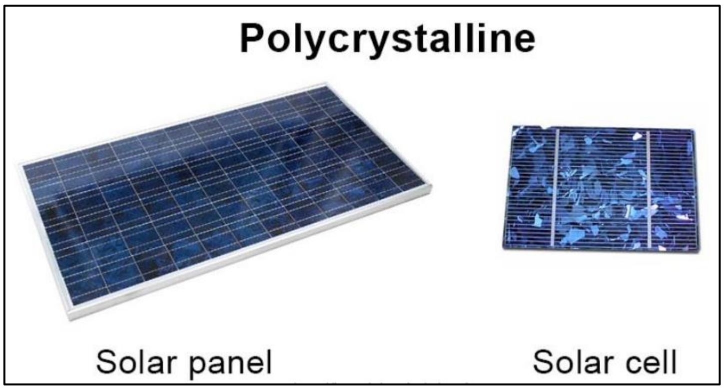


Figure I.2. Polycrystalline Solar Cells [5].

c. Thin-Film Solar Cells:

Thin-film technology uses layers of semiconductor materials deposited onto a substrate, such as glass, plastic, or metal. Common thin-film materials include Amorphous Silicon (a-Si), Cadmium Telluride (CdTe), and Copper Indium Gallium Selenide (CIGS). Thin-film cells are lightweight, flexible, and can be integrated into building materials or curved surfaces, offering versatility in design and applications (Figure 3). However, they generally have lower efficiency rates (typically 10-12%) compared to crystalline silicon cells [5].

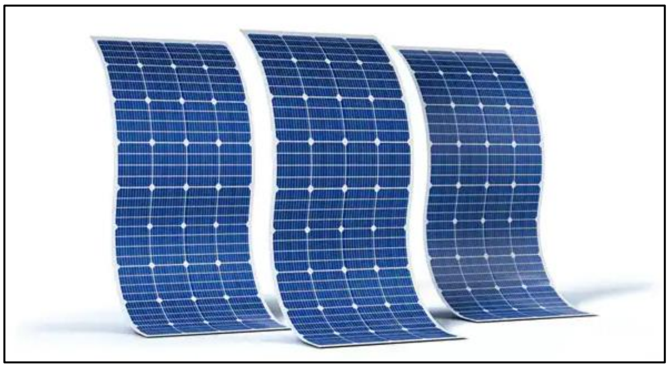


Figure I.3. Thin-Film Solar Cells.

I.3.2. Applications and Advantages

Photovoltaic (PV) systems are highly versatile and adaptable, making them suitable for a wide range of applications across various sectors due to their versatility, reliability, and sustainability. Here are some specific applications of photovoltaic systems [6].

- **Residential rooftops:** Providing clean energy for homes and reducing electricity bills.
- **Utility-scale solar farms:** large installations in open areas or deserts to contribute significantly to the grid’s electricity supply.
- **Renewable and sustainable:** Solar energy is abundant and inexhaustible, reducing reliance on fossil fuels and mitigating environmental impacts.
- **Energy independence:** PV systems allow users to generate their electricity, reducing dependence on centralized power grids and improving resilience.
- **Cost savings:** Over time, PV systems can lead to significant cost savings on electricity bills and provide a return on investment.

I.3.3. Maximum Power Point Tracking (MPPT) for Photovoltaic

MPPT techniques are essential in photovoltaic systems due to the varying maximum power point influenced by irradiation and temperature. Utilizing MPPT techniques is crucial to achieve the highest power output from a solar array. Given these limitations, employing MPPT technology becomes imperative for maximizing power transfer efficiency. The PV solar module exhibits à non-linear relationship between voltage and current. Figures 5 and 6 illustrate the characteristic curves of power voltage (P-V) and current voltage (I-V) respectively [7].

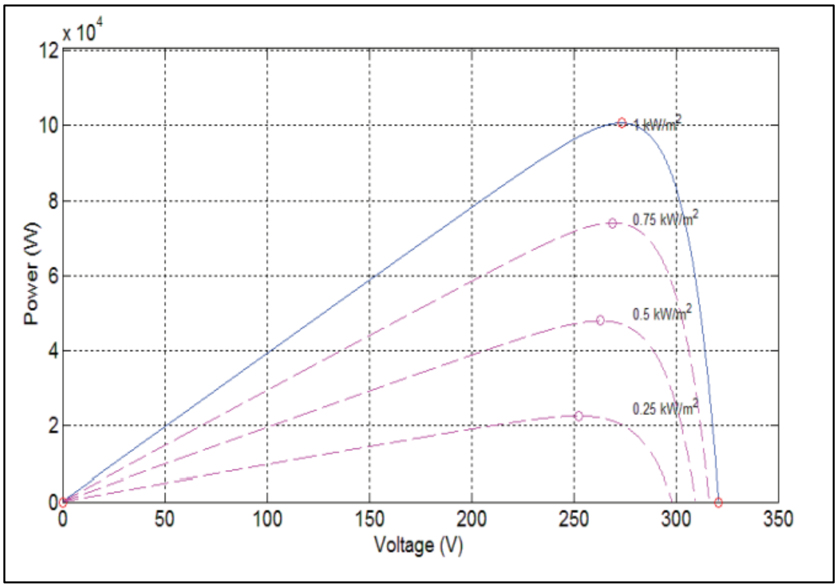


Figure I.4. PV power voltage characteristic curves **[7].**

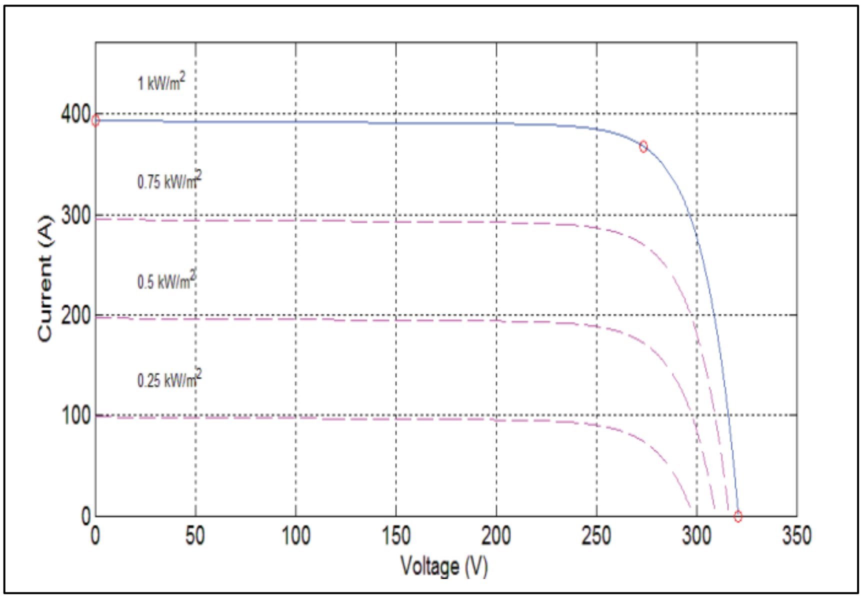


Figure I.5. PV current_ voltage characteristic curves **[7].**

There are several methods to track the maximum power point based on artificial intelligence, including Fuzzy Logic (FL), Artificial Neural Networks (ANN)

Fuzzy Logic is considered as one of the most suitable techniques for MPPT. The P-V curves exhibit non-linear function influenced mainly by weather conditions. FL control has several advantages; it does not require precise mathematical modeling . Furthermore, FL controller does not require exact knowledge of PV characteristics and needs only two low cost sensors voltage and current. Although its implementation needs a high level programming knowledge.

In recent times, Neural Network (NN) controllers have seen significant advancements, both in theory and practical application. They have gained considerable attention in the field of electrical engineering and have been implemented across various electro-technical applications. These controllers offer the advantage of robustness and relatively straightforward design, the major drawback of this controller is the additional cost of temperature and irradiance. Sensors in addition, this controller suffers from loss of robustness against aging of PV modules including the tracking of Maximum Power Point (MPP) in PV systems. These controllers offer the advantage of robustness and relatively straightforward design, as they do not necessitate precise knowledge of physical definitions or exact models for PV arrays [8, 9].

Overall, Photovoltaic (PV) Maximum Power Point Tracking (MPPT) is crucial because it ensures that the PV system operates at its maximum power output, regardless of environmental conditions.

I.3.4. Challenges and Limitations

The integration of photovoltaic (PV) systems is viewed as a component of the shift, towards sustainable energy. Although there are advantages, PV systems encounter obstacles and constraints. Therefore it is essential to recognize the challenges and limitations [6]:

- **Intermittency:** Solar energy generation is intermittent and depends on weather conditions, requiring energy storage solutions or backup power for continuous supply.

- **Initial costs:** The upfront costs of installing PV systems, including solar panels, inverters, and balance of system components, can be relatively high, although they have been decreasing over time.

- **Grid integration:** Integrating large-scale PV systems into existing grids may pose technical challenges such as voltage fluctuations, frequency control, and grid stability, requiring advanced control and monitoring systems.

- **Land use and environmental impact:** Utility-scale solar farms may require significant land area, raising concerns about land use, and visual impacts, necessitating careful site selection and environmental assessments.

All things considered, photovoltaic (PV) technology, which generates clean, renewable electricity from sunshine, is essential to the shift to a sustainable energy future.

I.4. Wind Energy Systems

Wind energy is a form of renewable energy that harnesses the kinetic energy of moving air to generate electricity, presenting a sustainable and clean alternative to fossil fuels. This form of energy aids in cutting greenhouse gas emissions and combating climate change. Its history spans centuries, initially seen in windmills for mechanical tasks and evolving into modern wind turbines for electricity generation. This transition to wind power is vital for fostering a sustainable energy ecosystem, delivering advantages such as energy self-sufficiency, reduced environmental harm, and job growth within renewable energy sectors. Ongoing technological advancements in wind turbine technology enhance efficiency and cost-effectiveness, positioning wind energy competitively in the global energy landscape [10,11].

I.4.1. Components of Wind Energy System

A wind energy conversion system comprises a turbine tower holding the nacelle and rotor, including blades and hub. Most modern turbines are horizontal-axis with three blades upwind of the tower and nacelle. As illustrated in Figure 6 .The nacelle typically houses anemometers, wind vanes, and aviation lights for wind measurement and safety. Internally, it contains crucial components like the gearbox, brake, generator, control systems, and yaw drive. Wind turbines are not just singularly placed but form wind farms with capacities comparable to conventional power units, impacting overall power system operations and control [10].

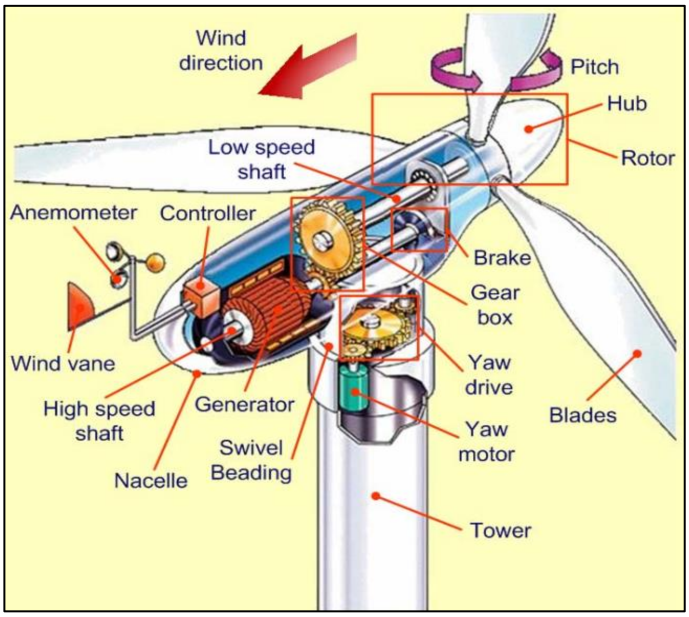


Figure I.6. Principal components of most wind energy conversion systems [10].

A wind turbine functions as a rotary device that harnesses energy from airflow, typically wind, using specially designed blades to convert it into mechanical power. The amount of power generated correlates with wind speed, but it's crucial to control and limit this power during high wind speeds to prevent damage to the turbine.

Three common types of wind generator systems are widely used. The first type employs à constant-speed wind turbine system with a standard Squirrel-Cage Induction Generator (SCIG) directly linked to the power grid. The second type features à variable-speed wind turbine system using a Doubly Fed Induction Generator (DFIG). The third type utilizes a variable-speed wind turbine with a full-rated power electronic conversion system and either a synchronous generator or SCIG. In the first two types, a multi-stage gearbox is typically incorporated, while synchronous generators, including Permanent Magnet Synchronous Generators (PMSG), can be directly driven through a low-ratio gearbox system, making a one or two-stage gearbox an attractive alternative. Figure 7 provides an overview of the key components involved in the mechanical and electrical power conversion of a typical wind turbine system [10,11].

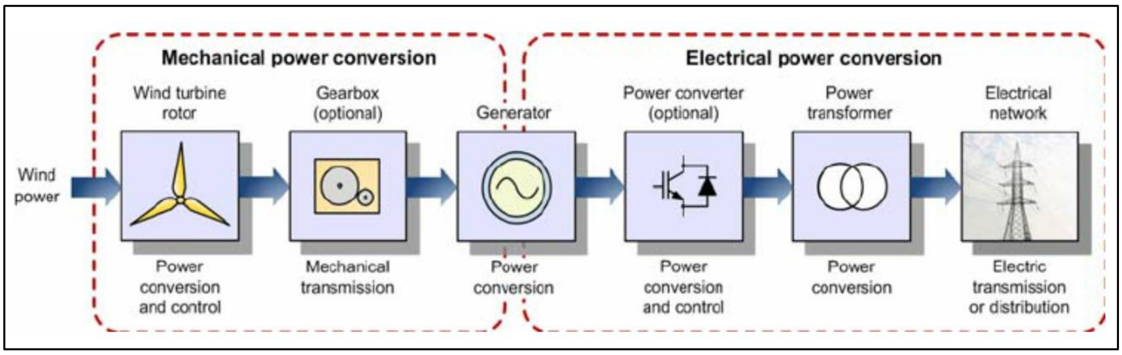


Figure I.7. General description of a wind turbine system [10].

The appropriate voltage for a wind turbine depends on its power output. In modern setups, a transformer is commonly used to increase the generator terminal voltage, typically below 1 kV (such as 575 or 690 V), to a medium voltage range of 20-30 kV for local electrical connections within a wind farm (distribution level). For large wind farms with substantial distances to the electrical grid, further voltage increase occurs using transformers, stepping up the medium voltage to a high transmission level, like over 100 kV for onshore farms of hundreds of MWs. Offshore wind farms, due to longer transmission distances, use submarine cables buried in the sea bed to transfer power to onshore grids. Turbines in these farms connect to à transformer substation, often offshore, over 5 km from the shore [10].

I.4.2. Types of Wind Turbines

Wind energy is a significant and eco-friendly source of power that has gained increasing importance in recent years. The installation of wind power capacity grows annually, with many countries planning substantial investments in this sector. Wind turbines come in various types, categorized based on the orientation of their axis of rotation into two groups: Horizontal Axis Wind Turbines (HAWTs) and Vertical Axis Wind Turbines (VAWTs) [12].

a. Vertical Axis Wind Turbines (VAWTs)

The main rotor shaft of a Vertical Axis Wind Turbines (VAWT) is arranged vertically, as shown in Figure 8. This arrangement has the benefit of working well even in situations where wind direction fluctuates considerably because it doesn't require exact alignment with the wind direction. Due to its natural ability to eliminate the need for steering systems, this flexibility is particularly beneficial for incorporating the turbine into buildings. Furthermore, direct driving from the rotor assembly is made possible by placing the generator and gearbox close to the ground, which improves accessibility for maintenance duties. But over time, VAWTs often produce less energy, which is a major disadvantage [11, 12].

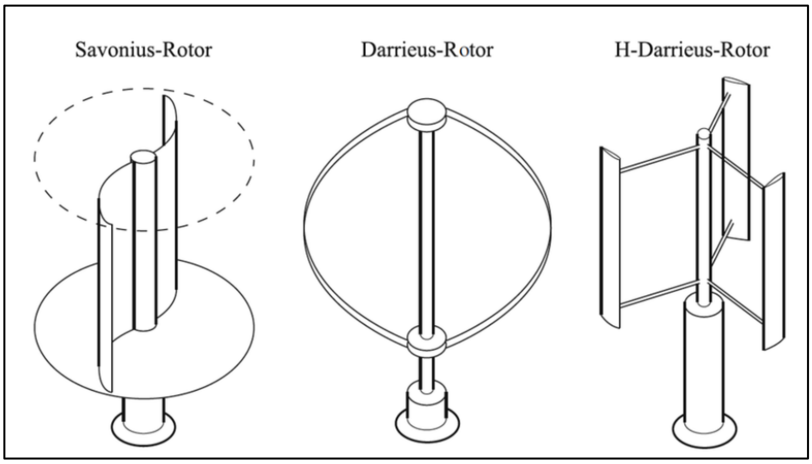


Figure I.8. Different types of vertical axis wind turbines [12].

a.1. Darrieus Wind Turbines

A Darrieus wind turbine is à Vertical Axis Wind Turbine (VAWT) with curved blades rotating around a vertical axis. It typically requires guy wires for support, is situated close to the ground, and has a simpler foundation design due to the absence of a tower [8].

a.2. Savonius Wind Turbines

A Savonius wind turbine is a Vertical Axis Wind Turbine (VAWT) characterized by its S-shaped rotor design. These turbines are known for being easy to manufacture and transport compared to other types. They can operate close to the ground, where winds are less turbulent, and often do not need guy wires for support [12].

b. Horizontal Axis Wind Turbines (HAWTs)

The Horizontal Axis Wind Turbine (HAWT) is the second type of wind turbine, featuring blades that spin on a horizontal axis as illustrated in Figure 9. Unlike its counterpart, the Vertical Axis Wind Turbine (VAWT), the HAWT is widely employed in commercial energy production to supply power to customers. Horizontal Axis Wind Turbines tend to capture more wind energy from their blades compared to Vertical Axis Wind Turbines because the entire swept surface of HAWT blades consistently faces into the wind during operation [11,13].

Figure I.9. Horizontal Axis Wind Turbines.

This particular turbine was manufactured in Germany and then transported to the United States for assembly. It belongs to the Horizontal Axis Wind Turbine (HAWT) type, featuring the main rotor shaft and electrical generator positioned atop a tower and requiring alignment with the wind direction for optimal operation. Smaller turbines are oriented using a wind vane, while larger ones utilize wind sensors coupled with yaw systems for alignment. HAWTs typically include a gearbox to increase the rotation speed of the blades for driving the electrical generator, although some use direct-drive systems that connect the rotor directly to the generator without à gearbox.

Large-scale HAWTs, with blade diameters exceeding 5 meters, are commonly deployed in wind farms or offshore locations, while smaller-scale HAWTs are often found in residential areas [11,14].

I.4.3. Maximum Power Point Tracking for Wind Turbine

The suggested power-control structure is implemented to track the maximum power point of the wind turbine. Maximum Power Point Tracking (MPPT) is achieved by ensuring that, at every generator speed, the electrical power consumed aligns with the maximum power curve. Bates theory provides a formulation for expressing the mechanical power output, denoted as P_m , attainable from a wind turbine [15,16].

$$P_m = \frac{1}{2}\rho S C_P V^3 \tag{1}$$

Where ρ is air density; s is the area swept by blades; v is wind speed C_p is wind energy utilization factor or power coefficient.

