République Algérienne Démocratique et Populaire

Ministère De l'Enseignement Supérieur et de la Recherche Scientifique

Université Ahmed Draia Adrar

Faculté des Sciences et de la technologie

Département d'hydrocarbures et énergies renouvelables

Thèse pour l'obtention du diplôme de Doctorat LMD en physique énergétique

Option : Energie renouvelable

<u>Intitulé :</u>

Modélisation, simulation et optimisation d'un system hybride autonome en trois sources

Soutenu publiquement le 26/12/2018 **par : Ammari Chouaib**

Devant le jury composé de :

Benatiallah Ali	Président	Professeur	Université Ahmed Draia-Adrar
Hamouda Messaoud	Rapporteur	Professeur	Université Ahmed Draia-Adrar
Makhloufi Salim	Co- Rapporteur	MCA	Université Ahmed Draia-Adrar
Azoui Boubekeur	Examinateur	Professeur	Université Batna 2
Othmane Abdelkhalek	Examinateur	Professeur	Université Tahri Mohammed-Béchar
Bentouba Said	Examinateur	MCA	Université Ahmed Draia-Adrar

DEMOCRATIC AND POPULAR REPUBLIC OF ALGERIA

MINISTRY OF HIGHER EDUCATION AND SCIENTIFIC RESEARCH

UNIVERSITY AHMED DRAIA-ADRAR

Faculty of sciences and technology

Department of hydrocarbon and renewable energy

THESIS

Presented by:

AMMARI CHOUAIB

SUBMITTED FOR THE DEGREE OF:

DOCTORAT OF SCIENCES

In Physics

Option: Renewable energy

Modeling, Simulation and Optimization of a standalone hybrid system based on three generators

Discussed on: 26/12/2018 **Members of the jury:**

Benatiallah Ali	Professor	Chairman	University Ahmed Draia-Adrar
Hamouda Messaoud	Professor	Supervisor	University Ahmed Draia-Adrar
Makhloufi Salim	MCA	Co-Supervisor	University Ahmed Draia-Adrar
Azoui Boubekeur	Professor	Examiner	University Batna 2
Othmane Abdelkhalek	Professor	Examiner	University Tahri Mohammed-Béchar
Bentouba Said	MCA	Examiner	University Ahmed Draia-Adrar

Dedication

With the help of God/my parents who gave me the power and the patience to work every day and finish this thesis.

I dedicate this thesis to the most valuable people in the world for me; my father the sun of my life and my mother the moon of my life who encouraged me during my study and gave me psychological and material assistance from my first day in school; I pray for God that they will stay safe.

I dedicate this thesis to

My brothers and sisters

Ammari, Gourari and Kabouya family

Everyone who helped me write this thesis

My friends who know me well.

Acknowledgments

First of all, great praise and thanks to God, the Merciful for giving me the strength and the ability to finish this work

The realization of this work was only possible due to the collaboration of several people, to whom I desire to express my gratefulness;

I would like to express my sincere gratitude to my supervisor Messaoud Hamouda and my co-supervisor, Salim Makhloufi for the trust placed in my work without a doubt, giving valuable sources of knowledge and unlimited encouragement throughout this research, especially when I encountered some difficult situations in the process.

I am also very grateful to Batoul Touhami, Hadiya Molay Omar (University Ahmed Draya), Miss Noura Allouane, the director of OPTIMA office (mentioned by United States Embassy and British Embassy in Algeria) and Miss Samira Mohammed Said, for accepting to revise, correct and approve my work.

I want to acknowledge:

The reviewers of my thesis, Professor Ali Benatiallah (University Ahmed Draia-Adrar), Professor Boubekeur Azoui (University of Batna), Professor Abdelkhalek Othmane (University Tahri Mohammed-Béchar) and Doctor Said Bentouba (University Ahmed Draia-Adrar) for accepting reviewing my work and for their valuable comments, discussions and suggestions to upgrade my thesis.

I am very grateful to everyone who works at University Ahmed Draia-Adrar and exactly at the Faculty sciences and technology especially professor Nouredine Djarfour (Director of University Ahmed Draya-Adrar) for unconditionally supporting, assisting and helping me to become a stronger and more independent researcher.

I would also like to acknowledge the support and assistance given to me by Renewable Energy Research Unit in Saharan Area, URERMS-Adrar and especially Abdelkader Didaoui.

Finally, I wish to thank Belbali Brahim, Hacene and Brahim Kabouya, Molay Omar Maharzi, Djamel Belatrache, Asma Chaabani, Sliman Bousaid, my uncles Hacene Gourari and all the individuals and professionals who were not named here before and who walked this road with me. They too are part of this achievement. Thank you.

Abstract

At the present day, many people in the world live without access to electricity because they are living in an isolated area and a poor country (58% of Africa) and so also because connecting them to the power grid is hard and expensive.

The most used solution for supplying isolated areas with power is the use of fossil power like fossil generator (diesel, kerosene…etc) due to the availability and simplicity. On one hand, this solution is polluting, noisy and consumes limited power from the earth. On the other hand, the use of Renewable energy is more efficient as it is available, clean and for free. Nevertheless, Renewable energy is not an economic choice for developed countries due to its expensive cost (investment cost, levilized cost…etc.) compared to fossils generators. This problem can be solved by combining many natural resources (renewable and fossils) to produce power, this is called "Hybrid System" (also known as "Hybrid Renewable Energy System" for a system with one or more renewable generator). The main objective of this system is to solve technical problems like the any-time supply , and economic problems like the decrease of levilized cost or ecologic problems such as minimizing dioxide carbon production. The hybrid system is, for people living in an isolated area, a hope to supply power with clean energy.