Take, for example, the wind turbine depicted in Figure 10, with a blade radius (Rblade) of 164 meters, operating at a rated wind speed of 12 meters per second and an air density (ρ) of 1.15 kilograms per cubic meter

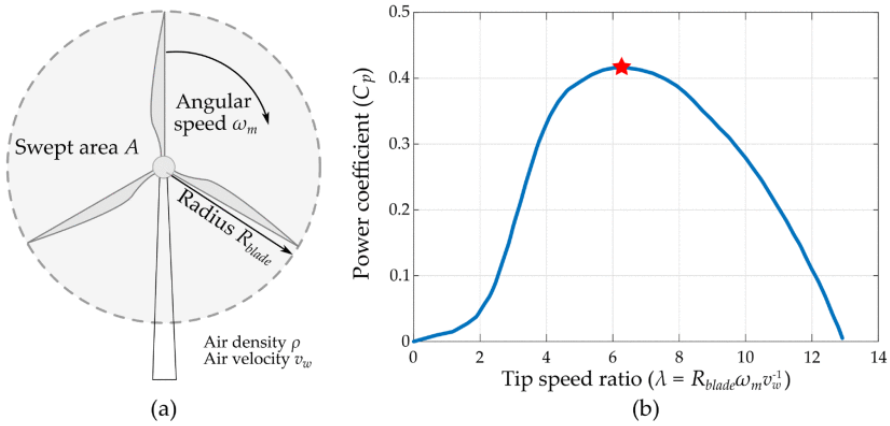


Figure I.10. (a) Illustration of a three-bladed wind turbine. (b) A typical wind turbine power coefficient vs tip speed ratio curve [15].

Figure 11 displays the mechanical power curves of the wind turbine at different wind speeds, represented by dashed lines. The maximum power curve is formed by connecting the peak values of these mechanical power curves. Let's the scenario at a wind speed of 12 meters per second. A vertical line drawn through the intersection of the maximum power curve and the mechanical power curve divides the graph into two regions.

In the gray region, the input mechanical power to the generator exceeds the output electrical power, resulting in an increase in generator rotational speed. As the generator enters the white region, the mechanical power becomes lower than the electrical power, causing the generator to slow down. Eventually, the generator settles at the boundary between these regions, where it generates its maximum power of 10 MW [15].

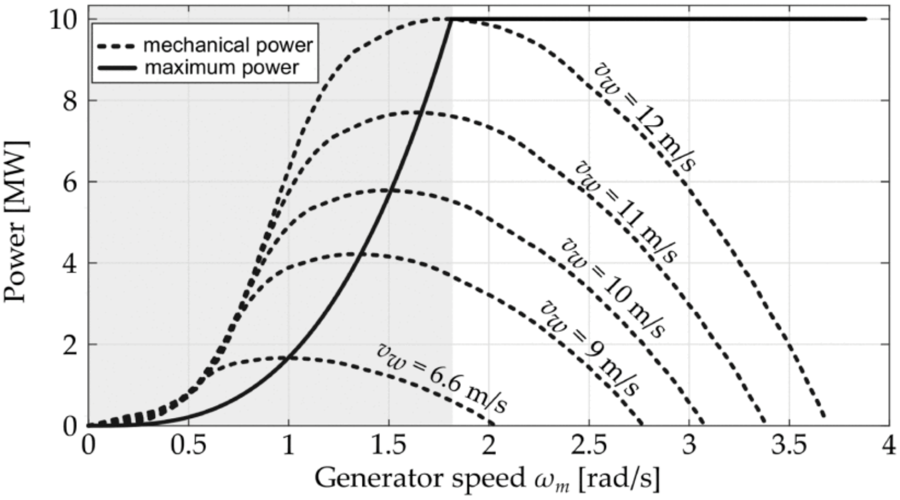


Figure I.11. Mechanical power curves and maximum power curve of à 3 MW wind turbine [15].

Effective utilization of Maximum Power Point Tracking (MPPT) is pivotal in optimizing the energy output and efficiency of wind turbines. Further advancements in MPPT technology, along with comprehensive evaluations of economic and technical factors, will contribute to enhancing the performance and viability of wind energy systems.

I.4.4. Advantages and Challenges

a. Advantages

In the contemporary era, the emphasis on sustainable and eco-friendly energy solutions has never been higher. Among the plethora of renewable energy sources, the advantages of wind energy have stood out prominently, We must consider both wind energy advantages emphasizing its significance in the current era, the advantages of wind energy are many of which [13].

- Variable blade pitch allows adjustment for different wind conditions, enhancing power efficiency.

- High overall efficiency as it utilizes power from the entire blade rotation.

- Wind energy generates no harmful emissions, contributing positively to environmental health and combating global warming.

- Wind turbines utilize an abundant and free fuel source, eliminating the volatility associated with fossil fuel prices.

- Energy payback for wind farms is rapid, typically taking only three to eight months to recoup the energy used in their construction, making wind energy one of the fastest technologies in terms of energy payback.

b. Challenge

Wind energy offer significant advantages but also come with certain challenges that need to be addressed. These challenges can include [13].

- Requires faster wind speeds to start generating sufficient power.

- Relies on directional wind input, necessitating sensors for optimal power output.

- Requires tall towers for optimal performance, especially to access higher wind speeds at elevated altitudes.

- Wind energy's intermittent nature necessitates backup power sources or energy storage systems for consistent electricity supply.

- Integrating wind power into existing grids requires upgrades to infrastructure and efficient transmission systems to manage energy fluctuations.

- Initial costs for installing wind turbines and infrastructure can be high, although long-term savings are achieved through reduced operating and fuel expenses.

In the end, wind energy systems are an essential component of our transition to a more sustainable future. We can produce electricity using wind power, which helps to lessen our dependency on fossil fuels and slow down the effects of climate change. Ultimately, the widespread use of wind energy is an important step toward creating an energy infrastructure that is greener, cleaner, and more resilient for future generations.

I.5. Energy Storage Systems

Incorporating Energy Storage Systems (ESS) into wind-solar hybrid energy storage system HRES architectures significantly reduces the uncertainty associated with renewable resources. The ESS plays a crucial role in providing ancillary services such as peak regulation, voltage fluctuation and flicker mitigation, harmonic reduction, frequency stability, load leveling, and transient stability. Among the various types of ESS available, batteries and Super Capacitors (SC) are the most commonly used components. Rechargeable batteries like lead-acid, nickel-cadmium, lithium-ion, and lithium-polymer are prevalent in the market, with their design tailored to meet system requirements including voltage and current, charging/discharging rates and duration, operating temperature, lifetime in terms of charging cycles, and cost, size, and weight constraints [3,17].

I.5.1. Role and Importance of Energy Storage

Energy storage is pivotal in modern energy systems, addressing challenges related to intermittent renewable energy sources, grid stability, and energy management. It emphasizes the significance of energy storage systems in enhancing grid reliability, integrating renewable sources, managing peak demand, and providing backup power during disruptions. These systems enhance energy resilience, flexibility, and efficiency, facilitating the transition to a sustainable energy [3].

I.5.2. Types of Energy Storage Technologies

There are several types of energy storage technologies, each with its characteristics and applications. Some common types include [6,17]

Chemical Storage: The primary focus in recent years has shifted towards the production of hydrogen through electrolysis, its storage, and conversion into usable energy via fuel cells.

Electrochemical Storage: Electrochemistry forms the basis of battery technology. Europe excels in Lead-Acid and Ni-Cd batteries, while Li-ion batteries are dominated by Asian countries like Japan, Korea, and China. The European battery market's joint development for transport and stationary applications is a significant opportunity, allowing European suppliers and research networks to compete strongly against Asian counterparts. This has led to a rapid increase in European capabilities in battery technology.

Mechanical Storage: Compressed Air Energy Storage (CAES), holds significant potential, with one of the two plants worldwide located in Germany (the other in Alabama, USA). This 290 MW plant has been operational since 1978. European expertise in CAES is highly advanced, particularly in key areas like compressor and turbine technology, as well as solution mining. These competencies are also crucial for storing gases such as hydrogen or synthetic methane, produced via electrolysis using renewable electricity sources.

Kinetic Energy Storage – Flywheels: This technology offers rapid energy storage capabilities, featuring high power and energy densities and the ability to separate power and energy during design. A notable aspect of this technology is its extensive lifespan and adaptability for installation in various locations. While it delivers high power, its energy capacity is typically lower compared to alternative technologies.

Thermal Storage: In Europe, this technology is rapidly advancing due to the introduction of new materials and systems. One example is the successful commercialization of thermal storage systems, such as Underground Thermal Energy Storage (UTES), which is notably implemented in the Netherlands, Sweden, and Germany.

Electrical Storage: Energy storage utilizing superconducting coils has been designed for small to medium-sized systems. These systems offer excellent performance, including high short-term power output, exceeding 95% overall efficiency, exceptional robustness, and a long lifespan with virtually limitless cycles. An example of a competitive and versatile hybrid solution is the integration of High-Temperature Superconductors with long-term energy storage using liquefied hydrogen.

I.5.3. Advancements and Future Trends

Advancements in energy storage technologies are ongoing to address evolving energy needs and overcome associated challenges. Future directions in energy storage encompass [18].

- Advancements in Battery Technologies: Ongoing research aims to enhance the energy density, lifespan, safety, and cost-effectiveness of batteries across diverse applications.

- Integration with Renewable Energy: Energy storage systems play a pivotal role in integrating renewable sources like solar and wind power into the grid, enhancing its stability and reliability.

- Grid-Scale Storage Solutions: Grid-scale storage solutions encompass large projects that aim to optimize load distribution and enable the implementation of energy management strategies.

Advancements and future directions in energy storage systems are critical for ensuring energy security, sustainability, and resilience in response to growing energy demands and challenges posed by climate change.

I.6. The Converters and the Control of HRESs

Various power converters are used in Hybrid Renewable Energy Systems to maximize power extraction from sources, interface different energy sources, and maintain power quality at the load end. Typically, a back-to-back AC-DC-AC converter is used to connect Wind Turbines (WTs) to the utility grid, while a unidirectional boost or buck-boost converter, along with an inverter, is used to integrate PV systems with the grid.

In a hybrid PV-Wind setup, cost savings of up to 25% can be achieved by using multi-port power converters, which allow a single converter to interface multiple energy resources, thus reducing the need for semiconductor switches. Power converter configurations in HRES generally fall into three categories: AC shunt-coupled HRES, DC shunt-coupled HRES and Multi-input coupled HRES [3].

I.6.1. AC Shunt Coupled HRES

In Figure 12, we see the AC shunt-coupled grid-connected Hybrid Renewable Energy System (HRES), which uses two separate inverters for grid integration. In this setup, a DC-DC converter with Maximum Power Point Tracking (MPPT) algorithms connects to the PV system, while an AC-DC active rectifier interfaces with the WT generator. Individual inverters are used to convert DC power from the PV and WT systems into AC, which is then fed into the utility grid through the AC bus. This AC shunt-coupled approach is straightforward and easy to control, but it requires synchronization between the two energy sources as a potential drawback.

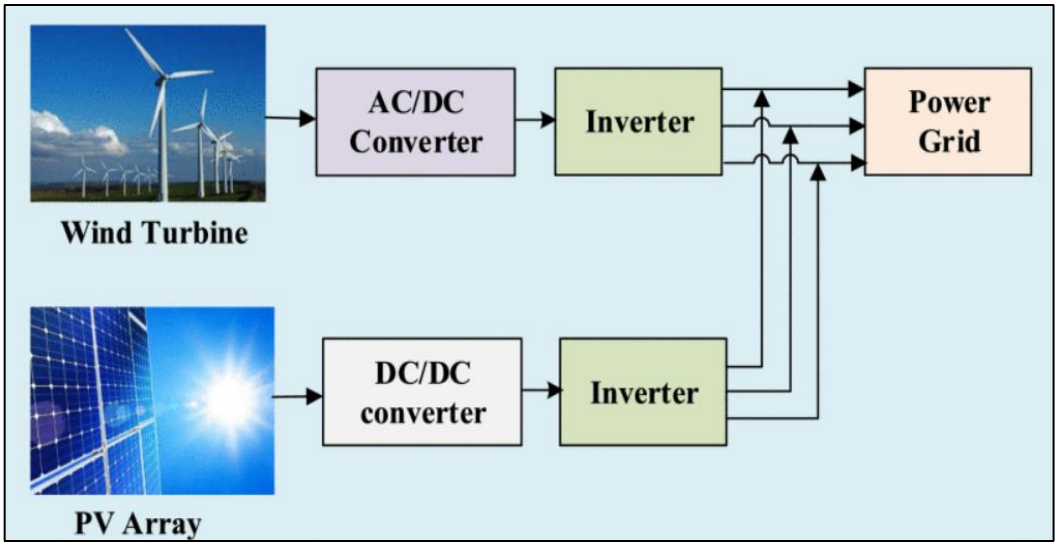


Figure I.12. AC shunt coupled HRES [3].

I.6.2. DC Shunt Coupled HRES

In the DC shunt-coupled HRES design, a single shared inverter integrates the hybrid PV-Wind system with the utility grid, as shown in Figure 13. Power converters are used to convert PV and wind power into DC power. A central inverter then manages and converts this DC power into AC power for integration with the utility grid, serving as the interface between the energy sources and the grid. This DC-coupled approach offers increased efficiency and power density in many cases due to a reduced number of cascaded converters. However, a potential drawback is that if the shared inverter fails, the entire system may experience malfunctions.

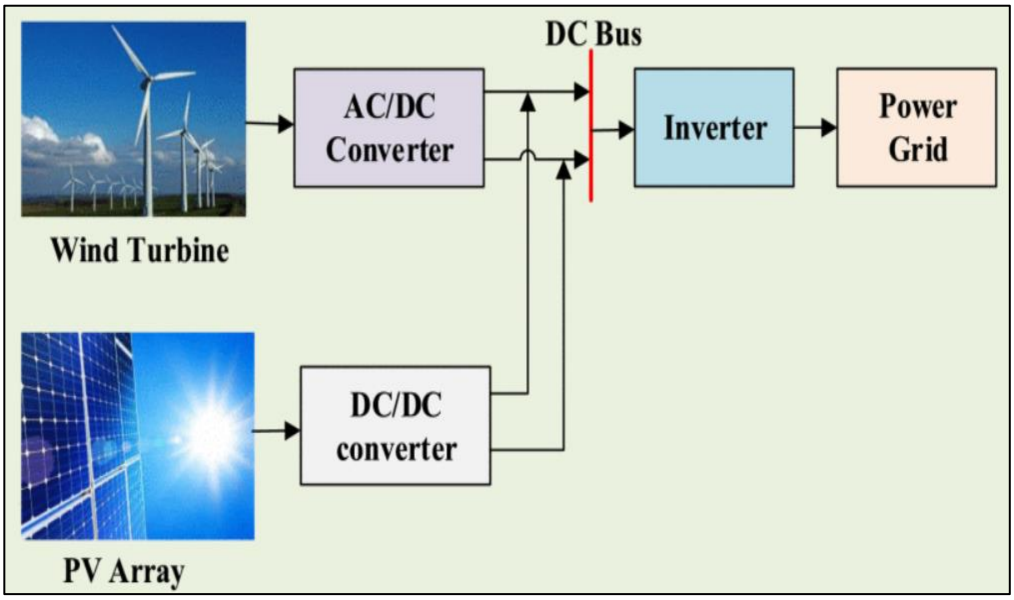


Figure I.13. DC shunt coupled HRES [3].

I.7. Conclusion

Finally, Hybrid Renewable Energy Systems (HRES) represent a promising avenue towards sustainable energy solutions. By integrating photovoltaic (PV) systems, wind energy, and energy storage technologies,

In this chapter, we have provided an introduction to hybrid systems and the importance of combining renewable energy sources to achieve economic and environmental efficiency. We have reviewed their advantages and disadvantages, highlighting the challenges and high costs they face.

We have focused on photovoltaic (PV) systems, explaining their technologies, types, and the importance of Maximum Power Point Tracking (MPPT) to maximize their benefits. After that, we have discussed wind energy systems, their components, types, and the importance of MPPT for optimal performance.

We have highlighted the importance of energy storage systems in the stability of HRESs, explaining their role and future developments. We have concluded with the role of converters and control techniques in ensuring the stability and performance of hybrid systems.

In the second chapter, we will present a study on modeling the components of the hybrid power system and introduction to the program HOMER PRO.

II.1. Introduction

A typical hybrid energy system comprises solar PV, wind turbines, diesel generator sets, fuel cell systems, and batteries. These technologies are complementary, working together to meet electricity demand. While wind turbines and solar PV systems have high installation costs but lower maintenance costs, they may not consistently produce usable energy due to factors like variable sunshine hours and high cut-in wind speeds. This mismatch between energy production and demand often leads to over sizing of systems, increasing costs. Despite their higher initial cost compared to diesel engine generators, solar and wind energy systems typically have lower operating and maintenance costs.

Recognizing the benefits of solar and wind energy, designers are increasingly integrating them into Hybrid Renewable Energy Systems (HRES), combining conventional generators like diesel engines with renewable sources like PV and wind. In remote areas, HRES are often the most cost-effective and reliable means of power production. Integrating solar and wind energy into HRES can mitigate power fluctuations, reducing the need for extensive energy storage. Battery storage is typically incorporated into HRES to meet peak load demand or compensate for intermittent renewable energy availability.

The design of HRES relies on the performance of individual components, which must be modelled and evaluated to reliably meet demand. Researchers commonly employ this approach to optimize system performance and minimize costs. This chapter talks about modelling of hybrid renewable energy system components, especially on solar and wind energy and batteries and Bidirectional converter. We will also talk about the HOMER Pro program and how to create a project related to hybrid renewable energy using it [19, 20].

II.2. Hybrid renewable energy system modelling

The modelling of HRES is an essential preliminary stage preceding any optimal sizing procedure. The block diagram illustrating the proposed HRES is depicted in Figure II.1.

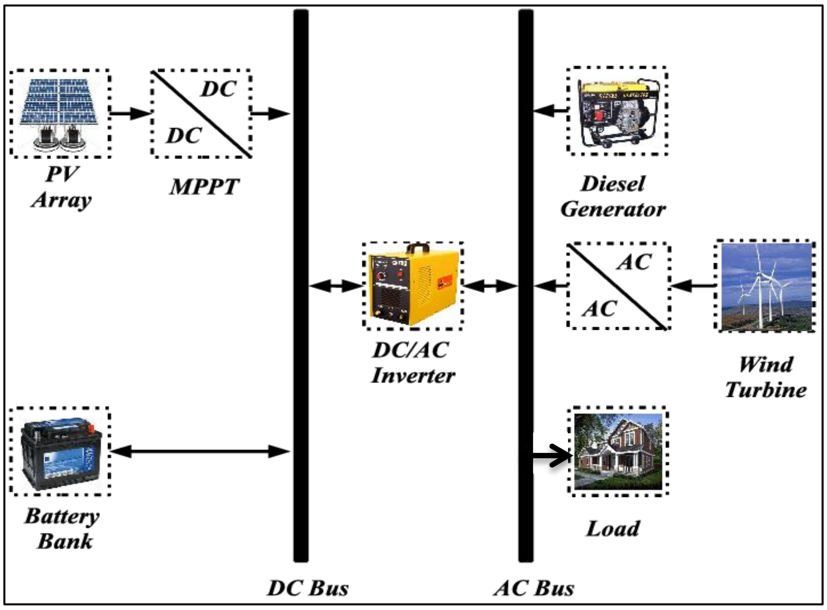


Figure II.1. Schematic diagram of HRES [21].