Many suggestions were proposed for the hybrid system to maximize efficiency by using the most and freely available resource. The selected rural village is situated in an isolated area in southwest Algeria named "Timiaouine", this rural village is characterized by high solar and low wind potentials.

Published articles on the hybrid system have increased last years with many objectives related to this system, the review of these articles shows a concentration on three axes on the hybrid system which is sizing, optimization and management in several objectives, the technical and economical objective remains the main aim of these articles.

One of the problems found in the hybrid system is the optimal size of this system. This problem can be solved by using genetic methods, classical methods or by using commercial software. HOMER PRO is one of this commercial software and the most used by researcher due to simplicity and efficiency results and remains the best used method uses is sizing hybrid system using many methods and that is achieved in this thesis by size hybrid system using a modified classical method and HOMER PRO. After sizing the hybrid system in two methods, we need to validate this result by simulating the hybrid system using two methods. The first simulation is by MATLAB Simulink and the second one is by using HOMER PRO. The obtained results show several differences in technical parameters, economic parameter and ecologic parameter. The comparison between these parameters shows that the hybrid system sized by a classical modified method is better technically and economically than the same system sized by HOMERRPO. In addition, and in one hand the system manager uses in MATLAB Simulink characterized by full control of generator production, use renewable generators (solar photovoltaic and wind turbine) to cover power demand more than diesel generator and eliminate unmet load. On the other hand, the hybrid system simulated in HOMER PRO produces power double what consumed by rural villages, uses diesel power when renewable generators are unavailable or not satisfying.

Keywords: hybrid system, rural village, HOMER PRO, solar photovoltaic, wind turbine, diesel generator.

ملخص

يعد توصيل الكهرباء الى مختلف المناطق المأهولة بالسكان تحديا صعبا في عصرنا الحديث نظرا للطبيعة الجغرافية والتضاريس الوعرة التي يعيش فيها عدد كبير من السكان (58 بالمئة من هؤلاء المحرومين من الكهرباء يعيشون في افريقيا) .

ويلجأ المختصون في هذه الحالات لاستخدام الوقود الأحفوري عن طريق المحولات المتنقلة التي تعتمد على هذا من النوع من الطاقة (البنزين والكيروزان) وهذا بسبب وفرته وسهولة استخدامه.

ومع ذلك يعد الخيار السابق ملوثا للبيئة ناهيك عن الضجيج الذي تصدره محولات الطاقة تلك، في حين تتوفر خيارات بديلة أخرى أكثر نظافة للبيئة مع وفرتها وتجددها المستمر، لكن ارتفاع تكاليفها الباهضة (تكاليف الاستثمار وسعر البيع...) جعل المسؤولين يتجنبونها ويتحاشون استخدامها.

ويمكن حل هذا المشكل عن طريق دمج موارد متجددة واحفورية من اجل انتاج الطاقة بما يعرف باسم أنظمة توليد الطاقة الكهربائية الهجينة، والهدف الأساسي لهذا النظام هو حل المشاكل التقنية مثل توفير الطاقة في أي وقت والمشاكل الاقتصادية كتخفيض تكاليف الإنتاج او المشاكل البيئية مثل تقليل انبعاث غاز ثاني أوكسيد الكربون.

إن النظام الهجين هو امل المناطق المعزولة في تلبية احتياجاتهم الطاقوية عن طريق طاقة نظيفة، وقد طرحت الكثير من الاقتراحات من اجل زيادة كفاءة هذا النظام عن طريق استخدام الموارد المتاحة والمجانية.

ولتعزيز هذه الدراسة تم اختيار منطقة نائية في الجنوب الغربي للجزائر والمسماة تيمياوين والتي تمتاز بساعات اضاءة مرتفعة وسرعة رياح ضعيفة.

وعرفت البحوث حول النظام الهجين تزايدا ملحوظا في السنوات الأخيرة، المتتبع لهذه البحوث يلاحظ بانها تركز على ثلاث محاور أساسية وهي: تحديد ابعاد, تحسين وتسيير هذه الانظمة من اجل تحقيق عدة اهداف أهمها تقنية واقتصادية.

أحد اهم مشاكل هذا النظام هو العثور على ابعاد مناسبة له. لكن تم حل المشكل بواسطة استخدام طرق جينية, طرق كلاسيكية او برامج تجارية. "HOMER PRO " هو أحد أكثر البرامج استخداما من طرف الباحثين نظرا لسهولة استخدامه وكفاءة نتائجه ومن اجل الحصول على أفضل النتائج في تحديد ابعاد الأنظمة الهجينة يجب استخدام أكثر من طريقة.

بعد تحديد ابعاد النظام بطريقتين, نقوم بالتأكد من النتائج المتحصل عليها وذلك باستخدام طريقة المحاكاة بواسطة برنامجين: الأول هو MATLAB Simulink والثانية عن طريق برنامج HOMER PRO.

النتائج المتحصل عليها تبرز فروقات عدة في الجانب التقني, الاقتصادي والبيئي. مقارنة بين النتائج المتحصل عليها توضح ان استخدام الطرق الكلاسيكية المعدلة في تحديد ابعاد الأنظمة الهجينة تعتبر أفضل تقنيا واقتصاديا من مثيلتها باستخدام برنامج HOMER PRO. إضافة الى ذلك تسيير هذه الأنظمة بواسطة برنامج MATALB Simulink يتميز بتحكم كامل في انتاج المحولات الكهربائية, الاعتماد على مصادر الطاقة المتجددة (الطاقة الشمسية وطاقة الرياح) أكثر منه البنزين لسد الاحتياجات هذه المحولات والقضاء على العجز في توفير الطاقة. من جهة أخرى يسمح العمل ببرنامج HOMER PRO على انتاج ضعف الطاقة المستهلكة من طرف هذه القرى باستخدام البنزين كطاقة بديلة حينما لا تتواجد الطاقة المتجددة او لا تكفي لسد الاحتياجات.

الكلمات الدلالية : الطاقات المتجددة, الانظمة الهجينة, الطاقة الشمسية, طاقة الرياح, HOMER PRO

Résumé

En ce jour, de nombreuses personnes dans le monde vivent sans accès à l'électricité à cause de l'éloignement de leurs régions. Ils sont situés dans des régions isolées et pauvres (58% en Afrique) et leur liaison au réseau électrique est difficile et coûteuse.

La solution la plus utilisée pour alimenter ces zones isolées est l'utilisation des ressources combustibles (diesel, essence, kérosène…etc.) à cause de leur disponibilité et simplicité. D'un côté, cette solution est polluante, bruyante...etc., et d'un autre côté, l'utilisation des énergies renouvelables est plus efficace, propre et à la portée de l'utilisateur. Cependant, les énergies renouvelables restes un mauvais choix économiques. Ce problème peut être résolu par le mixage de nombreuses ressources naturelles (renouvelables et fossiles) pour produire l'électricité à partir d'un système appelé «système hybride». L'objectif principal de ce système est de limiter les problèmes techniques comme la coupure d'électricité et les problèmes économiques comme la diminution du coût de l'énergie ou les problèmes écologiques (minimisation de l'émission du dioxyde de carbone). Le système hybride permet aux personnes vivant en région isolée de disposer d'une énergie propre est inépuisable.

Le nombre d'articles publiés sur les systèmes hybrides a augmenté au cours des dernières années, ces recherches se sont intéressés à trois axes ; le dimensionnement, l'optimisation et le management. Les deux côtés, technique et économique, sont les objectifs principaux de ces recherches.

Le problème le plus rencontré dans la conception d'un système hybride est son dimensionnement optimal. Ce problème peut être résolu par l'utilisation de méthodes classiques, des algorithmes génétiques ou par des logiciels commerciaux. HOMER PRO est le logiciel commercial le plus utilisé par les chercheurs en raison de sa simplicité et des résultats optimaux qu'il offre.

Dans ce travail, on a étudié l'installation d'un système hybride dans le site isolé de «Timiaouine» ; c'est un village situé au sud-ouest de l'Algérie. Ce village est caractérisé par un grand potentiel solaire et un faible potentiel éolien.

Après le dimensionnement du système hybride par deux méthodes, on a validé ce résultat en simulant le système hybride par deux méthodes. La première méthode est une simulation par MATLAB Simulink, la deuxième méthode utilise le logiciel HOMER PRO. Les résultats obtenus montrent certaines différences dans les paramètres techniques et économiques entre les deux méthodes. La comparaison entre ces paramètres montre que le système hybride dimensionné par la méthode classique modifié est mieux techniquement, économiquement et écologiquement que le même système dimensionné par logiciel HOMER PRO.

Mots-clés: système hybride, énergies renouvelables, HOMER PRO, méthodes classiques, Timiaouine.

Table of Contents

Abbreviation

HRES	hybrid renewable energy system
PV	Photovoltaic
WT	Wind turbine
DG	Diesel generator
FC	Fuel cell
Rs	Resistance series
I_L	Photocurrent at reference conditions
I_0	Saturation current at reference conditions
γ	Empirical diode PV curve fitting factor
I_{sc}	Short circuit current
V_{oc}	Open circuit voltage
I_{mp}	Maximum power point current
V_{mp}	Maximum power point voltage
α	Temperature coefficient of current
β	Temperature coefficient of voltage
ρ	Air density (equal approximate 1,22 kg/m^3)
S	Circular Surface brushed by the turbine [m^2]
V	Wind speed
C_p	Power coefficient
λ	Speed report
$\Omega_{turbine}$	Turbine speed

C_m	Motor torque
f	Coefficient of viscous
$f\Omega$	Couple of viscous
J	Moment of inertia
T_{DM}	Mechanical torque
TD_1	The electrohydraulic actuator time constant
TD_2	Time constant present delay of torque change
z(s)	The fuel rack position
$e^{-sT_{D2}}$	The transportation delay
$\bar{E}_{wind}$	Annual average of wind power
$\bar{E}_{solar}$	Annual average of solar power

List of figures:

List of tables

General introduction

Energy is one of the most basic requirements for humanity due to its influence on every part of our lives like heat, air-condition, food cooking, transportation and electricity generation. Energy sources such as conventional or renewable sources cannot be used directly to perform work. These sources are converted to generate heat, mechanical or electrical energy [1].

It is clear that in order to meet the ever-growing energy needs of the world, we will need to use all of the available resources in the close future. However, we will need to convert these energy resources more efficiently. It is also clear that renewable resources will have to continue to increase their share of the total energy consumption. There are many new developments in the conversion technologies for solar, wind, biomass, and other renewable energy resources [2,3].