II.3. PV generator model

The concept of photovoltaic, rooted in the fundamental physics of the photoelectric effect, represents a cornerstone of renewable energy technology. This process involves the absorption of photons by semiconductor materials, which then release electrons, thereby generating an electric current. Photovoltaic systems harness this phenomenon to convert sunlight directly into usable electricity, offering a clean and sustainable alternative to conventional energy sources. With advancements in materials science and engineering, photovoltaic technology continues to evolve, driving innovation and expanding its applications in various sectors, from residential solar panels to large-scale solar farms. As society increasingly embraces the transition towards renewable energy, photovoltaic play a pivotal role in reducing carbon emissions and mitigating climate change while promoting energy independence and resilience [22].

Solar radiation serves as the input energy for the PV system, and the total solar radiation on an inclined surface is approximated as follows [19]:

$$I_T = I_b R_b + I_d R_d + (I_b + I_d) R_r \tag{II.1}$$

Here, $\mathrm{I_b}$and I_d represent the direct normal and diffuse solar radiations, while $R_d$and R_r denotethe tilt factors for the diffuse and reflected portions of the solar radiations.

The total estimated solar radiation is influenced by the position of the sun in the sky, which changes monthly. The hourly power output from a PV system with an area A_{pv} (m^2) on an average day of the month, when the total incident solar radiation on the PV surface is I_T(kWh/m^2), is expressed as [19]:

$$P_{sj} = I_{Tj}\eta A_{pv} \tag{II.2}$$

Where system efficiency $\eta$is given by:

$$\eta = \eta_m \eta_{pc} P_f \tag{II.3}$$

And, the module efficiency η_m is given by:

$$\eta_m = \eta_r[1 - \beta(T_c - T_r)] \tag{II.4}$$

Where η_r is the module reference efficiency, η_{pc} is the power conditioning efficiency, P_f is the packing factor, β is the array efficiency temperature coefficient, T_r is the reference temperature for the cell efficiency and T_c is the monthly average cell temperature and can be calculated as follows:

$$T_c = T_a + \frac{\alpha\tau}{U_L} I_T \tag{II.5}$$

Here T_c is cell temperature (°C), $T_a$is the instantaneous ambient temperature, and $\alpha\tau$ is transmittance of the cover over of the PV module, U_L is coefficient of heat transfer to the surroundings (kW/ m^2), I_T is the total solar radiation.

And :

$$\frac{\mathrm{U_L}}{\alpha\tau} = \frac{\mathrm{I_{T,NOCT}}}{(\mathrm{NOCT} - \mathrm{T_{a,NOCT}})} \tag{II.6}$$

$$T_c = T_a + (\frac{\mathrm{NOCT} - 20}{800}) I_T \tag{II.7}$$

Where NOCT is normal operating cell temperature, $T_{a,NOCT} = 20°C$and $I_{T,NOCT} = 800W/\,m^2$, for a wind speed of 1 m/s.

II.4. Wind turbine system model

Wind has served as a power source for millennia, employed to perform various tasks such as propelling ships, milling, water pumping, and numerous others. The wind turbine plays a vital role in harnessing wind energy, converting it—either as kinetic energy inherent in the wind—into mechanical or electrical energy. Notably, wind turbines have emerged as the world's fastest-growing energy sector, surpassing solar photovoltaic systems, with over 838 TWh generated in 2015, compared to just 247 TWh from solar photovoltaic sources [22].

The power generated by a wind turbine generator at a particular location is contingent upon the wind speed at the hub height and the turbines speed characteristics. The wind speed at the hub height can be determined using the power-law equation [19].

$$V_z = V_i[\frac{Z}{Z_i}]^x \tag{II.8}$$

Where V_Z and V_i are the wind speed at hub and reference height Z and Z_i, and x is power law exponent.

Figure II.2. Illustrates typical characteristics of a wind turbine. The power output, denoted as P_w (kW/m^2), from the wind turbine generator can be computed as follows [19]:

$$\begin{aligned} P_w &= 0 && V < V_{ci} \\ P_w &= aV^3 - bP_r && V_{ci} < V < V_r \\ P_w &= P_r && V_r < V < V_{co} \\ P_w &= 0 && V > V_{co} \end{aligned} \tag{II.9}$$

Where $a = P_r/(V_r^3 - V_{ci}^3)$, $b = V_{ci}^3/(V_r^3 - V_{ci}^3)$, P_r is the rated power, V_{ci}, V_{co} and V_r are the cut-in, cut-out and rated speed of the wind turbine.

Actual power available from wind turbine is given by:

$$P = P_w A_w \tag{II.10}$$

Where A_w is the total swept area, η is efficiency of wind turbine generator and corresponding converters.

The figure II.2 give a simple explain of the modeling outputs of the previous equations:

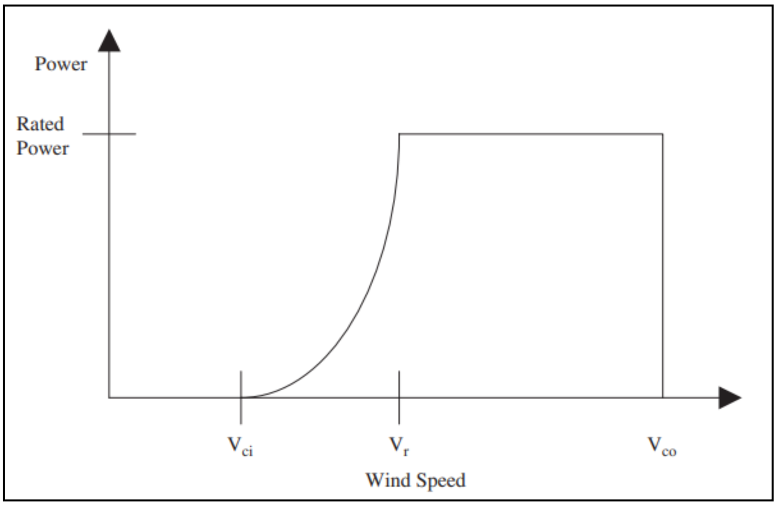


Figure II.2. Wind turbine characteristics [19].

II.5. Battery storage model

The battery storage system is dimensioned to fulfil the load demand when renewable energy sources are unavailable, known as days of autonomy, typically set at 2 or 3 days. Battery sizing relies on various factors including maximum depth of discharge, temperature correction, rated battery capacity, and battery lifespan. The necessary battery capacity in ampere-hours is determined by [19]:

$$B_{rc} = \frac{E_{c(Ah)} D_s}{(DOD)_{max} \eta_t} \tag{II.11}$$

Here, $E_{c(Ah)}$represents the load in ampere-hours, D_s denotes the battery autonomy or storage days, DOD_{max} signifies the maximum battery depth of discharge, and η_t stands for the temperature correction factor. The disparity between the power generated and the load determines whether the battery is charging or discharging. The charge level of the battery bank at time t can be computed by:

$$B_{rc} = E_B(t-1)(1-\sigma) + (E_{GA}(t) - \frac{E_L(t)}{\eta_{inv}})\eta_{battery} \tag{II.12}$$

In this context, $E_B(t)$ and $E_B(t-1)$ represent the charge levels of the battery bank at times t and $t-1$ respectively, with σ denoting the hourly self-discharge rate. $E_{GA}(t)$ stands for the total energy generated by the renewable energy source after accounting for losses in the controller, while $E_L(t)$ represents the load demand at time t. η_{inv} and η_{battery} refer to the efficiency of the inverter and the charging efficiency of the battery bank respectively.

The charge level of the battery bank must adhere to the following limitations:

$$E_{B_{min}} \leq E_B(t) \leq E_{B_{max}} \tag{II.13}$$

$E_{B_{max}}$ and $E_{B_{min}}$ represent the maximum and minimum charge levels of the battery bank, respectively.

II.6. Bidirectional converter model

Electric converters play a vital role in hybrid energy systems by facilitating the exchange of power between AC/DC and DC/AC. They become indispensable components in systems incorporating Renewable Energy Sources (RESs) and Battery Storage Systems (BSS) since these sources generate DC power, while most electric loads require AC power. Consequently, this study includes a bidirectional converter to address this requirement. The converter under consideration comprises both a rectifier and an inverter, enabling the conversion of DC to AC power and vice versa. Their efficiency characteristics can be outlined as follows [23]:

$$P_{INV,OUT} = \eta_{INV} P_{DC} \tag{II.14}$$

$$P_{REC,OUT} = \eta_{REC} P_{AC} \tag{II.15}$$

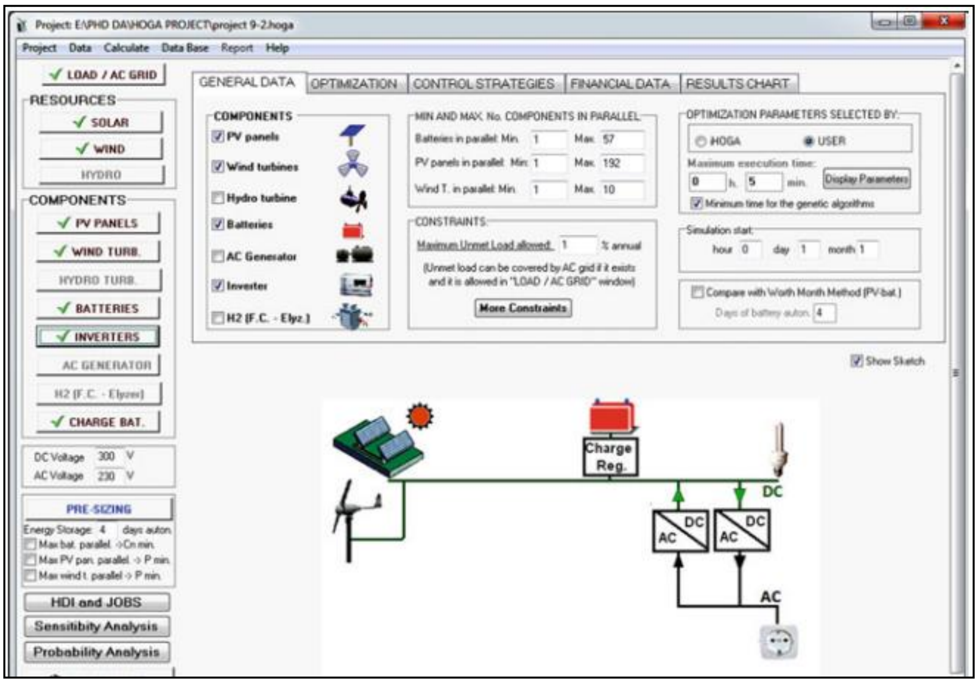
Where $P_{INV,OUT}$ inverter output power (kW), $P_{REC,OUT}$ rectifier output power (kW),η_{REC}, η_{REC} inverter and rectifier efficiency (%) P_{AC}, P_{DC} AC and DC power (kW)

II.7. Software programs for techno-economic analysis of HRESs

There are numerous software programs available that are designed to find the optimal configurations and sizing of hybrid renewable energy systems (HRESs) under a wide range of conditions. These programs provide a comprehensive techno-economic analysis of the overall system, taking into account various factors such as energy demand, resource availability, system components, and economic considerations. Some of the most commonly employed software tools for this purpose include: HOMER Pro, HYBRID2, IHOGA, TRNSYS, and RET Screen are among the most commonly employed.

II.7.1. Improved Hybrid Optimization Genetic Algorithm (IHOGA)

Researchers from the University of Zaragoza (Spain) developed the IHOGA software in C++ for simulating and optimizing Stand-alone HRES. It models systems with AC/DC electrical loads, hydrogen consumption, and water usage from pumped tanks or reservoirs. IHOGA optimizes system component sizing for energy systems comprising wind turbines, PV generators, hydroelectric turbines, batteries (lead acid or lithium), auxiliary generators (e.g., diesel, gasoline), inverters, charger controllers, hydrogen components (electrolysers, hydrogen tanks, fuel cells). It simulates and optimizes grid-connected or standalone systems of any size, offering options for mono/multi-objective optimization and minute-based time step simulations. The software supports sensitivity analysis, probability analysis [24].


Project: E:\PHD DA\HOGA PROJECT\project 9-2.hoga

COMPONENTS
☑ PV panels
☑ Wind turbines
☐ Hydro turbine
☑ Batteries
☐ AC Generator
☑ Inverter
☐ H2 (F.C. - Elyz.)

MIN AND MAX. No. COMPONENTS IN PARALLEL
Batteries in parallel: Min. 1 Max. 57
PV panels in parallel: Min. 1 Max. 192
Wind T. in parallel: Min. 1 Max. 10

CONSTRAINTS
Maximum Unmet Load allowed: 1 % annual
(Unmet load can be covered by AC grid if it exists and it is allowed in "LOAD / AC GRID" window)

OPTIMIZATION PARAMETERS SELECTED BY:
○ iHOGA ● USER
Maximum execution time: 0 h. 5 min.
☑ Minimum time for the genetic algorithms

Simulation start: hour 0 day 1 month 1

☐ Compare with Worth Month Method (PV-bat.)
Days of battery auton. 4

☑ Show Sketch

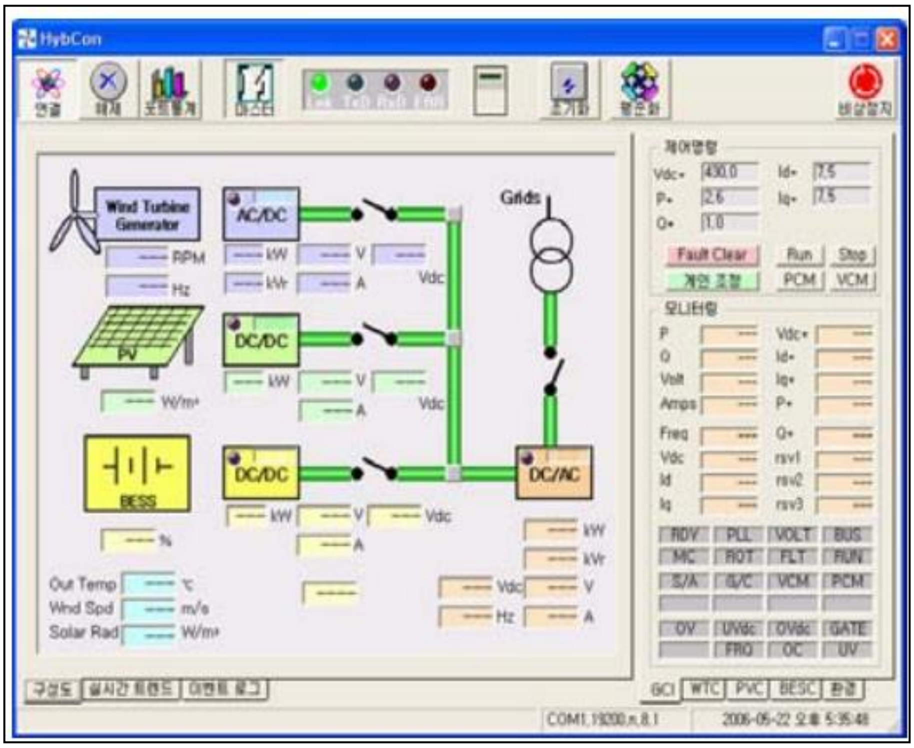
DC Voltage 300 V
AC Voltage 230 V

Energy Storage: 4 days auton.
☐ Max bat. parallel. -> Cn min.
☐ Max PV pan. parallel. -> P min.
☐ Max wind t. parallel -> P min.

Figure II.2. IHOGA simulated model of hybrid system [25].

II.7.2. HYBRID2

The Hybrid2 software is user-friendly, enabling comprehensive analysis of various hybrid power systems. It utilizes probabilistic/time series modelling, incorporating data on loads, wind speed, solar insulation, and temperature to predict system performance. It considers wind speed and load variations in performance predictions, but not short-term system fluctuations. Hybrid2 can analyze systems with diverse components like electrical loads, wind turbines, photovoltaic, diesel generators, and battery storage, with options for AC, DC, or both buses. It offers various control strategies and an economic analysis tool. The software features a user-friendly the Graphical User Interface (GUI), a glossary of relevant terms, and a library of equipment for system design, including sample projects. Output includes both summary and detailed descriptions of power flows, with a Graphical Results Interface for easy review [26].

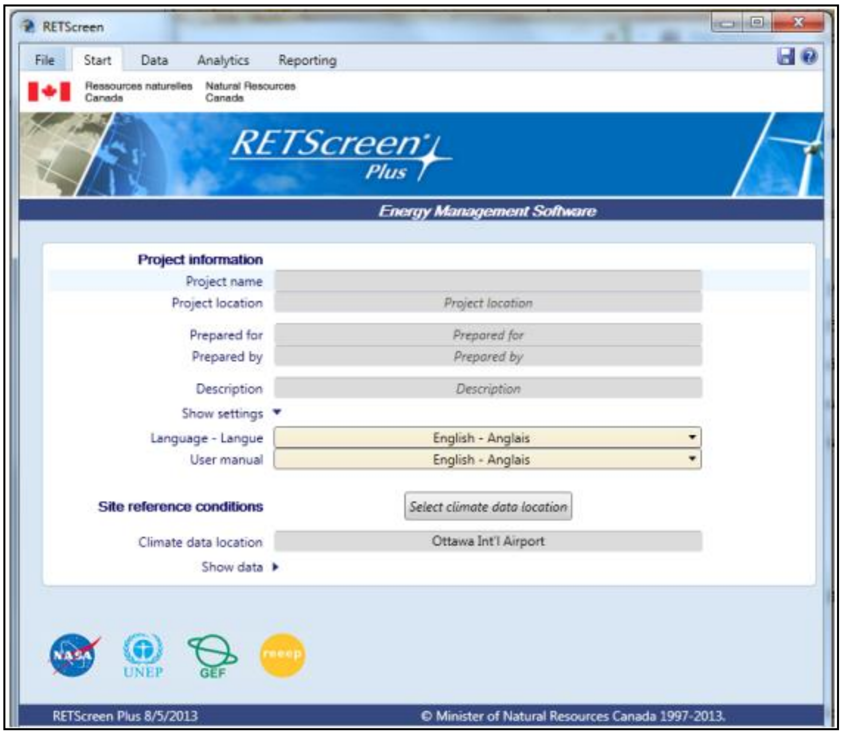


Vdc* 430.0
P* 2.6
Q* 1.0
Id* 7.5
Iq* 7.5

Figure II.3. HYBRID2 system control interface [27].

II.7.3. Renewable Energy and Energy Efficiency Technology Screen (RETScreen)

RETScreen International, a collaborative effort involving Natural Resources Canada's CANMET Energy Diversification Research Laboratory (CEDRL) and various experts from industry, government, and academia, including partnerships with organizations like the United Nations Environment Programme (UNEP) and the National Aeronautics and Space Administration (NASA), is a globally accessible renewable energy tool. It provides standardized software for evaluating energy production, costs, and emissions reductions for renewable energy technologies, particularly photovoltaic, using Microsoft Excel spreadsheets. The tool, available free-of-charge, includes databases, manuals, case studies, and training courses, serving both educational and industry development purposes. Originally designed for on-grid applications, it has recently expanded to cover off-grid PV systems. This summary highlights the models used in RETScreen to calculate monthly energy production for PV systems, including solar radiation computation, PV array efficiency, battery modelling, and utilizability concepts, aiding in predicting annual system energy output [28].