Standalone power system combining different energy sources and energy storage devices appears to be an attractive way to supply consumption in a remote area and overcome renewable energies limitations [4]. Hybrid Renewable Energy Systems (HRES) are composed of one or more renewable sources with or without conventional energy sources, they can work on either stand-alone or grid-connected mode, different types of the hybrid system combinations are feasible, depending on the need and resource availability at a particular location, HRES is one of the solutions becoming popular for increasing efficiency in Renewable energy technologies and power electronic converters and so also economical limitation of single Renewable energy source [5].

Renewable energy in all its forms has the advantage of being inexhaustible, an environmental friend and will be essential in the long term. Solar photovoltaic and wind energy are the most renewable energies used in worldwide.

Currently, photovoltaic energy is the most renewable energy used worldwide and especially on the isolated area. But the major disadvantage of this energy is its efficiency which is relatively low. To overcome this problem, several algorithms of optimization and control were developed to maximize the power output of the photovoltaic generator.

For wind power, development of generators (synchronous, asynchronous or MADA) takes the most interesting research as well as the power converter.

In the case of auto power plants, the use of a wind generator or photovoltaic system alone may not meet the electrical consumption. It is necessary to use a storage system (battery, fuel cell...) or fossil resources. The combination of these renewable energy sources (photovoltaic-wind) has become better compared to single systems.

In most remote areas, the diesel generator is the main source of electrical energy. For these regions, fuel is generally more expensive due to the additional cost of transportation. This is why the use of diesel generators combined with a renewable energy source, and a storage system will play an essential role to cover consumption without unmet load.

Optimal sizing and good management of the hybrid system ensure covering consumption and improving quality and performance of the system operation. Optimal control should, therefore, ensure better functioning of all components of the system by allowing them to operate at their maximum power points and minimize the unused energy (excess energy).

Our country, due to geographical location, has one of the most important solar and wind fields in the world. With a duration of daylight that exceeds 3500 hours and an average wind speed more than 6 m/s especially in Sahara and the highlands. [6]

Algeria has designed a strategy for developing renewable energies by installing 22 GW in horizon 2030, which consists in the establishment of a program to meet national market requirements and export excess energy. [6]

The region of Adrar, in the southwest of Algeria, will benefit from its potential in renewable energy and will have an important part of this program by the realization of 19 projects with 288 MW, 63MW will come from seven photovoltaic plants and a wind farm of 10MW. [6]

The main objective of this study is supplying electricity to an isolated village in the providence of Adrar called "Timiaouine" by a hybrid system. The main source of electrical energy in this area is a diesel generator with insufficient power to feed 450 houses. In addition, transportation of fuel to this remote area is hard and expensive. This is why the use of diesel generators combined with renewable energy sources and storage systems can guarantee:

- covering consumption without unmet load
- minimizing fuel consumption
- Ensuring environmental protection

The presentation of this manuscript was divided into five chapters:

The first chapter starts with describing the energy situation worldwide and in Algeria. Then, the definition of the hybrid system is given, followed by the classifications of this system. Next part is on combinations of hybrid systems, for each combination are given the elements, interconnection, advantages, drawbacks and also electrical centrals installed in the world.

The second chapter covers the last researches published on sizing methods for the hybrid system, optimization methods and management methods.

The third chapter concentrates on rural village consumption and sizing of the hybrid system components using two methods; the first one is a classical modified method and the second one uses commercial software. This chapter is finished with a comparison between these methods.

Chapter four describes mathematical models for each component of the hybrid system.

The last chapter uses mathematical models from chapter four and sizing results from chapter three to simulate the hybrid system using MATLAB Simulink and HOMER PRO. This chapter is finished by technical, economical end ecological comparison between results obtained. As a conclusion, this thesis will be completed by conclusions and perspectives on future research.

Chapter I
Overviews on hybrid system

In this chapter, the researcher describes power condition in the world and in Algeria, then the hybrid system, is given some definitions, after that it is classified in many ways. Last but not least, the researcher finishes by possible configuration on the

I.1 Introduction

The power in two liquid forms (fuel or gas) or electrical affects deeply our life and controls every part of our lives like transportation, heating, air conditioners, TV, Internet and many appliances used every day [1].

Global power used in the last 50 years has grown quickly and continues to grow in the next 50 years. This increase in use reduces oil resources in the close future due to global climate change. [2] On the positive side, the development of electricity generation from power sources has become a major objective in the world for environmental reasons, mainly the limitation of carbon dioxide production and for longer-term sustainability of power supplies [3].

One proposed form of solution for power world problems is hybrid renewable energy system (HRES). This solution has become popular for grown efficiencies in Renewable energy technologies and power electronic converters and also the economic limitation of single Renewable energy source [4,5]. This advantage also makes HRES integrated effectively into the national or regional grid, if applicable.

This chapter started by a short description on power condition in the whole world, generally and in Algeria, specifically, then a description of hybrid systems; configuration, advantages and inconveniences…etc, finally it is finished by a short description on hybrid central in the world.

I.2 Definition

Energy

Michael Arthur Laughton (Professor in university Queen Mary & Westfield, United Kingdom) and D.F. Warne define power in a small sentence and wrote; "Energy is the capacity for `action' or work" [3]. This definition is also used by Gilbert Masters (Professor in Stanford University, USA) who wrote in his book "Renewable and Efficient Electric Power Systems"; Energy can be thought of as the ability to do work, and it has units such as joules or Btu [7].

Professor Max Planck (University of Kiel, Germany) "Nobel Prize in physic quantic and the creator of Planck constant", describes energy as the ability of a system to cause external action [8].

But Professor Zachary and Katrina (Northern Arizona University, USA), the authors of "Renewable and alternative energy resources" find difficulty in describing energy because there are many meanings depending on different contexts, in this case, authors use general definition agreed-on physically and wrote "…is the capacity of specific forces to do work"[9]

For Professor Martin Kaltschmitt (Technical University of Hamburg), Kinetic and potential energy is just a form of mechanical energy and wrote in his book entitled "Renewable energy": "…In this respect the following forms of energy are distinguished: mechanical energy (i.e. potential or kinetic energy), thermal, electric and chemical energy, nuclear energy and solar energy."[8].

In addition, energy resource is generally classified in two types; Non-Renewable energy Sources and Renewable energy Sources [1].

Non-Renewable Energy Sources

It is every resource that can't be continuously replaced or take too much time for that (between 2 to 270 million years with temperature 100° to 300°), besides it is based completely on natural processes (like Petroleum, Coal, Natural Gas, uranium…) [1]

Professor Martin Kaltschmitt calls this type of energy "Fossil energy resources" and wrote in the same book: "…are stocks of energy that have formed during ancient geologic ages by biologic and/or geologic processes". [8]

Renewable energy Sources

"Renewable energy is considered as any energy resource that is available naturally on the incessant basis or over a short period of time; which may be on a daily basis, or over several days, or several years". This definition is written by Professor Tushar K. Ghosh (North Carolina State University, USA) and professor Mark A. Prelas (University of Missouri, USA) in their book entitled "Energy Resources and Systems". [1]. In the same book, authors said that renewable energy derived from three sources; the sun (directly like thermal or indirectly like wind), geothermal energy and tidal energy.

Professor Muhammad H. Rashid (Florida Polytechnic University, USA) define renewable energy in his book " Electric Renewable Energy Systems" and wrote in one line; "Renewable energy resources are forms of energy that are naturally replenished on our planet." [10],for Professor Martin Kaltschmitt, this type of energy is named "Recent resources" and wrote "Recent resources are energy resources that are currently generated, for instance, by biological processes", in the same book of Professor Martin Kaltschmitt, renewable energy mean unlimited resource in human vision and wrote exactly: "…are regarded as inexhaustible in terms of human (time) dimensions." [8]

I.3 Energy situation

Energy is the heart of the economy for any country. The demand for power grows as we try to improve our quality of life. As we said previously, energy is defined as the capability to do work and uses, for this purpose, all types of work contained in the form of movement, displacement or light. [1]

A. In the world

Due to development of industry and technology [12], the world uses, until 2015, double quantity compared to that used during forty years(figure 1.1) [13]. The International Bank and International Energy Agency (IEA) estimated that use will double in installed energy capacity over the next 25 years to meet the anticipated demands of developing countries [14]. In another part, the IEA mentioned in the annual outlook of 2017 that 1.1 billion people in the world live without access to electricity, out of which 48% live in Africa (figure 1.2). [15]

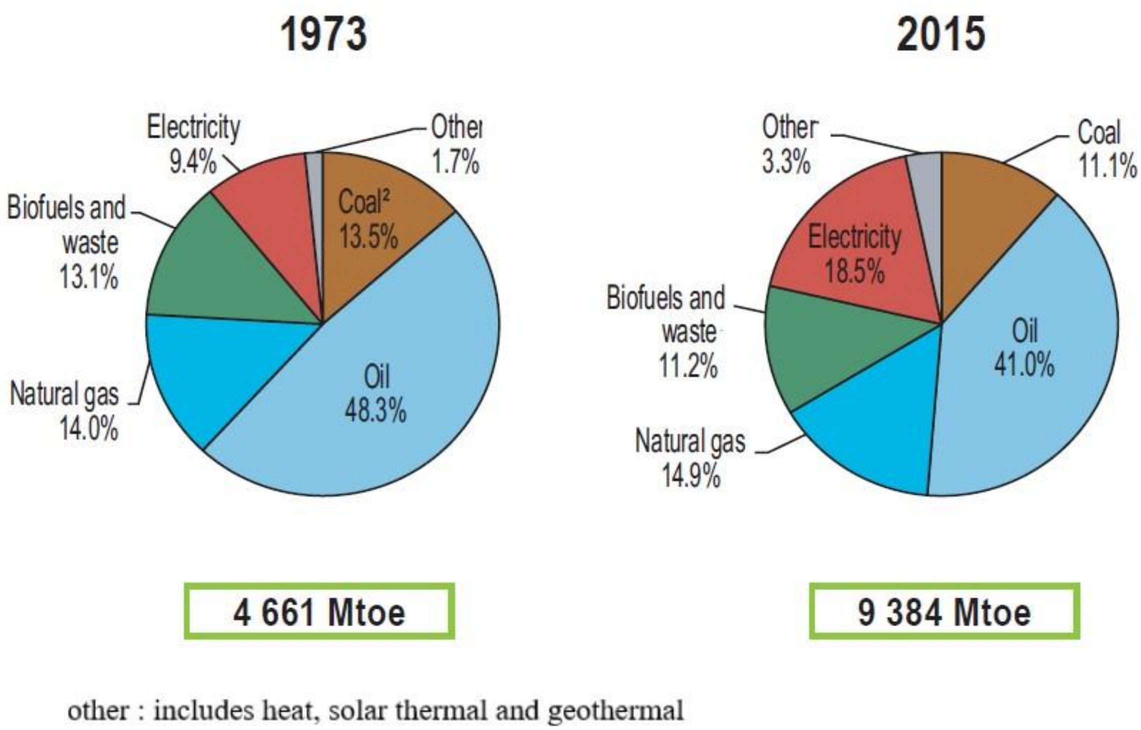


Figure 1.1: World electricity use by sector [13]