Language - Langue: English - Anglais

User manual: English - Anglais

Climate data location: Ottawa Int'l Airport

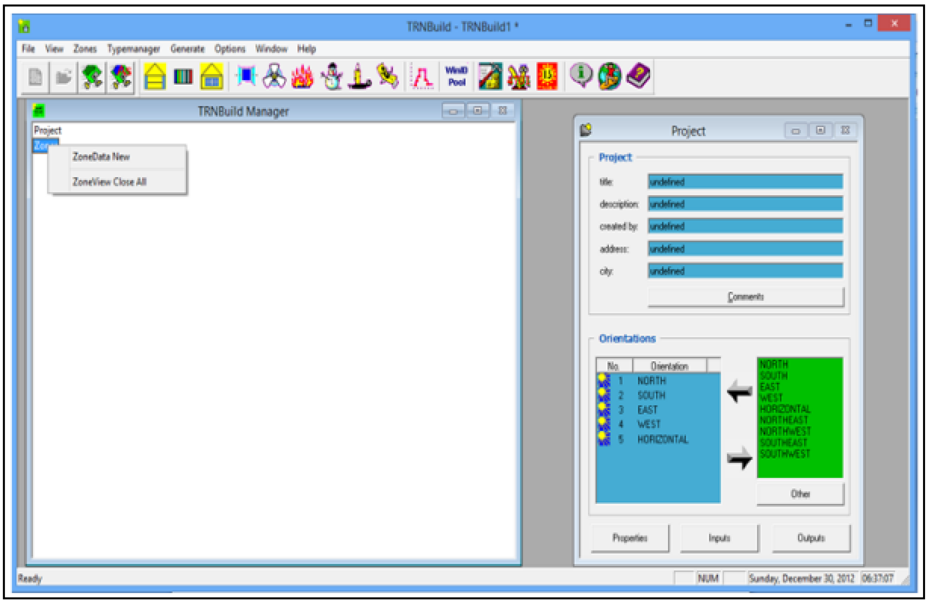
RETScreen Plus 8/5/2013

© Minister of Natural Resources Canada 1997-2013.

Figure II.4. Interface of RET Screen [29].

II.7.4. Transient System Simulation Tool (TRNSYS)

TRNSYS stands as dynamic simulation software adept at conducting hourly simulations of building energy systems like the Solar Assisted Ground Coupled Heat Pump System (SAGCHPS). Its versatility in modelling and robust simulation capabilities enables the representation of novel or specialized energy systems across diverse conditions. Recently, a new module for Vertical Ground Heat Exchangers (VGHEs) was introduced to enhance TRNSYS's ability to model high-temperature VGHE applications. Nonetheless, validation with real-world field data is essential to ensure accuracy and reliability [30].



title: undefined
description: undefined
created by: undefined
address: undefined
city: undefined

No.	Orientation
1	NORTH
2	SOUTH
3	EAST
4	WEST
5	HORIZONTAL

Figure II.5. Interface of TRNSYS **[31].**

The table below outlines the benefits and disadvantages of each software.

Table II.1. Comparison between different softwares **[22]**

Software	Advantages	Drawbacks
IHOGA	-Use multi or mono objective optimization - Low time of simulation	- Absence of sensitivity and probability analysis - Limited daily load (10 kWh)
Hybrid2	- Much electrical load options - Detailed dispatching option	- Take long time for simulation - While project is written successfully, some simulation errors are shown
RETScreen	- Best meteorological database - Excel based tool	- Less data input - Can’t import time series data
TRNSYS	- Flexibility in simulation - Great precision with graphics	- Cannot simulate some generators like hydropower. - Absence of optimization option
HOMER	-Plot results in efficiency graph - Easy to understand	-Uses first degree linear equations - Can’t import time series data

For this study, we chose Hybrid Optimization Model for Electric Renewable (HOMER). HOMER has the capability to simulate tens of thousands of distinct solutions. One approach involves conceptualizing the desired system by estimating expenses related to installation, operation, replacement, maintenance, fuel, and interest rates. During the optimization process, the configuration generates a prioritized list of outcomes based on the Total Net Present Cost (TNPC) following simulation. HOMER explores various system configurations in ascending order of TNPC, from the lowest to the highest. Conversely, the user's selection of sensitivity variables impacts the system configuration based on TNPC. In the optional sensitivity analysis phase, factors such as wind speed, solar radiation, and fuel prices are introduced to assess how the optimal system adapts to changes in these variables. HOMER takes into consideration numerous factors including technological feasibility, climatic conditions, load demand, and economic parameters. The utilization of the HOMER tool necessitates collaboration among stakeholders, including advocates of renewable energy, power engineers, utility operators, and financiers [32].

II.8. HOMER Software

II.8.1. HOMER-Pro

The HOMER-Pro software represents a powerful tool for crafting an optimal hybrid design aimed at ensuring continuous and cost-effective electricity provision in specific scenarios. Furthermore, it evaluates critical variables for both grid-connected and off-grid models to ascertain the most efficient hybrid configuration. By exploring diverse combinations of available resources, HOMER-Pro yields precise and impartial results. Leveraging meteorological data from the National Aeronautics and Space Administration (NASA), the program assesses the renewable resource potential at any given location. Its operation unfolds in three stages: firstly, inputting project details such as site-specific location, resource availability, load profiles, and system components. The second stage entails simulation and optimization using specified parameters of interest, while the third stage presents the outcomes and furnishes comprehensive information on economic metrics, performance, and system sizing [32].

II.8.2. Methodology of HOMER-Pro

HOMER Pro, developed by the National Renewable Energy Laboratory (NREL 2021), is utilized for simulating and optimizing hybrid power systems at specific locations. Renowned as the world's most advanced microgrid modelling software, HOMER enables the evaluation of system performance, Net Present Cost (NPC), and Levelized Cost of Energy

(LCOE) across various configurations, including those with or without energy storage and connected to the grid or off-grid. HOMER can conduct simulations on extensive datasets, which may require several hours to ensure the optimal balance between demand and supply. Figure II.6. illustrates the flow diagram for the HOMER software [33].

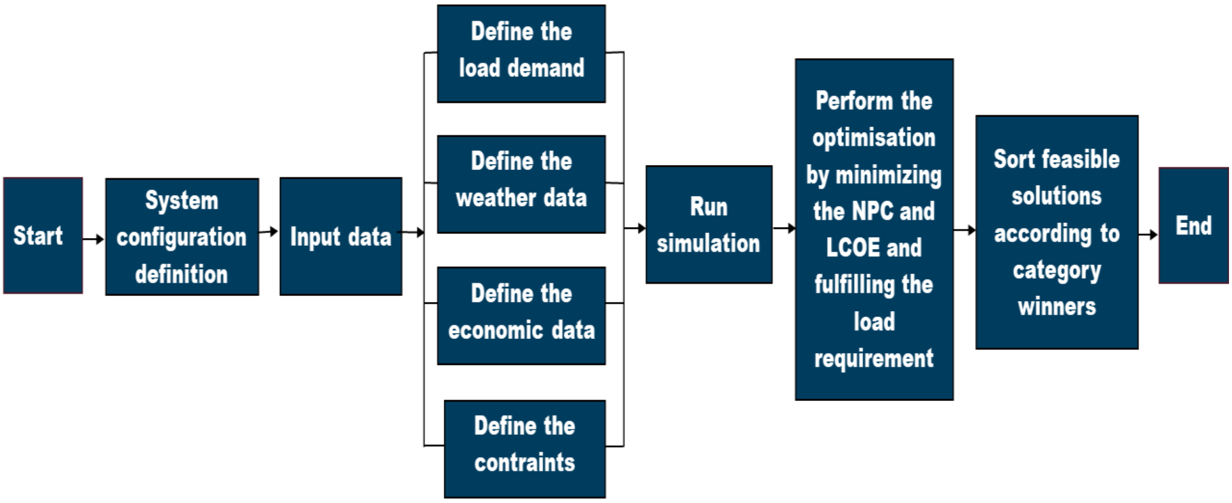


Figure II.6. Streamlined diagram depicting the optimization algorithm of HOMER Pro **[33].**

The algorithm illustrated in the figure outlines a process for optimizing a system configuration related to energy production, with the presence of renewable energy sources. Initially, inputs are defined, including three sets of data: anticipated energy demand (load demand), solar irradiance data crucial for solar energy production, and wind speed data for wind energy production (weather data), and economic data encompassing fuel costs and electricity pricing for selling back to the grid. Next, the system configuration is specified in terms of the technical details, such as the types and capacities of generators and energy storage devices. Constraints, such as emissions limitations or budget restrictions, are then established. Following this, the system configuration is simulated using the defined load demand, weather, and economic data to evaluate the system's performance. After the simulation, feasible solutions are sorted based on criteria that include minimizing the Net Present Cost (NPC) and the Levelized Cost of Energy (LCOE) while meeting load requirements.

a. Net Present Cost

The Net Present Cost (NPC) of the hybrid system represents the present value of all expenses incurred by the system throughout its specified useful life, minus the salvage value at the end of this period. These expenses encompass capital costs, replacement costs, and operation and maintenance costs, as described in Equation (II.16). The HOMER Pro software calculates the NPC for each system component [34].

$$\mathrm{NPC} = \sum (\mathrm{C}_{\mathrm{capital}} + \mathrm{C}_{\mathrm{replace}} + \mathrm{C}_{\mathrm{maint}} - \mathrm{C}_{\mathrm{salvage}}) \qquad \text{(II.16)}$$

Where $\mathrm{C}_{\mathrm{capital}}$ is an initial cost, $\mathrm{C}_{\mathrm{replace}}$ is replacement value, $\mathrm{C}_{\mathrm{maint}}$ is maintenance cost and $\mathrm{C}_{\mathrm{salvage}}$ is salvage value.

b. Levelized Cost of Electricity

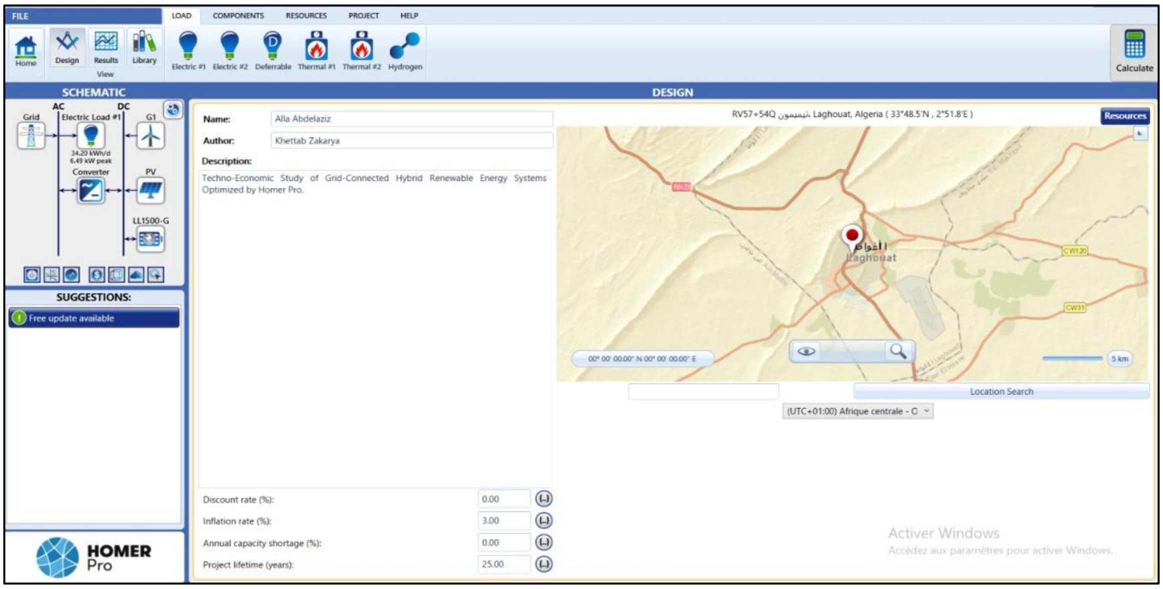
It is defined as the average cost per kilowatt-hour of electrical energy generated by the specified system. To calculate the Levelized Cost of Electricity, HOMER Pro software divides the total annualized cost by LprimeAC and LprimeDC, as outlined in Equation (II.17) [34].

$$\mathrm{LCOE} = \text{Total annualized cost}/(\mathrm{L}_{\mathrm{primAC}} + \mathrm{L}_{\mathrm{primeDC}}) \qquad \text{(II.17)}$$

Where $\mathrm{L}_{\mathrm{primAC}}$ is the alternating current primary load and $\mathrm{L}_{\mathrm{primeDC}}$is the direct current main load.

II.9.Interfaces of HOMER Pro

The HOMER software boasts user-friendly features, with an interface resembling typical software programs. It offers a top menu along with accessible icons, allowing users to navigate without delving into menus extensively. The HOMER interface can be categorized into three key sections, as illustrated in Figure II.7: the system definition area (House), the resource definition area (Design), and the results area (Results) [35].



Name: Alla Abdelaziz

Author: Khettab Zakarya

Description: Techno-Economic Study of Grid-Connected Hybrid Renewable Energy Systems Optimized by Homer Pro.

Discount rate (%): 0.00

Inflation rate (%): 3.00

Annual capacity shortage (%): 0.00

Project lifetime (years): 25.00

RV57+54Q تيميمون، Laghouat, Algeria (33°48.5'N , 2°51.8'E)

(UTC+01:00) Afrique centrale - O

Figure II.7. Interface of HOMER pro.

II.9.1. Components in HOMER pro

Various components can be added to a project to design and optimize energy systems. These components are categorized into power sources, storage systems, converters, and loads.

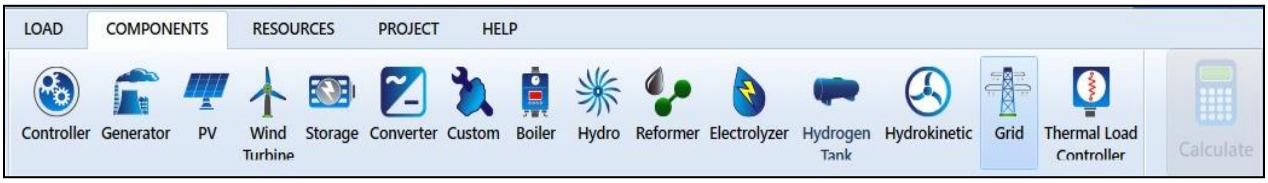


Figure II.8. HOMER components.

II.9.2.Resources in HOMER pro

Encompass diverse inputs used for energy system modelling, including data on renewable energy sources like solar, wind, and hydro, along with fuel prices and energy demand profiles.

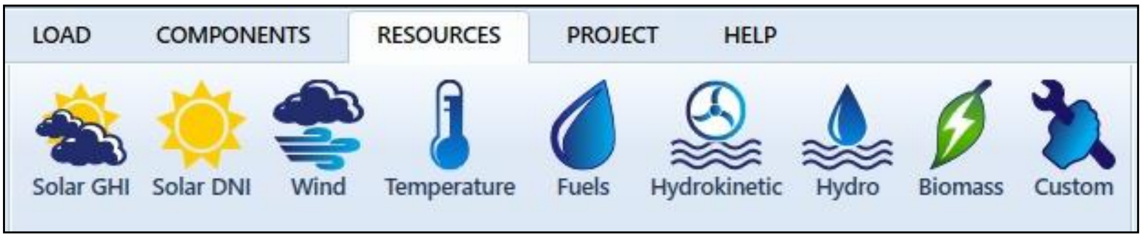


Figure II.9. Resources in HOMER.

II.10. How to start a project

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

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

Figure II.9. The site selected for study**.**

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

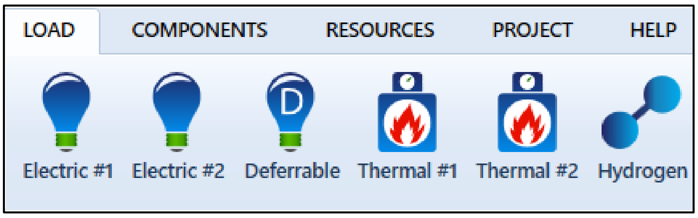
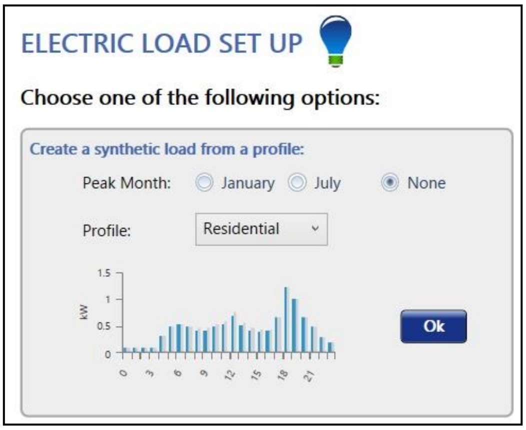


Figure II.10. Choosing the right load for the project**.**

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


ELECTRIC LOAD SET UP

Choose one of the following options:

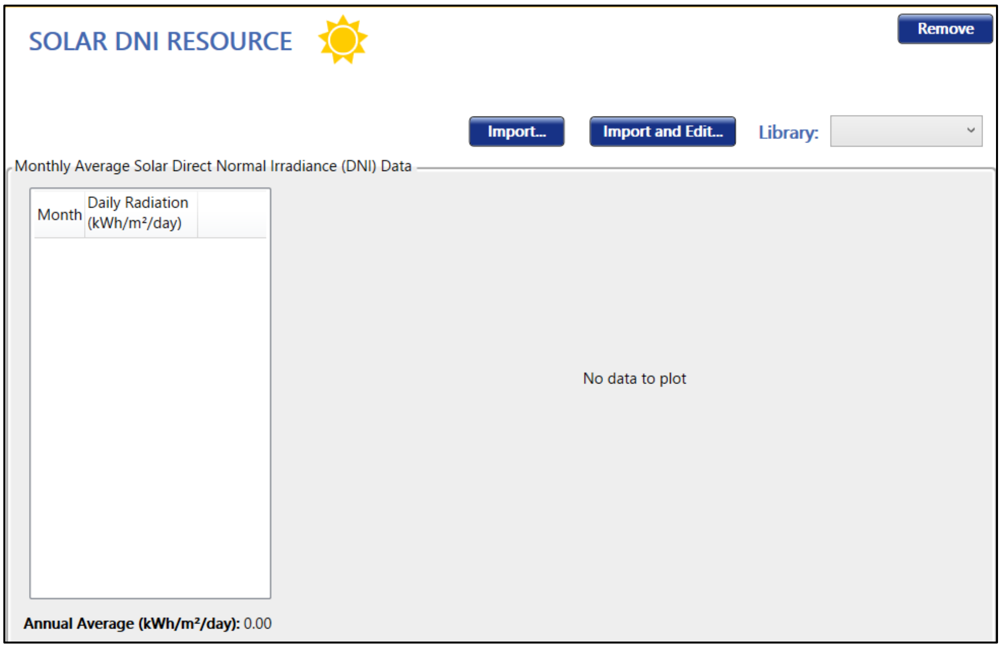
Create a synthetic load from a profile:

Peak Month: ○ January ○ July ● None

Profile: Residential

Figure II.11. Electric load set up.