Figure 1.2: Number of people living in the dark [15,16]

In 2016, people in the world use more than 13,9 Billion teo (oil, coal, gas, biomass, electricity and heat) with 1% more compared to 2015 and most of these resources used in Asia, North America and Europe (figure 1.3).[17]

Figure 1.3: Energy use per country in 2016 [17]

One of the most important conditions of development at a household and community level is access to power, but in some poor areas without any access to power, a large part of their income may be spent due to power low quality, such as using of kerosene, candles for lighting, mobile phone charging at retail stations and dry cell batteries for electricity. [15]All these conditions put primary energy (oil, coal and gas) with 80% as the highest energy type level used in the world (figure 1.4). [17]

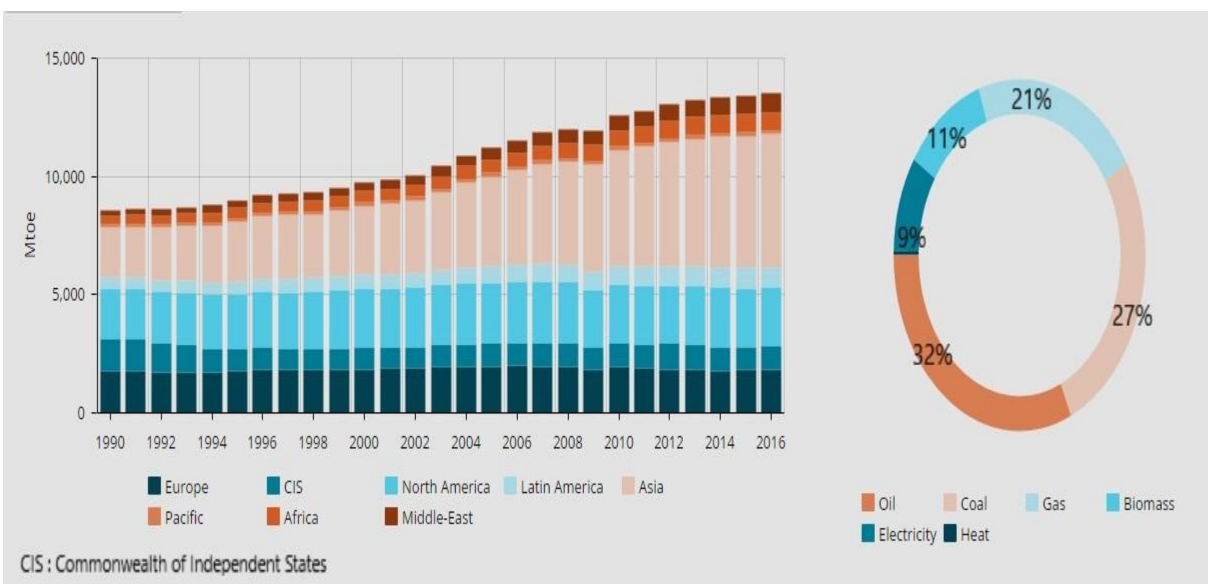


Figure 1.4: Increase of energy use by country in left and by type in right [17]

B. In Algeria

Algeria is situated in the north of Africa with more than 2, 38 million kilometer square, and it's composed of 48 provinces. In 2017, Algerian population was estimated to 40,9 million (33rd in the world), major of it is installed in the extreme northern part of the country along the Mediterranean Coast.[18]

Algeria is classified as the largest country in Africa and the tenth in the world [18], and so also the 55th in energy use (7% from Africa global use) as it uses 55 Mteo in 2016 (two times more than the last two decades) (figure 1.5) and like in other part of the world, most of used energy is fossils (more than 70% (figure 1.6)).

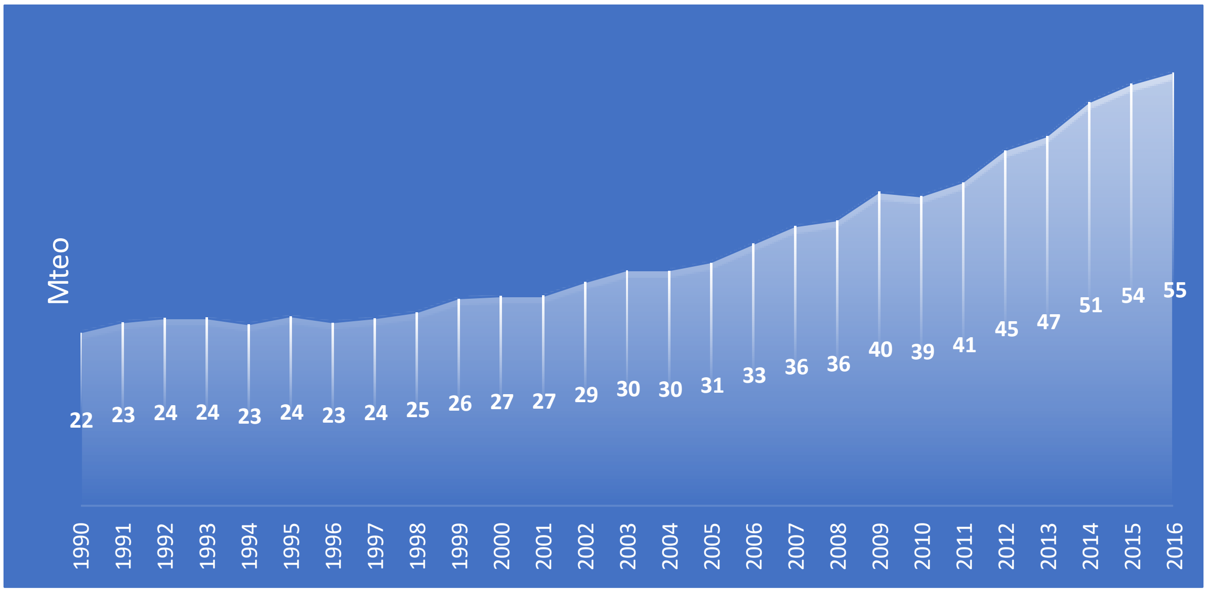


Figure 1.5: Algeria energy use from 1990 to 2016 [17]

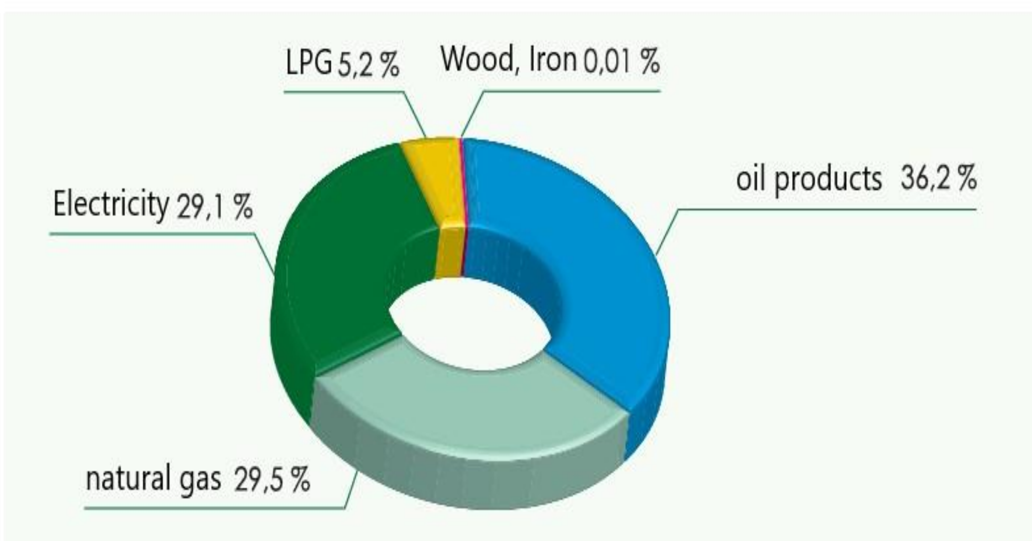


Figure 1.6: Algeria energy use in 2016 by types [19]

Algeria has 99, 4% of electrification (100% in urban area and 97% in rural area), where the lowest percentage is noticed in areas where people live out of power access (400 000 people lives without electricity) in world and Africa[17,19] (figure 1.7).This percentage of electrification reflects high power personnel use with 5123 kWh/year in south Algeria compared to 200 kWh yearly in sub-Saharan Africa and 1600 kWh in European Union [15,20]

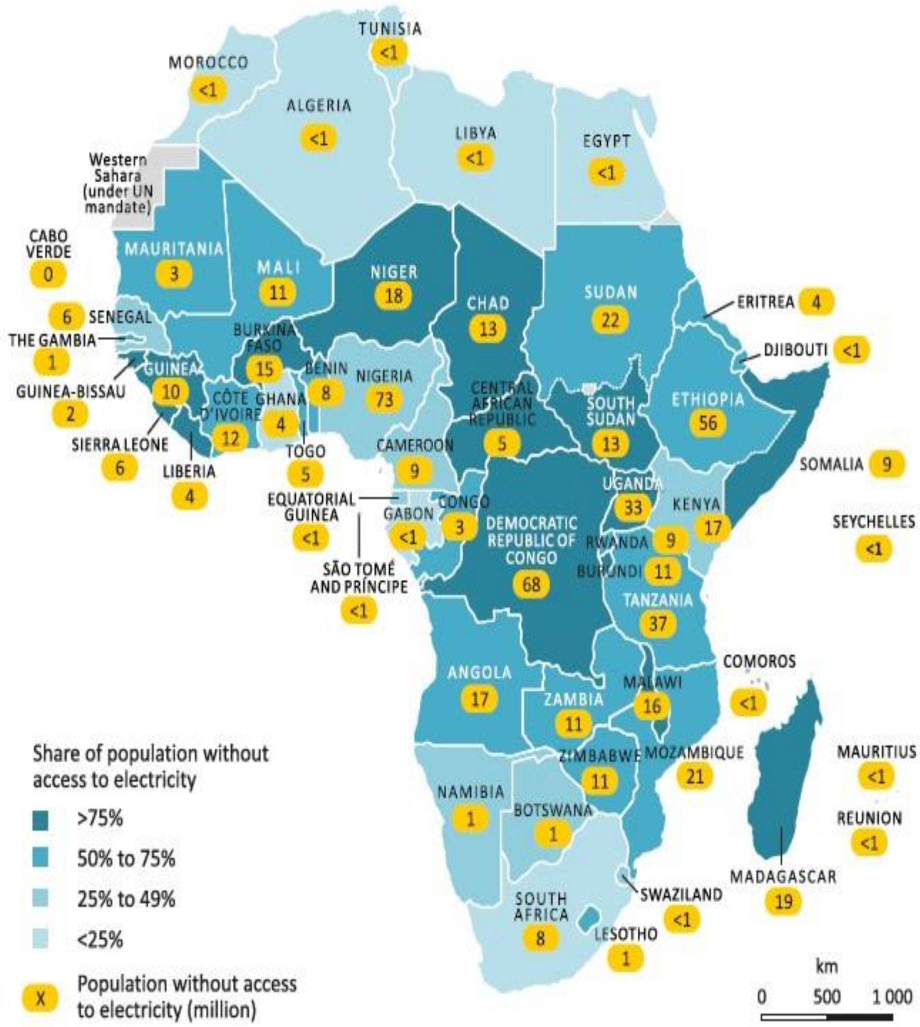


Figure 1.7: Population without access to electricity in Africa per country in 2016 [15]