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


SOLAR DNI RESOURCE

Monthly Average Solar Direct Normal Irradiance (DNI) Data

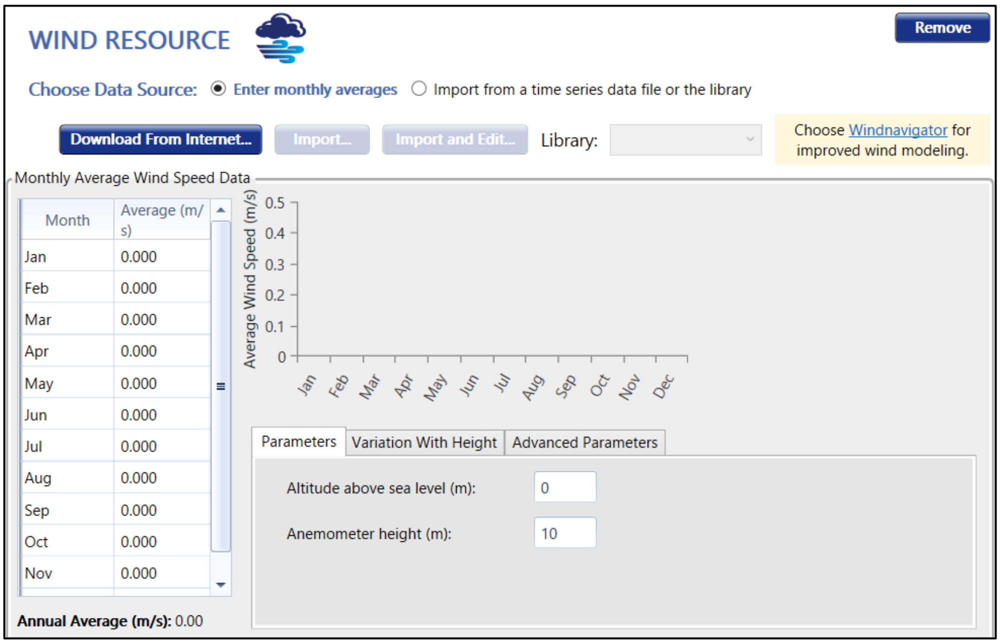
Month	Daily Radiation (kWh/m²/day)

No data to plot

Annual Average (kWh/m²/day): 0.00

Figure II.12. Enter the information for Solar Resource**.**

- Download wind speed data.



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

Choose Windnavigator for improved wind modeling.

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

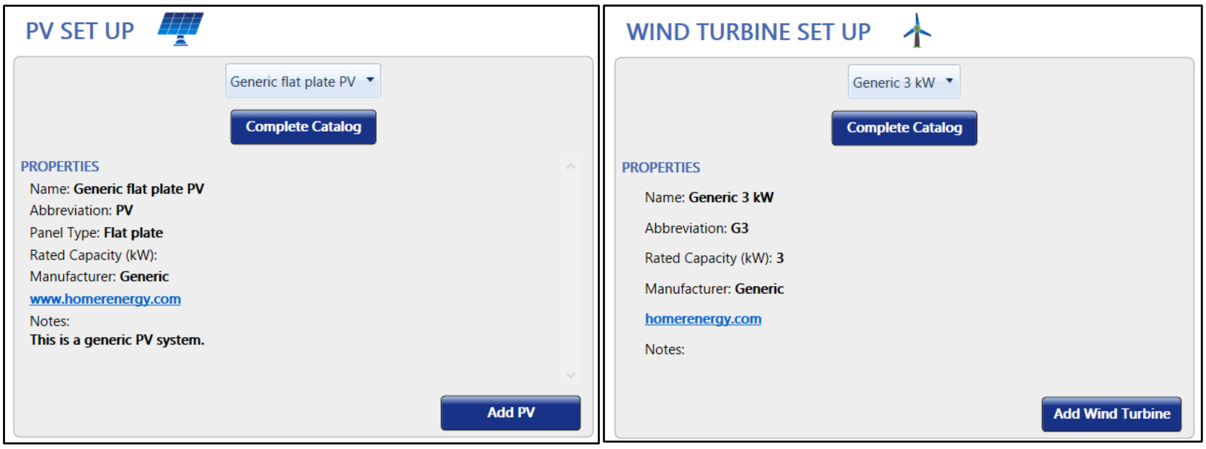
Altitude above sea level (m): 0

Anemometer height (m): 10

Annual Average (m/s): 0.00

Figure II.13. Enter the information for Wind resource.

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

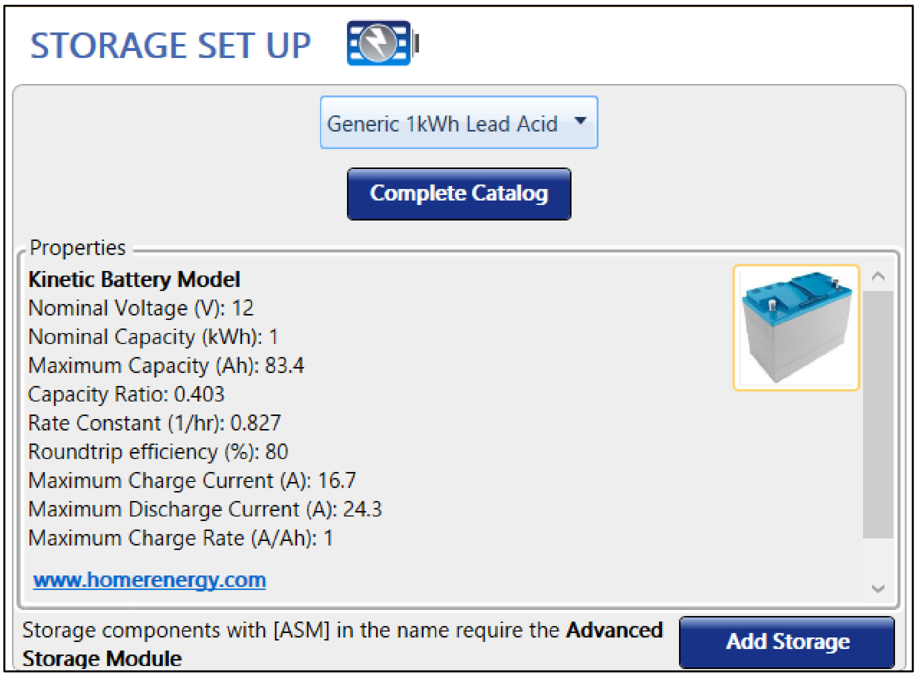


PROPERTIES
Name: **Generic flat plate PV**
Abbreviation: **PV**
Panel Type: **Flat plate**
Rated Capacity (kW):
Manufacturer: **Generic**
www.homerenergy.com
Notes:
This is a generic PV system.

PROPERTIES
Name: **Generic 3 kW**
Abbreviation: **G3**
Rated Capacity (kW): **3**
Manufacturer: **Generic**
homerenergy.com
Notes:

Figure II.14. Enter characteristics of the PV and the wind turbine in HOMER Pro**.**

- To choose battery storage appropriate for the project



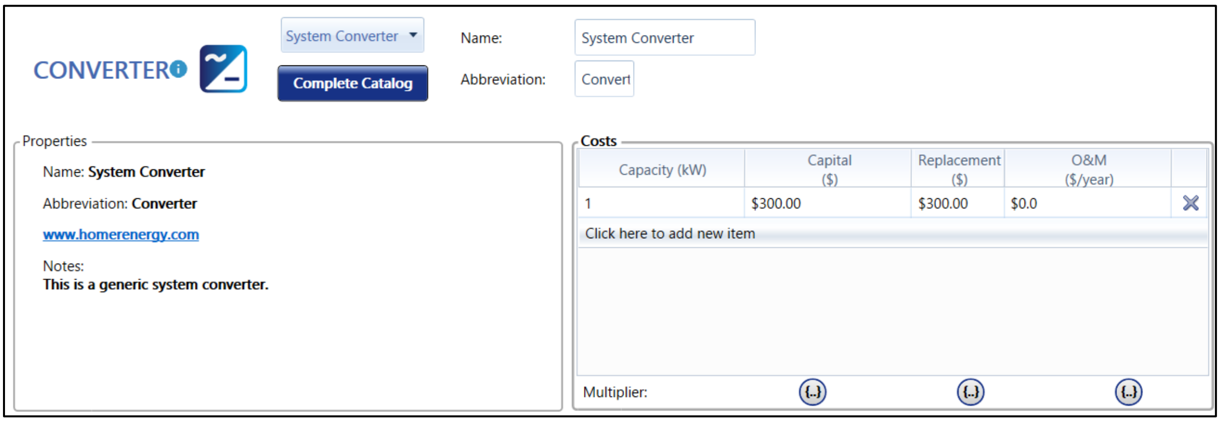
Kinetic Battery Model
Nominal Voltage (V): 12
Nominal Capacity (kWh): 1
Maximum Capacity (Ah): 83.4
Capacity Ratio: 0.403
Rate Constant (1/hr): 0.827
Roundtrip efficiency (%): 80
Maximum Charge Current (A): 16.7
Maximum Discharge Current (A): 24.3
Maximum Charge Rate (A/Ah): 1

www.homerenergy.com

Storage components with [ASM] in the name require the **Advanced Storage Module**

Figure II.15. Battery characteristics under HOMER Pro.

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



Name: System Converter
Abbreviation: Convert

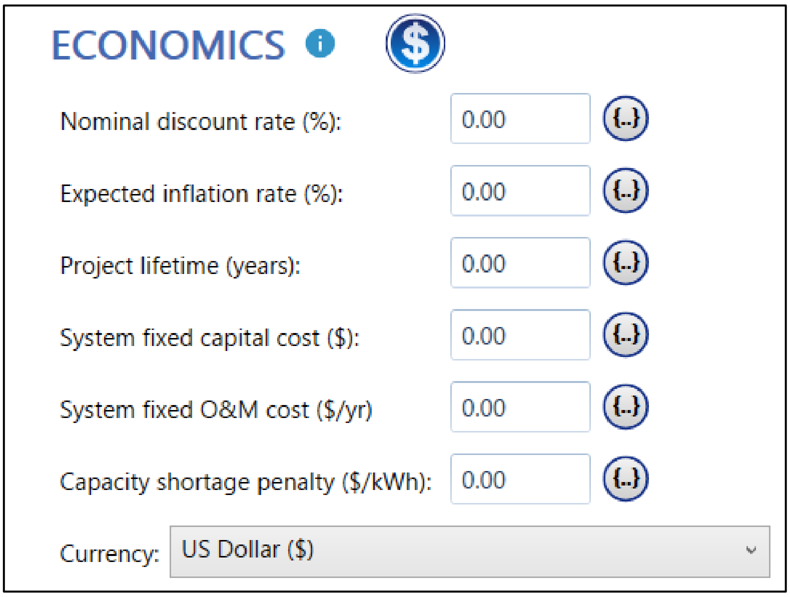
Name: **System Converter**
Abbreviation: **Converter**
www.homerenergy.com
Notes:
This is a generic system converter.

Capacity (kW)	Capital ($)	Replacement ($)	O&M ($/year)
1	$300.00	$300.00	$0.0

Click here to add new item

Figure II.16. Features of the conversion system with HOMER Pro.

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



ECONOMICS

Nominal discount rate (%): 0.00

Expected inflation rate (%): 0.00

Project lifetime (years): 0.00

System fixed capital cost ($): 0.00

System fixed O&M cost ($/yr) 0.00

Capacity shortage penalty ($/kWh): 0.00

Currency: US Dollar ($)

Figure II.17. Enter economic information for the project**.**

- We will have hybrid system architecture with a storage system following the appropriate dimensioning. As shown in the following figure:

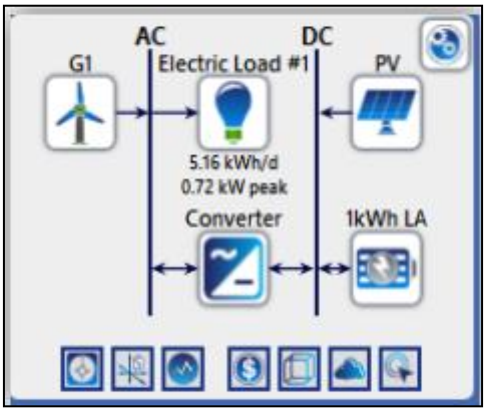
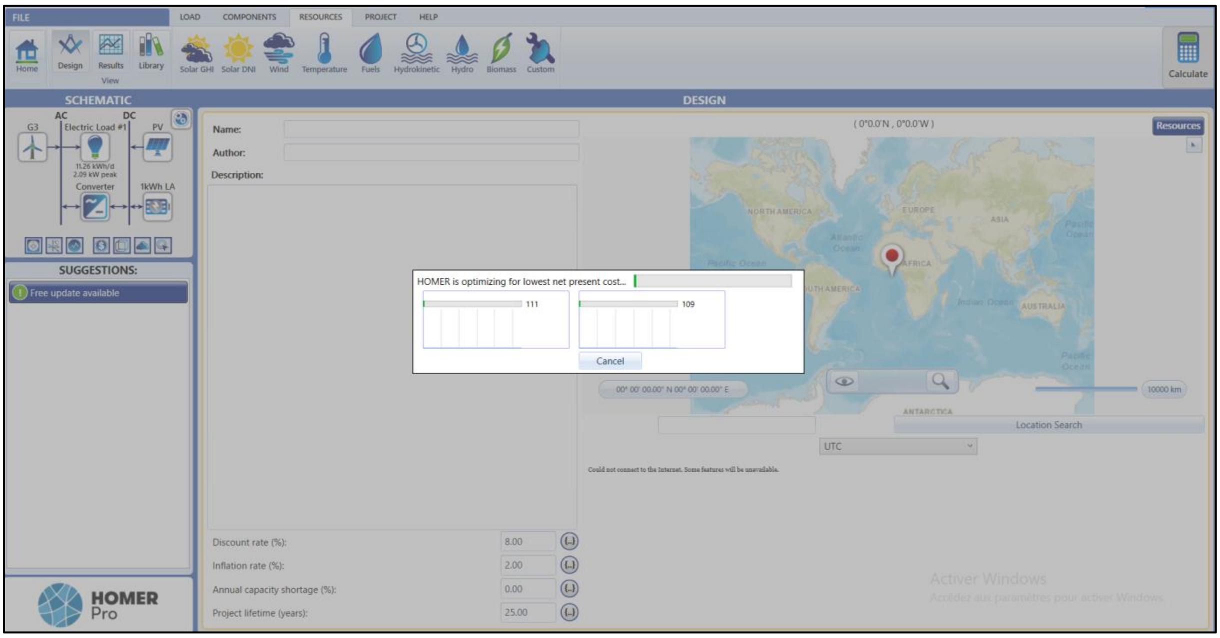


Figure II.18. Diagram representing the architecture of the installation.

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



Name:
Author:
Description:

(0°0.0'N , 0°0.0'W)

HOMER is optimizing for lowest net present cost...

111

109

00° 00' 00.00" N 00° 00' 00.00" E

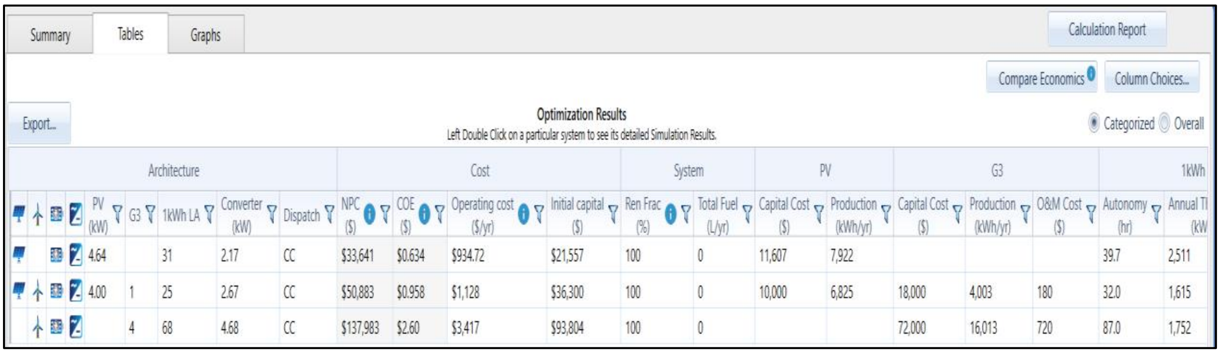
UTC

Could not connect to the Internet. Some features will be unavailable.

Discount rate (%): 8.00
Inflation rate (%): 2.00
Annual capacity shortage (%): 0.00
Project lifetime (years): 25.00

Figure II.19.The beginning of a process simulate**.**

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



Optimization Results
Left Double Click on a particular system to see its detailed Simulation Results.

Architecture					Cost				System		PV		G3			1kWh	
PV (kW)	G3	1kWh LA	Converter (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Total Fuel (L/yr)	Capital Cost ($)	Production (kWh/yr)	Capital Cost ($)	Production (kWh/yr)	O&M Cost ($)	Autonomy (hr)	Annual Tl (kW
4.64		31	2.17	CC	$33,641	$0.634	$934.72	$21,557	100	0	11,607	7,922				39.7	2,511
4.00	1	25	2.67	CC	$50,883	$0.958	$1,128	$36,300	100	0	10,000	6,825	18,000	4,003	180	32.0	1,615
	4	68	4.68	CC	$137,983	$2.60	$3,417	$93,804	100	0			72,000	16,013	720	87.0	1,752

Figure II.20. Optimal result for the hybrid system by Homer Pro**.**

Once the simulation is completed, HOMER ranks configurations from lowest to highest Net Present Cost (NPC). NPC accounts for lifetime costs discounted to present value. The output lists feasible options ranked by NPC, with the lowest NPC configuration being optimal and most cost-effective. This top-ranked configuration represents the best energy system composition for the project, as shown in Figure II.20. Users can easily identify the most economically viable components by examining HOMER's top-ranked result.

II.11. Conclusion

In this chapter, we have studied the modelling of components of the hybrid renewable energy system represented by PV generator, wind turbine system, battery storage, and bidirectional converter models. Additionally, we discussed software programs for techno-economic analysis specific to hybrid renewable energy systems (IHOGA, Hybrid2, RET Screen, TRNSYS). Finally, we have explored the HOMER Pro program interface and how to create a project using it.

The next chapter will examine a various system under diverse conditions and analyse the results from economic and technical aspects.

III.1. Introduction

Stand-alone renewable energy systems constitute an alternative to the grid connected systems. They include solar radiation, wind and hydraulic sources which are essentially inexhaustible resources. However, currently, the generation of electricity based on Renewable Energy Technologies (RET) is more expensive than the conventional technologies using fossil fuels, large hydropower and nuclear energy. These systems usually include batteries due to the instability of these resources and to ensure reliable electricity supply [36].

This chapter conducted two tests to investigate factors influencing the economic viability of renewable energy systems. The first assessed the impact of pricing mechanisms for purchasing from and selling excess electricity to the grid (Grid Power Price/Grid Sellback Price) on potential returns for renewable energy project investors. The goal was to identify pricing scenarios that would incentivize investment by ensuring attractive returns.

The second test examined the effects of renewable energy source configurations on the Net Present Cost (NPC) under three grid conditions: fully reliable, completely unavailable (Grid Off), and unreliable with periodic outages. This aimed to determine the optimal system configuration and analyse economic viability considering varying grid conditions.

III. 2. System description

a. Site selection

For the implementation of microgrid concept, the chosen site is tested; and it is crucial to carefully choose the site to ensure accurate data on wind speed, solar radiation, etc. We chose the city of Laghouat for this study, which is located at longitude 2.55 and latitude 33.4 (Figure III.1).

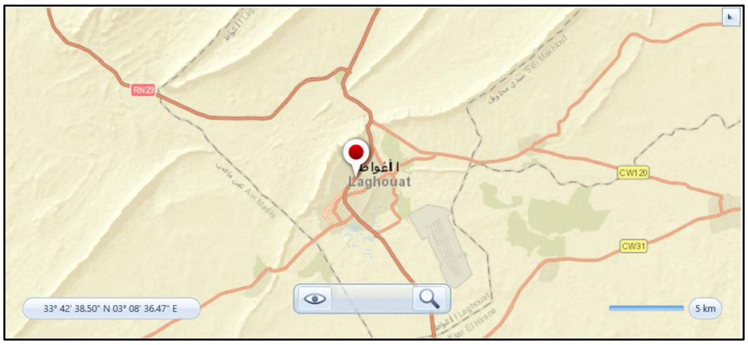


Figure III .1. The site selected for study

b. Load profile

We chose a house, took measurements from it, and recorded them in a table. Table III.1 shows us the power consumption of various appliances throughout the day. The first column shows the time of day, and the subsequent columns show the power consumption of various appliances in watts (W).

The table continues for each hour of the day, showing the power consumption of each appliance. The bottom row of the table shows the total power consumption for all devices throughout the day 34,200 (Wh/day).

The value of the number of consumption hours is determined on the basis of several factors, including:

- Lighting, which depends on the time of sunrise and sunset, and this depends on the geographical location of the site

- Wake-up and go-to-sleep times for family members, sunrise and sunset times vary in local time from season to season. By knowing the times when the family wakes up and goes to sleep, we can easily determine the number of consumption hours related to the home in the place in question.

After that, in the program we chose the Residential load type based on the estimated scaled average of 34.20 kWh/day and fill out the data based on the Table III.1 , as depicted in the following Figure:

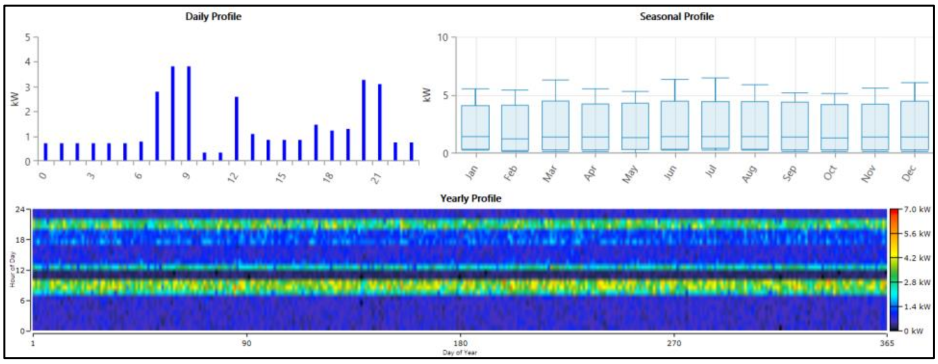


Figure III.2. The load fluctuates throughout the year.

Table III.1. Load profile used**.**

Time	**Refrigerator**	**Economic Lightning**	**Air conditioner**	**Water pomp**	**Computer**	**Television**	**Washing machine**	**Electric oven**	**Mobile phone charger**	**(Wh/day)**
00:00	200		500							700
01:00	200		500							700
02:00	200		500							700
03:00	200		500							700
04:00	200		500							700
05:00	200		500							700
06:00	200	60	500						15	775
07:00	350	60		370				2000	15	2795
08:00	350			370	80		3000		15	3815
09:00	350			370	80		3000			3800
10:00	350									350
11:00	350									350
12:00	350					250		2000		2600
13:00	350		500			250				1100
14:00	350		500							850
15:00	350		500							850
16:00	350		500							850
17:00	350		500	370		250				1470
18:00	350		500	370						1220
19:00	350	60	500	370					15	1295
20:00	350	60	500		80	250		2000	15	3255
21:00	200	60	500		80	250		2000	15	3105
22:00	200	60	500							760
23:00	200	60	500							760
Total load AC (Wh/day)										**34200**

c. PV system

The solar radiation data was obtained for in the Laghouat region. Figure 3 shows the average daily solar radiation data on the left axis and the solar radiation's clearness index values on the right axis.

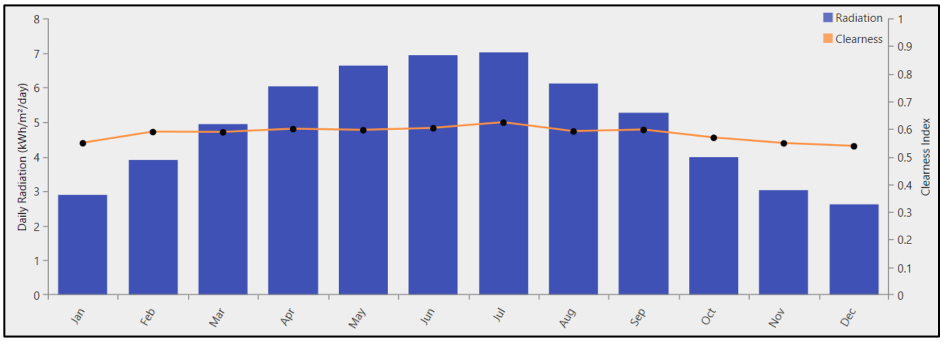


Figure III.3. The monthly clearness index and daily radiation levels in the Laghouat region.

Each photovoltaic (PV) panel has a power rating of 1 kW, with projected initial and replacement costs of US$350 per kilowatt. and there is an annual operating cost of US$10 and their lifetime is around 25 years total [37,38].

d. Wind system

The wind speed and direction data from is needed in order to have a good wind resource assessment and estima, Figure 4 shows the average monthly wind speed in Laghouat region.

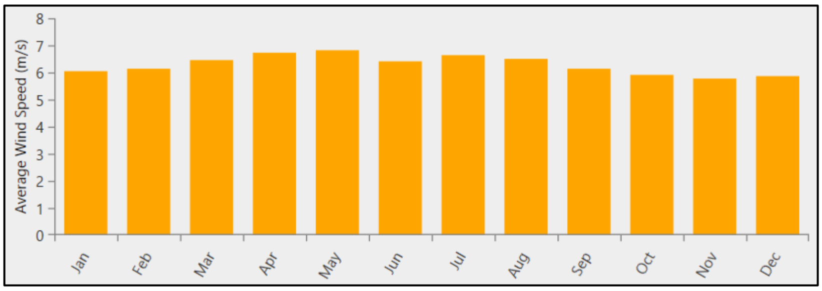


Figure III .4. The average monthly wind speed in Laghouat.

The turbine chosen, labeled as "Generic 1 kW," carries a capital expense of US$850 per kilowatt, with fixed operating and maintenance costs amounting to US$10. It is anticipated to function for roughly 20 years at a hub elevation of 17 meters [38].

e. Bidirectional converter.

The converter operates in both inverter and rectifier modes. The converter has a capacity of 1 kW. Its initial capital cost is 300 US$ and its replacement is at 300 US$. and the operation and maintenance cost add further to the annual total cost. The lifetime and efficiency of inverter input were considered at 15 years and 95% efficiency, respectively [39].

f. Battery storage system

We selected Hitachi reference batteries LL1500-W, designed to be integrated into within the hybrid system as a basis for battery performance. This configuration utilizes a Lead Acid battery with an initial cost of US$3,233 and a replacement cost of US$3,111. Its yearly operational expense is US$10, and it has a nominal capacity of approximately 17 kWh [40]. The next Table provides summary cost of components used in the study:

Table III.2. Cost of components

Name	Capital	Replacement	O&M
PV [**37,38**]	350 $/KW	350 $/KW	10 $/KW/yr
Wind teurbine [**38**]	850 $/KW	850 $/KW	10 $/KW/yr
Converter [**39**]	300 $/KW	300 $/KW	0 $/KW/yr
Storage unit [**40**]	$ 3.233.00	$ 3.111.00	10$/yr

III.3. Scenario's information

In our study, we performed two tests. The first aimed to assess the impact of the price of purchasing Grid Power Price (GPP) and Grid Sellback Price (GSP) on the returns of investors in renewable energies. The second test centered on exploring how the configuration of renewable energies and grid conditions impacted the NPC spanning a 25-year timeframe.

III.4. Test 01

III.4.1. System 01: Load + Grid (GPP = $ 0.039 / GSP = $ 0.00)

This system contains only the network and the load, and does not contain any renewable energy. The purchase price of the network is estimated at $0.039 and the resale price of the grid is $0.00. See Figure III.5.

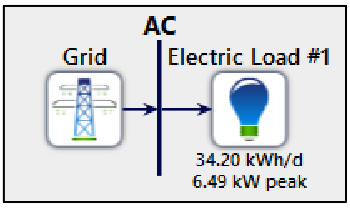


Figure III.5. Load + Grid (GPP = $ 0.039 / GSP = $ 0.00)

Note: This price is applicable in oil-producing countries and is considered a state-subsidized price.

III.4.2. System 02: Load + Grid + PV (GPP = $ 0.039 / GSP = $ 0.00)

This system contains the grid, loads, and solar energy (PV). The purchase price of the network equals $0.039 and the resale price of the network equals $0.00, see figure III.6

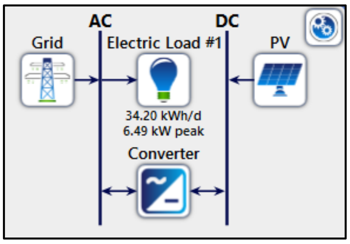


Figure III.6. Load + Grid + PV (GPP = $ 0.039 / GSP = $ 0.00)

III.4.3. System 03: Load + Grid + PV (GPP = $ 0.039 / GSP = $ 0.01)

This system contains the grid, load and solar energy (PV), where in this case the resale price changes and is estimated at $0.01 and the purchase price remains constant, see Figure III.7.

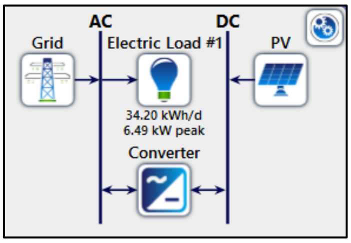


Figure III.7. Load + Grid + PV (GPP = $ 0.039 / GSP = $ 0.01)

III.4.4. System 04: Load + Grid + PV (GPP = $ 0.1 / GSP = $ 0.05)

This system contains the network, the load, and solar energy (PV). In this study, we change the local price with the European price, which is estimated at $0.1, the network purchase price, and the network resale price $0.05[37], Figure III.8.

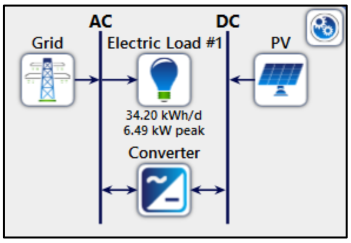


Figure III.8. Load + Grid + PV (GPP = $ 0.1 / GSP = $ 0.05)

Note: This price applies in countries that do not subsidize the price of electricity per kilowatt-hour.

III.4.5. Results analysis and discussion

After we add the systems to the program and input the data for each system, we run the simulation. After that, the possible solutions are sorted based on criteria that include the Net Present Cost (NPC), the Cost of Energy (LCOE), the value of emissions (CO_2), and the size of renewable energy production while meeting load requirements. They are summarized in next tables:

Table III.3. NPC, Initial Cost, LCOE, and $CO2$ Comparison for Different Grid Power Prices (GPP) and Grid Sellback Prices (GSP).

	Grid connected (Reliable)			
Cost type	**System 01**	**System 02**	**System 03**	**System 04**
GPP	$ 0.039	$ 0.039	$ 0.039	$ 0.1
GSP	$ 0	$ 0	$ 0.01	$ 0.05
NPC	$ 18,282	$ 16,564	$ 15,619	$ -51,545
Initial cost	$ 0.00	$ 1,180	$ 2,917	$ 21,250
LCOE	$ 0.0390	$ 0.0327	$ 0.0239	$ -0.0187
Ren frac	0 %	28.2%	54.4%	92.4%
CO_2	7,889 kg/yr	6,129 kg/yr	5,024 kg/yr	3,522 kg/yr

From Table III.3, we observe that it illustrates the variations in NPC, Initial Cost, LCOE, Renewable Fraction, and the CO_2 ratio in terms of the changes in the values of Grid Power Price (GPP) and Grid Sellback Price (GSP). System 4 is the most cost-effective option, with a Net Present Cost (NPC) of -$51,545, indicating a financial benefit over its lifetime due to its high GPP and GSP. These prices motivate investors to invest in producing energy from renewable sources. This helps reduce the percentage of CO_2 emissions, as shown in the table.

Table III.4. Optimal size for components in different systems.

	System01	**System02**	**System03**	**System04**
Grid	ON	ON	ON	ON
PV	-	2.21 kW	5.40 kW	35 kW
converter	-	1.35kW	3.42 kW	30 kW

The Table III.4 represents the optimal size configuration for each component. We note that when the GPP and GSP rise, the optimal economic size of the PV system also rises. This indicates that when the GPP and GSP are not state-subsidized, the use of renewable energy becomes more economically effective.

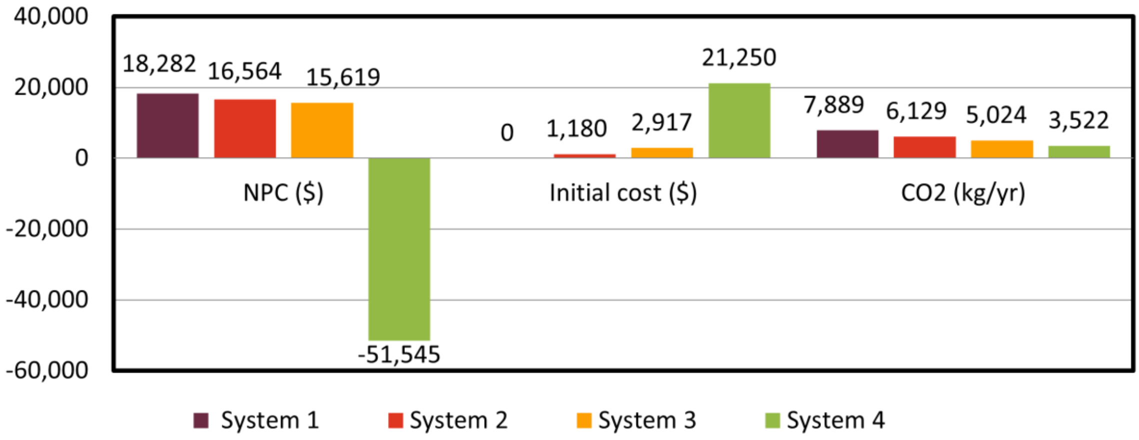
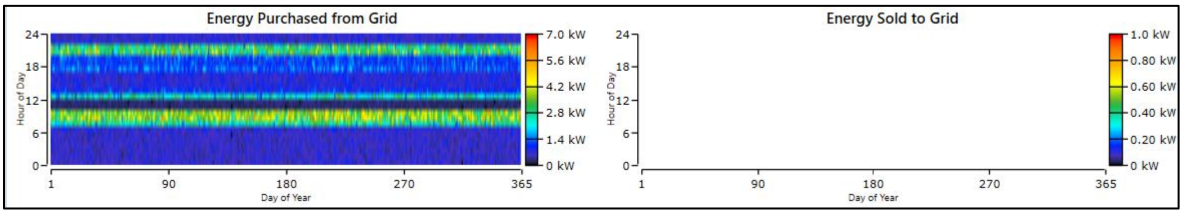


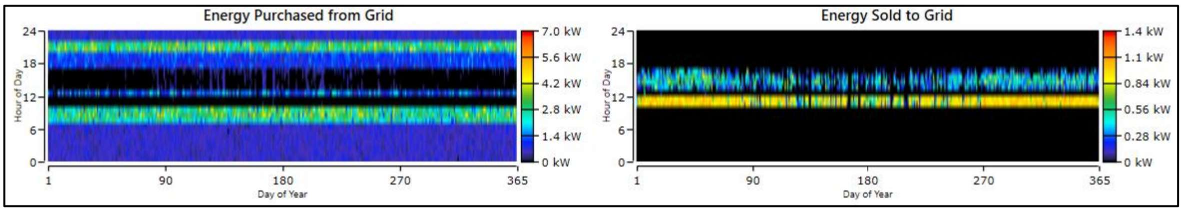
Figure III.9. NPC, initial cost, and CO_2 comparison for different Grid power prices and Grid sellback prices.

Figure III.9 shows that System 4 is identified as the most cost-effective and environmentally friendly option, with the lowest Net Present Cost (NPC) and CO_2 emissions, but it has the higher initial cost due to the large size of the PV system. In contrast, Systems 1, 2, and 3 have higher NPC and CO_2 emissions, and this is due to the small percentage of renewable energy fraction (Ren frac) because of the cheap energy price imported from the grid, which is lower than the price of production with renewable energy.


Energy Purchased from Grid

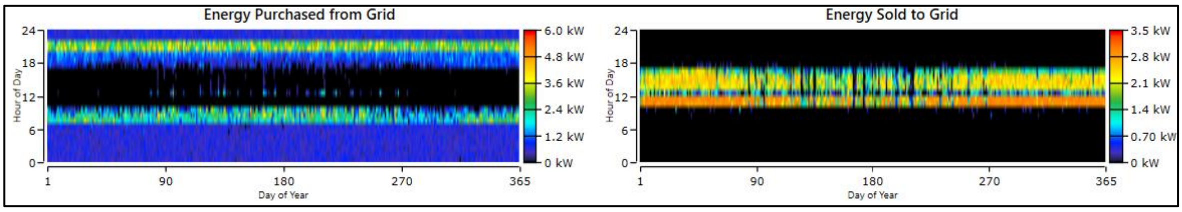
Energy Sold to Grid

Figure III.10. Grid energy for the system 01.


Energy Purchased from Grid

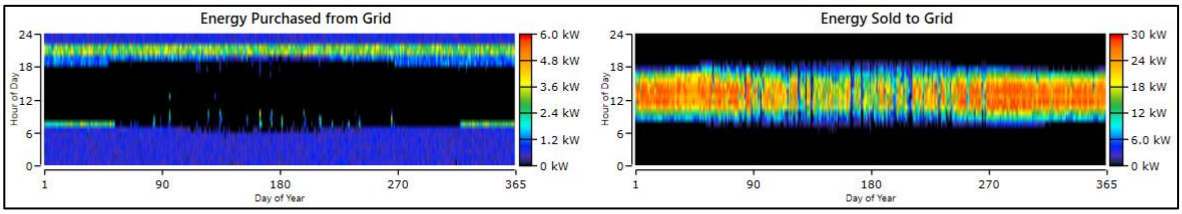
Energy Sold to Grid

Figure III.11. Grid energy for the system 02


Energy Purchased from Grid

Energy Sold to Grid

Figure III.12. Grid energy for the system 03


Energy Purchased from Grid

Energy Sold to Grid

Figure III.13. Grid energy for the system 04

Figures III.10, 11, 12, and 13 showcase the changes in energy exchange between the system and the grid. We observe in Figure 10 that when the GSP is $0, the energy exported to the grid is negligible due to the presence of the load only and the absence of energy production. However, upon adding the solar energy unit, we notice a slight increase in energy export to the grid, as observed in Figure 11. In Figure 12, for System 3, when we set the GSP price to $0.01, there is a noticeable rise in the energy exported to the grid, which helps make the system more economical. In System 4, when we set the non-subsidized price from the state as referenced in [37], there is a significant increase in electricity sales to the grid, making the system the most economically advantageous for investors.

III.5. Test 02

In this test, we investigate into different cases: the initial one is connection to a reliable grid, the second arises when the grid is off, and the third relates to being connected to an unreliable grid. We fixed Grid Power Price $ 0.1 and Grid Sellback Price $ 0.05 [37].

III.5.1. Grid connected (Reliable)

a. System 01: Grid + Load

System 01 relies entirely on the grid to provide power to the connected load. This system has no renewable energy components or energy storage systems; The grid acts as the sole source of electricity, the next figure shows that:

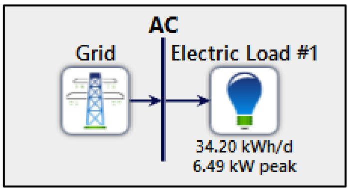


Figure III.14. The design for the Grid Reliable (Grid + Load)

b. System 02: Grid +Load + PV

System 02 integrates grid power with a load and photovoltaic (PV) solar panels, providing a hybrid approach to power supply. The primary goal is to reduce dependence on the grid and lower electricity costs by utilizing solar energy, See Figure III.15.

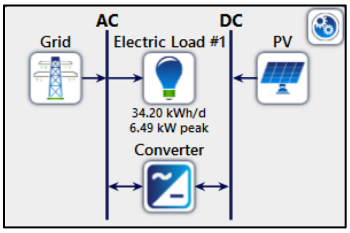


Figure III.15. The design for the Grid Reliable (Grid +Load + PV)

c. System 03: Grid +Load + WT

System 03 integrates grid power with a load and a wind turbine, providing a hybrid approach to power supply. See Figure III.16.

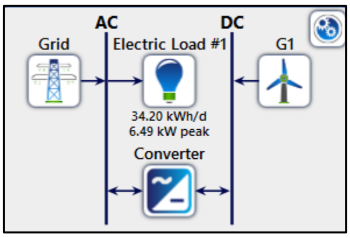


Figure III.16. The design for the Grid Reliable (Grid +Load + WT)

d. System 04: Grid +Load + WT + PV

System 04 is a hybrid power system that integrates grid power with a load, a wind turbine, and photovoltaic (PV) solar panels. This leverages multiple renewable energy sources, See Figure III.17.

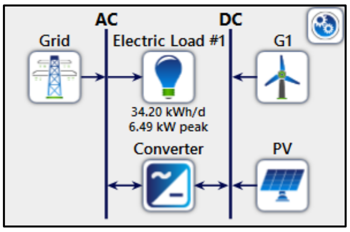


Figure III.17. The design for the Grid Reliable (Grid +Load + WT + PV)

III.5.2. Grid OFF

a. System 05: PV +Load + Battery

System 05 is an off-grid power system that combines photovoltaic (PV) solar panels with a load and a battery storage system. This setup is designed to operate independently from the grid.

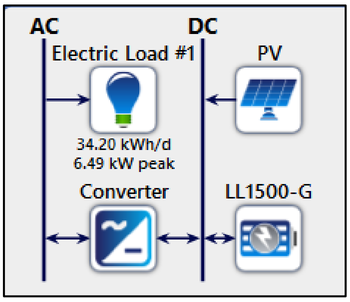


Figure III.18. The design for the off-grid (PV +Load + Battery)

b. System 06: WT +Load + Battery

System 06 is an off-grid power system that integrates a wind turbine with a load and a battery storage system.

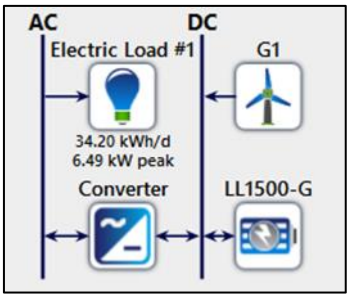


Figure III.19. The design for the off-grid (WT +Load + Battery)

c. System 07: PV + WT + Load + Battery

System 07 is an off-grid power system that integrates photovoltaic (PV) solar panels, a wind turbine, a load, and a battery storage system. This hybrid configuration is designed to harness both solar and wind energy to provide a reliable power supply, with battery storage ensuring continuous availability of electricity. The system aims to maintain a steady power supply through efficient utilization renewable energy and storage.

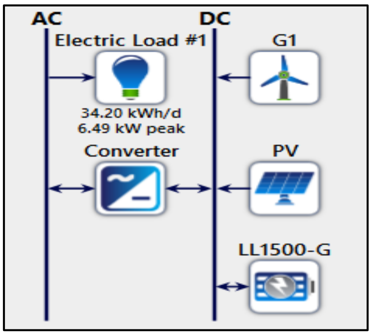


Figure III.20. The design for the off-grid (PV + WT + Load + Battery)

III.5.3. Grid connected (Unreliable)

a. System 08: Grid +Load + PV + Battery

System 08 is a hybrid power system designed for areas with unreliable grid access with photovoltaic (PV) solar panels, a load, and battery storage to compensate for grid unreliability.

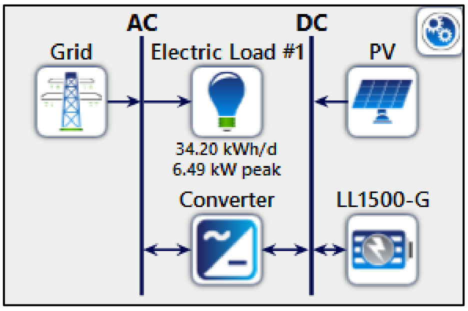


Figure III.21. The design for the Grid Unreliable (Grid +Load + PV + Batter)

b. System 09: Grid +Load + PV +WT + Battery

System 09 involves a unreliable grid-connected hybrid renewable energy system (HRES) comprising a load, photovoltaic (PV) panels, wind turbines, and a battery storage system. This configuration aims to ensure a stable and reliable energy supply by leveraging multiple energy sources and storage to mitigate the impact of grid unreliability.

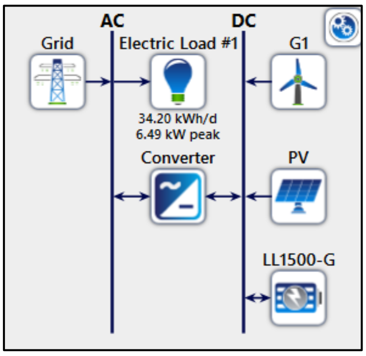


Figure III.22. The design for the Grid Unreliable (Grid +Load + PV +WT + Battery)

III.5.4. Results analysis and discussion

HOMER Pro simulated all the possible configurations to achieve the most cost-effective system. Cost, electrical, and environmental analyses were performed.

After the simulation, a list of possible schemes is organized by minimum net present cost, to compare available options for system design, and is expressed in Table III.5.

Table III.5 NPC, initial cost, LCOE, and CO2 comparison for different hybrid systems

	Grid connected (reliable)				**Grid off**			**Grid connected (unreliable)**	
Cost type	**System01**	**System02**	**System03**	**System04**	**System05**	**System06**	**System07**	**System08**	**System09**
NPC	$ 46,877	$-51,545	$ -58,366	$-120,413	$55,947	$ 81,135	$ 40,919	$ -34,474	$-112,695
Inital cost $	$ 0.00	$ 21,250	$ 38,750	$ 51,000	$29,919	$ 51,093	$ 21,442	$30,713	$ 54,233
LCOE	$ 0.100	$-0.0187	$ -0.0181	$ -0.0248	$ 0.119	$ 0.173	$ 0.0873	$ -0.0113	$ -0.0238
Ren frac	0%	92.4%	96.1%	98.6%	100%	100%	100%	100%	99.7%
CO_2	7,889kg/yr	3,522kg/yr	2,117kg/yr	1,122kg/yr	0 kg/yr	0 kg/yr	0 kg/yr	3.09kg/yr	200 kg/yr

Table III.12. Optimal size for components in different systems**.**

	System01	**System02**	**System03**	**System04**	**System05**	**System06**	**System07**	**System08**	**System09**
Grid	ON	ON	ON	ON	OFF	OFF	OFF	ON	ON
PV	-	35 kW	-	35 kW	14.9 kW	-	8.92 kW	35 kW	35 kW
Wind	-	-	35 kW	35 kW	-	12 kW	4 kW	-	35 kW
converter	-	30 kW	30 kW	30 kW	6.96 kW	6.99 kW	6.62 kW	29.2 kW	30 kW
Storage	-	-	-	-	7	12	4	3	1

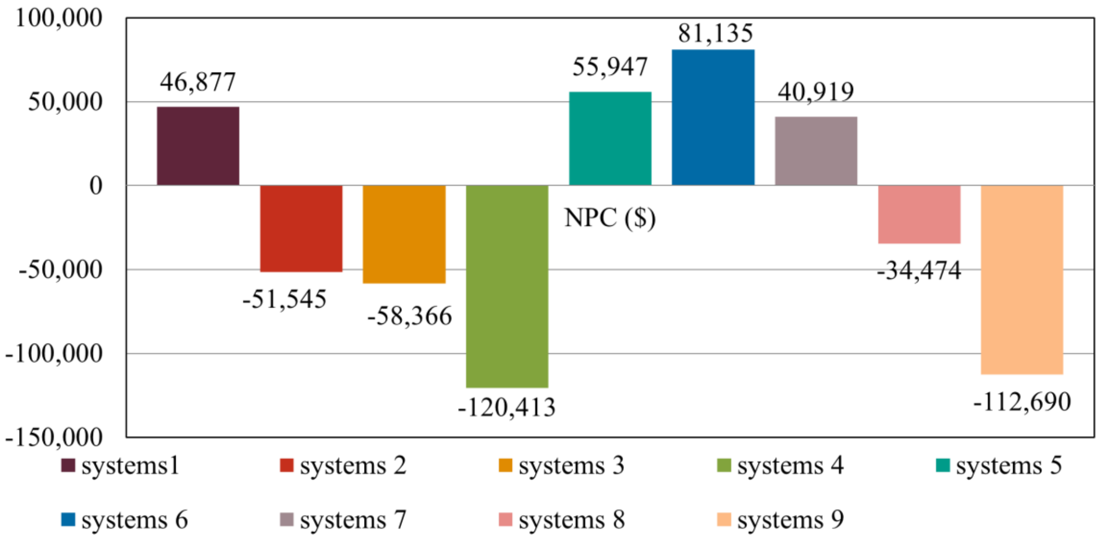


Figure III.23. NPC comparison for different hybrid systems.

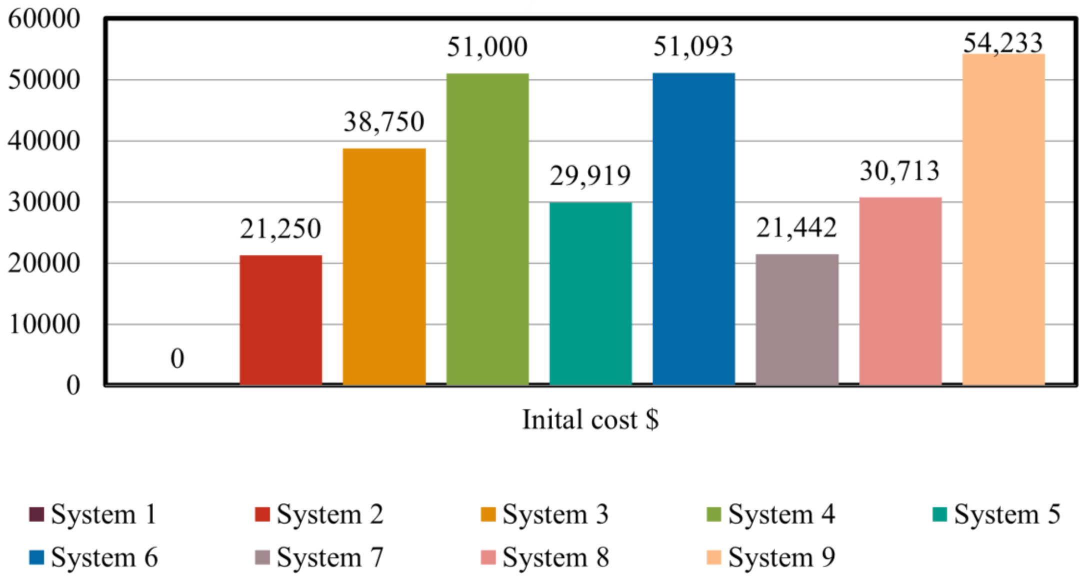


Figure III.24. Initial cost comparison for different hybrid systems.

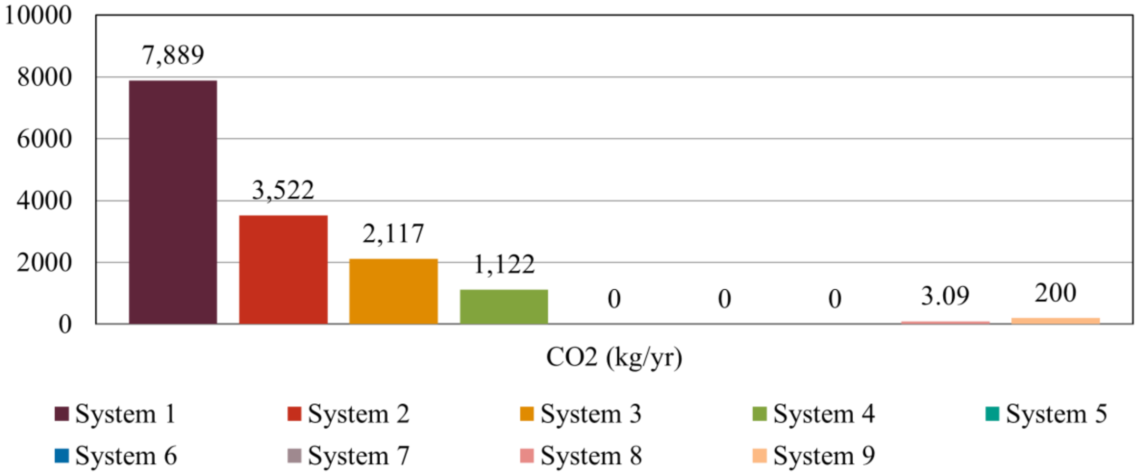


Figure III.25. CO_2 comparison for different hybrid systems.

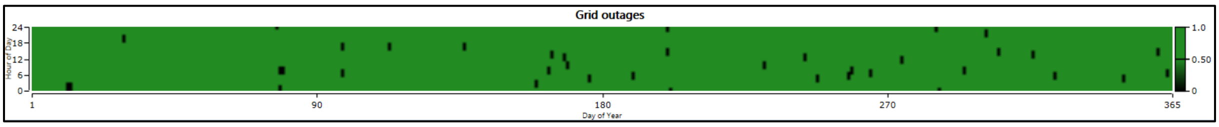


Figure III.26. Unreliable grid outages.

Figure III.27 shows us System 9 dependence on grid power throughout the year.

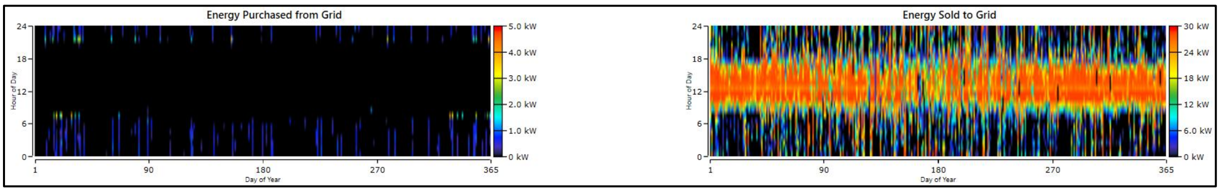


Figure III.27. Grid energy for the system 9.

Figure III.28 shows the changes in battery status throughout the year.

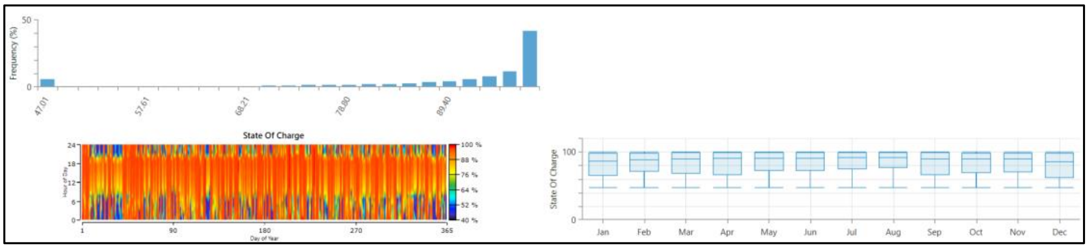


Figure III.28. Battery state of the system 9.

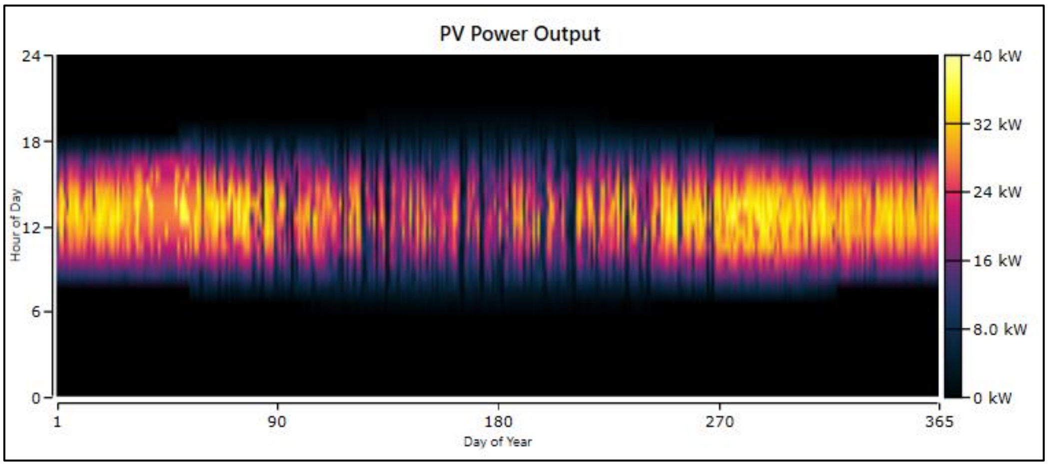


Figure III.29. The PV system power of system 9

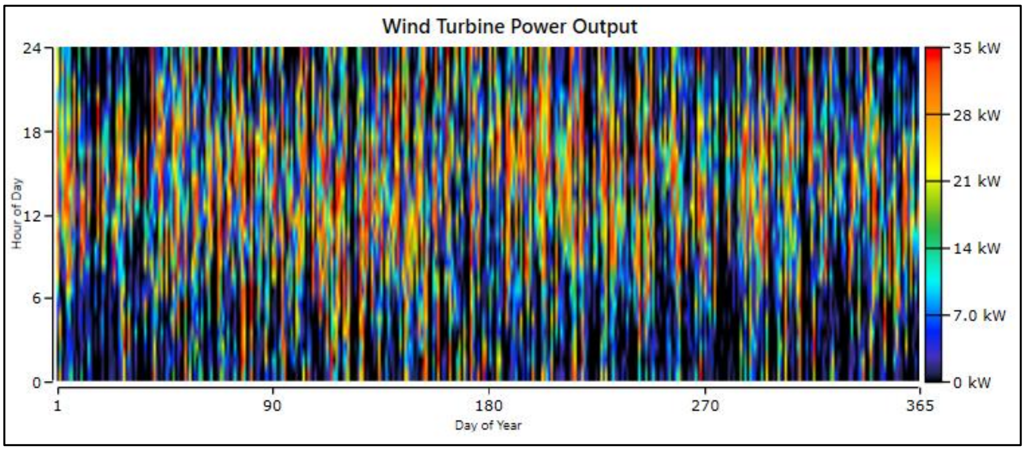
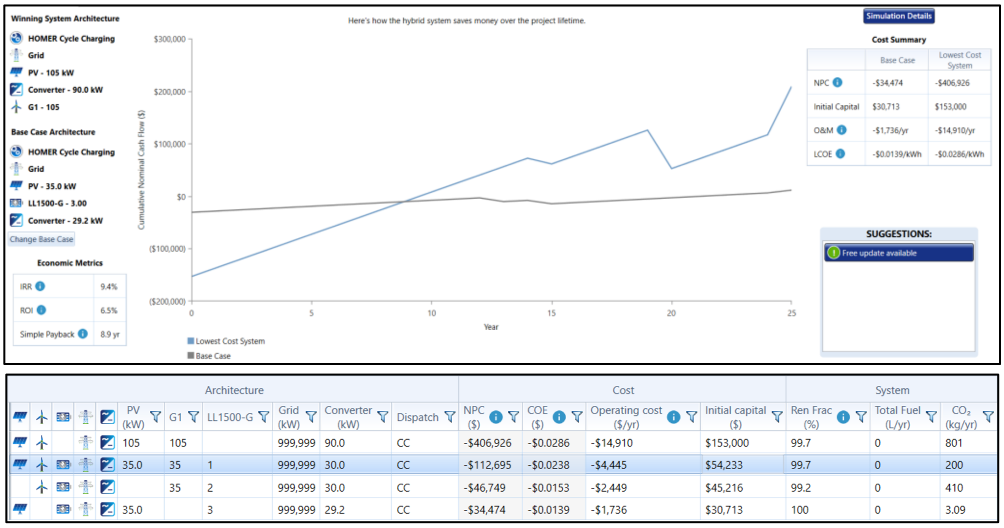


Figure III.30. The WT power of system 9



Winning System Architecture

- HOMER Cycle Charging
- Grid
- PV - 105 kW
- Converter - 90.0 kW
- G1 - 105

Base Case Architecture

- HOMER Cycle Charging
- Grid
- PV - 35.0 kW
- LL1500-G - 3.00
- Converter - 29.2 kW

Economic Metrics

IRR	9.4%
ROI	6.5%
Simple Payback	8.9 yr

Cost Summary

	Base Case	Lowest Cost System
NPC	-$34,474	-$406,926
Initial Capital	$30,713	$153,000
O&M	-$1,736/yr	-$14,910/yr
LCOE	-$0.0139/kWh	-$0.0286/kWh

Architecture											Cost					System		
					PV (kW)	G1	LL1500-G	Grid (kW)	Converter (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Total Fuel (L/yr)	CO_2 (kg/yr)
✓	✓		✓	✓	105	105		999,999	90.0	CC	-$406,926	-$0.0286	-$14,910	$153,000	99.7	0	801
✓	✓	✓	✓	✓	35.0	35	1	999,999	30.0	CC	-$112,695	-$0.0238	-$4,445	$54,233	99.7	0	200
	✓	✓	✓	✓		35	2	999,999	30.0	CC	-$46,749	-$0.0153	-$2,449	$45,216	99.2	0	410
✓		✓	✓	✓	35.0		3	999,999	29.2	CC	-$34,474	-$0.0139	-$1,736	$30,713	100	0	3.09

Figure III.31. The winning system (System 9) in comparison of base system

III.6. Total results analysis discussion

In Table III.5, we observe significant variations in the values of Net Present Cost (NPC), Initial Cost, Levelized Cost of Energy (LCOE), Renewable Fraction (Ren frac), and CO_2 ratio in response to changes in system conditions and structure. These variations highlight the impact of different configurations and operational strategies on the economic and environmental performance of the systems.

Table III.6 details the optimal component sizes for each system, providing insights into the design requirements for achieving the best performance. Figure III.23 presents a bar graph comparison of NPC values across all systems. Notably, System 1, which consists of a reliable grid coupled with load, shows a positive NPC value, indicating financial losses. In contrast, Systems 2, 3, and 4, which integrate renewable energy sources, generate financial returns. Among these, the wind system is more economically advantageous compared to the PV system. Furthermore, the hybrid system, combining both wind and solar energy, offers the highest financial returns in terms of NPC. When the grid is unavailable, all systems experience financial losses, though the extent of these losses varies. The hybrid system consistently demonstrates the least losses in both reliable and unreliable grid scenarios, underscoring its resilience and economic viability.

Figure III.24 illustrates the Initial Cost values for each system. Although System 1 has the lowest Initial Cost, it lacks sustainability and results in high financial losses, and the system with the highest initial cost is System 9 due to the use of wind generators, PV system and batteries, but in return it has the highest financial return for investors. Figure III.25 highlights the correlation between investment in renewable energies and a reduction in CO_2 emissions, contributing to environmental preservation. Figure III.26 depicts the occurrence of random interruptions in the unreliable grid, providing a visual representation of grid stability issues.

Figure III.27 shows the energy exchange dynamics between the grid and System 9, while Figure III.28 tracks changes in battery state throughout the year, indicating the storage system's performance and capacity utilization. Figure III.29 showcases the energy production from solar panels in System 9, and Figure III.30 presents the energy generated by wind turbines in the same system. These figures collectively illustrate the contribution of each renewable source to the system's overall energy mix.

In Figure III.31, a comparative analysis of systems during unreliable grid conditions identifies System 9 as the most profitable. It achieves better financial returns and reduced carbon emissions, highlighting the benefits of a well-integrated hybrid system.

In summary, the integration of renewable energies is crucial for reducing CO_2 emissions and promoting environmental sustainability. Despite the initial investment costs, these systems can provide significant financial returns under appropriate conditions, making them attractive options for investors aiming to balance economic and environmental goals.

III.7. Conclusion

All our discussions of various graphs and tables point out the importance of careful consideration when choosing a renewable energy system. In this study, we have how the Grid Power Price (GPP) and Grid Resale Price (GRP) affect investors' decisions. The rise in GPP and GRP prices leads to achieving higher profits in the energy field and encourages more investors in this field. And we have conclude from the results of test 2 that the optimal system is the hybrid system between solar and wind energy, which is planned to help companies transition from using traditional resources to investing in renewable energy resources in the near future due to the increased demand for electricity.

Economic and environmental development is absolutely necessary to meet energy needs, reduce environmental impacts, and make systems more environmentally friendly. The use of renewable energy sources, such as hybrid systems (photovoltaic and wind), can be a good solution. These sources are abundantly available, exceeding current energy consumption, and do not emit greenhouse gases during their operation. As part of the exploitation of solar and wind energy for generating electrical energy, this study is conducted for the technical and economic analysis and improvement of grid-connected hybrid renewable energy systems.

Hybrid Renewable Energy Systems (HRESs) represent a significant innovation for achieving sustainable and reliable energy solutions. Chapter 1 provides an overview of these systems, explaining the fundamental concepts, benefits, and drawbacks, as well as discussing the technologies, applications, and challenges associated with Photovoltaic (PV) Systems and wind energy. It also emphasizes the role of energy storage systems, along with the discussion of converters and control mechanisms aimed at optimizing the performance of these systems.

Chapter 2 focuses on enhancing the design of hybrid renewable energy systems through accurate modeling of their components, which contributes to improving their performance. The chapter includes detailed models for solar power generators, wind turbine systems, battery storage, and bidirectional converters. It also covers various optimization methods, particularly using HOMER software. Additionally, the chapter provides practical advice on navigating HOMER Pro interfaces and initiating projects within the software.

The chapter 3 begins by discussing site selection and data description, focusing on residential load profiles and essential components. It details various tested scenarios, offering an in-depth analysis and discussion of the results for each system configuration. The chapter evaluates system performance in both grid-connected and off-grid scenarios, considering reliable and unreliable grid conditions.

In this study, we have investigated how investors' decisions are impacted by the Grid Power Price (GPP) and Grid Resale Price (GRP). Increased profits in the energy sector are a result of rising GPP and GRP prices, which also attract additional investors. According to the results of test 2, the best system is a hybrid system that combines solar and wind energy. In terms of Net Present Cost (NPC) and Carbon Dioxide (CO_2) emissions, the use of renewable energies helps reduce CO_2 emissions and preserve the environment.

Perspectives

To continue the research, the following suggestions are recommended:

- **Use of Other Hybrid Renewable Energy Sources**

Explore and integrate additional renewable energy sources such as geothermal energy, biomass, or hydropower to enhance the system's diversity and flexibility.

- **Use of Different Types of Storage Systems**

Investigate the use of alternative energy storage systems such as compressed air energy storage or advanced battery technologies to improve the system's efficiency and reliability.

- **Use of Other Software and Comparison**

Employ different software tools to analyze and optimize the hybrid renewable energy system, such as HYBRID2, IHOGA, TRNSYS, and RET Screen, and compare the results with those obtained from Homer Pro.

REFERENCES

[1] León Gómez, Juan Carlos, Susana Estefany De León Aldaco, and Jesus Aguayo Alquicira. "A review of hybrid renewable energy systems: Architectures, battery systems, and optimization techniques." Eng 4.2 (2023): 1446-1467.

[2] Ganguly, Piyali, Akhtar Kalam, and Aladin Zayegh. " Design a Control Mechanism for the Power Management of a Standalone Renewable Energy System." 2019 International Conference on Power Electronics, Control and Automation (ICPECA). IEEE, 2019.

[3] Pranoy.R., JiangBiao.H, Tiefu.Z, Yash.V.S. Recent Advances of Wind-Solar Hybrid Renewable Energy Systems for Power Generation. IEEE Open Journal of the Industrial

[4] IEEE Guide for Selecting, Charging, Testing, and Evaluating Lead-Acid Batteries Used in Stand-Alone Photovoltaic (PV) Systems. (n.d.).

[5] Chowdhury, Sabrina. "Design & estimation of rooftop grid-tied solar photovoltaic system." no. May 2017 (2016).

[6] Faisal, M., Hannan, M. A., Ker, P. J., Hussain, A., Mansor, M. B., & Blaabjerg, F. (2018). Review of Energy Storage System Technologies in Microgrid Applications: Issues and Challenges. IEEE Access, 6, 35143–35164. doi:10.1109/access.2018.2841407.

[7] Hasan.W.S, Shaorong.W.B, Sakeen.F, A Novel GA-PI Optimized Controller for MPPT Based PV in a Hybrid PV-Diesel Power System "Preprints of the 5th international conference on Electric Utility Deregulation and Restructuring and Power Technologies" November 26-29, 2015.

[8] Rihab.M.E. Mansour.S Hsan.H.A "The fifth International Renewable Energy Congress IREC" Maximum Power Point Tracking Control Technique for Photovoltaic Systems Using Neural Networks, March 25 ،27, 2014

[9] Kermadi, M. (2018). A Hybrid Global Maximum Power Point Tracker For Photovoltaic Systems Under Complex Partial Shading Conditions [Thèse de Doctorat, École Nationale Polytechnique - Alger.

[10] Gustavo, M., & Enrique, P. (2011). Modelling and Control Design of Pitch-Controlled Variable Speed Wind Turbines. Wind Turbines. Doi:10.5772/15880.

[11] Noureddine, Z. AbdElkerim, M. Mohammed (2022). Wind Turbines-component And Design Basics [Mémoire de Master, Université Hamma Lakhdar – Eloued].

[12] Eriksson, S., Bernhoff, H., & Leijon, M. (2008). Evaluation of different urbine concepts for wind power. Renewable and Sustainable Energy Reviews, 12(5), 1419–1434. doi:10.1016/j.rser.2006.05.017.

[13] Dang, T. (2009). Introduction, history, and theory of wind power. 41st North American Power Symposium. doi:10.1109/naps.2009.5484084.

[14] Schaffarczyk, A. P. (2014). Introduction to Wind Turbine Aerodynamics. Green Energy and Technology. Doi:10.1007/978-3-642-36409-9.

[15] Huynh, P., Tungare, S., & Banerjee, A. (2019). Maximum Power Point Tracking for Wind Turbine Using Integrated Generator-Rectifier Systems. 2019 IEEE Energy Conversion Congress and Exposition (ECCE). doi:10.1109/ecce.2019.8912871.

[16] Xie, Shaorong, et al. "Maximum power point tracking control strategy for variable speed wind turbine generation system." 2014 International Conference on Information Science, Electronics and Electrical Engineering. Vol. 2. IEEE, 2014.

[17] Megateli, Redouane M., Saida Makhloufi, and Amar Hadj Arab. "Renewable Energy Storage Benefits and Economic Impact."

[18] Smith, S. C., Sen, P. K., & Kroposki, B. (2008). Advancement of energy storage devices and applications in electrical power system. 2008 IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century. doi:10.1109/pes.2008.4596436.

[19] Deshmukh, M. K., & Deshmukh, S. S. (2008). Modeling of hybrid renewable energy systems. Renewable and Sustainable Energy Reviews, 12(1), 235–249. doi:10.1016/j.rser.2006.07.011

[20] Swarnkar, N. M., Gidwani, L., & Sharma, R. (2016). An application of HOMER Pro in optimization of hybrid energy system for electrification of technical institute. 2016 International Conference on Energy Efficient Technologies for Sustainability (ICEETS). doi:10.1109/iceets.2016.7582899

[21] Belgana, S., Dabib, A., Bilil, H., &Maaroun, M. (2013). Hybrid renewable energy system design using multobjective optimization. 2013 International Conference on Renewable Energy Research and Applications (ICRERA). doi:10.1109/icrera.2013.6749890 10.1109/icrera.2013.6749890

[22] Ammari, C. & Hamouda, M. (2018). *Modélisation, Simulation Et Optimisation D'un System Hybride Autonome En Trois Sources* [Thèse de Doctorat, Université Ahmed Draia - Adrar].

[23] Qiu, T., &Faraji, J. (2021). Techno-economic optimization of a grid-connected hybrid energy system considering electric and thermal load prediction. Energy Science & Engineering, 9(9), 1313–1336. doi:10.1002/ese3.906 10.1002

[24] Ganguly, P., Kalam, A., &Zayegh, A. (2017). Design an optimum standalone hybrid renewable energy system for a small town at Portland, Victoria using iHOGA. 2017 Australasian Universities Power Engineering Conferenc (AUPEC). doi:10.1109/aupec.2017.8282487 10.1109/aupec.2017.8282487

[25] Fulzele, J. B., Daigavane, M. B., &Daigavane, P. M. (2019). Techno-economical and Feasibility Analysis of Hybrid PV–Wind System–Case Study. Lecture Notes on Multidisciplinary Industrial Engineering, 71–82. doi:10.1007/978-981-13-6148-7_8 10.1007/978-981-13-6148-7_8

[26] Baring-Gould, E. Ian. "The Hybrid System Simulation Model." (1998).

[27] Jeon, Jinhong, et al. "Development of a grid-connecteded wind/pv/bess hybrid distributed generation system." Power Electronics (2007).

[28] Thevenard, Didier, Gregory Leng, and Sylvain Martel. "The RETScreen model for assessing potential PV projects." Conference record of the twenty-eighth IEEE photovoltaic specialists conference-2000 (Cat. No. 00CH37036). IEEE, 2000.

[29] Ganoe, Rene D., Paul W. Stackhouse Jr, and Russell J. DeYoung. RETScreen plus software tutorial. No. NASA/TM-2014-218544. 2014.

[30] Lu, C., Zheng, M., & Leong, W. H. (2011). Verification and analysis of a TRNSYS model of a demonstration house equipped with a solar assisted ground coupled heat pump system. 2011 International Conference on Consumer Electronics, Communications and Networks (CECNet). doi:10.1109/cecnet.2011.5769151 10.1109/cecnet.2011.5769151

[31] Al-Zubaydi, Ahmed Y. Taha. Architectural modifications: performance assessment of the solar cooling system for a small size office building. Diss. University of Technology, Sydney, 2013.

[32] Khaled, Osamah, et al. "Techno-Economic Feasibility of Hybrid Energy Systems Installation in Pakistan." IEEE Access 12 (2024): 41643-41658.

[33] Ayed, Yasmine, et al. "Optimal design and techno-economic analysis of hybrid renewable energy systems: A case study of Thala city, Tunisia." Energy Sources, Part B: Economics, Planning, and Policy 19.1 (2024): 2308843.

[34] Ur Rashid, Mamoon, et al. "Techno-economic analysis of grid-connected hybrid renewable energy system for remote areas electrification using homer pro." *Journal of Electrical Engineering & Technology* 17.2 (2022): 981-997.

[35] MIMMI, Soumia. Study and optimization of standalone PV-wind-Diesel Battery Hybrid System In Remote Site In ALGERIA. Diss.

[36] Dinica, Valentina. "Support systems for the diffusion of renewable energy technologies—an investor perspective." Energy policy 34.4 (2006): 461-480.

[37] M. Ur Rashid, I. Ullah, M. Mehran, M. N. R. Baharom, et F. Khan, « Techno-Economic Analysis of Grid-Connected Hybrid Renewable Energy System for Remote Areas Electrification Using Homer Pro », *J. Electr. Eng. Technol.*, vol. 17, n° 2, p. 981-997, mars 2022, doi: 10.1007/s42835-021-00984-2.

[38] J. Liu, L. Jian, W. Wang, Z. Qiu, J. Zhang, et P. Dastbaz, « The role of energy storage systems in resilience enhancement of health care centers with critical loads », *Journal of Energy Storage*, vol. 33, p. 102086, janv. 2021, doi: 10.1016/j.est.2020.102086

[39] V. M. Fontalvo, G. J. Nelson, O. Pupo-Roncallo, M. E. Sanjuan, et H. A. Gómez, « A techno-economic assessment for fuel cells hybrid systems in stationary applications », *International Journal of Sustainable Energy*, vol. 42, n° 1, p. 889-912, déc. 2023, doi: 10.1080/14786451.2023.2244605.

[40] B. Belmahdi et A. E. Bouardi, « Simulation and Optimization of Microgrid Distributed Generation: a Case Study of University Abdelmalek Essaâdi in Morocco », *Procedia Manufacturing*, vol. 46, p. 746-753, 2020, doi: 10.1016/j.promfg.2020.03.105