I.4 Renewable energy situation

A. In the world

"Rapid improvements in the competitiveness of renewable energy mean that increases in renewables, together with nuclear and hydro energy, provide around half of the increase in global energy out to 2035" this is what star Bob Dudley (executive chief of British Petroleum group) mentioned in the introduction of BP energy outlook 2017. In the same report, renewable energy is classified as the fastest growing power in the world with 7,1 % in 2015(figure 1.8) [21], renewable and nuclear energy will represent 25% from world energy to be used in 2040, as it is expected Exxon Mobil company in the last energy outlook.[22]

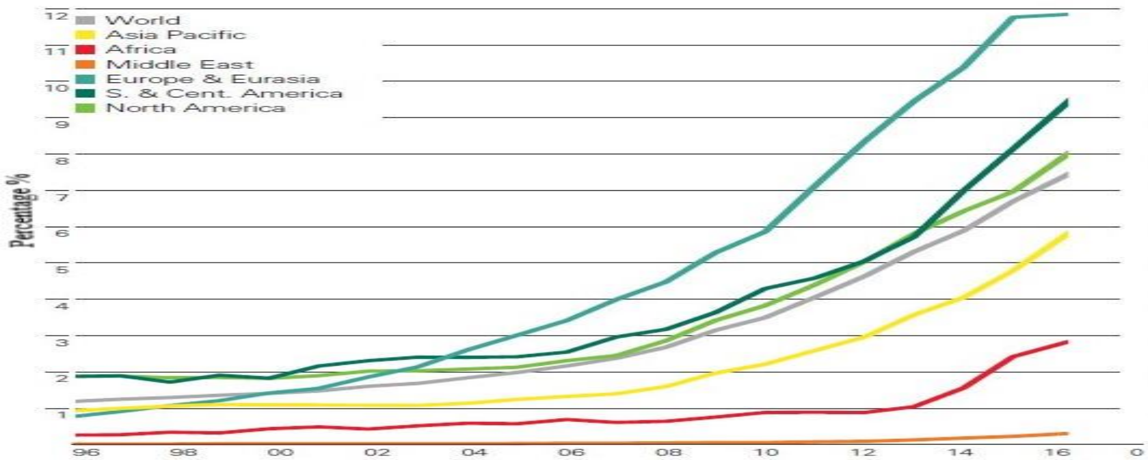


Figure 1.8: Evolution of renewable energy in the last 20 years by region [23]

As for electricity, people in the world used 24255 TWh in 2015, and the main part of this energy was generated from fossil resource (more than 66%) and renewable energy represents more than 23% (16% hydraulic and 7,1% renewable resource), besides 42% from produced electricity in world is used in industry (figure 1.9) [12].

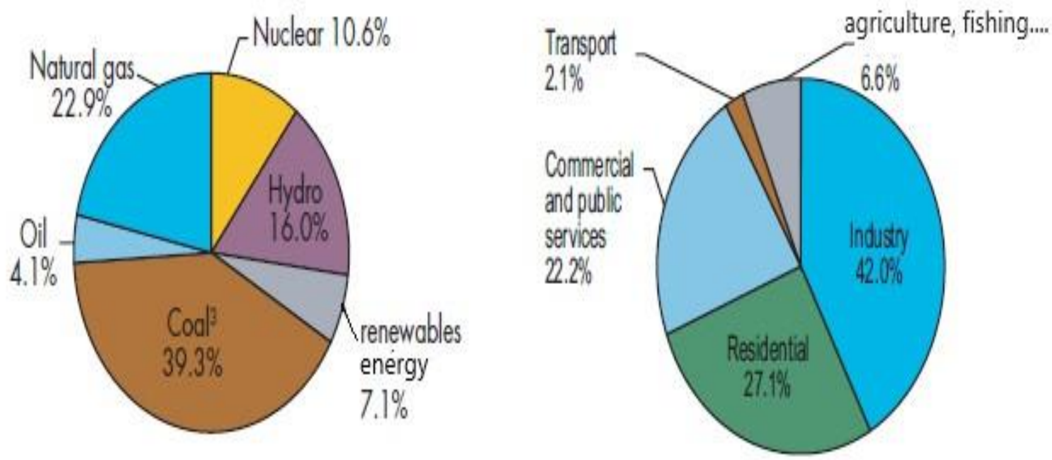


Figure 1.9: World electricity production by sources in left and by sector in right [12]

Renewable energy technologies (exactly wind and solar power) have developed economically in the last twenty years and may replace fossil production. Therefore, hybridization convention source with renewable energy is an essential step to reduce dioxide carbon emissions.[2]

B. In Algeria

In electricity use, Algeria is classified 47th in the world with 60 TWh in 2016 (10% out of Africa global use), 44th in electricity production with 78 TWh (10% out of Africa global production) (figure 1.10) [17,18].

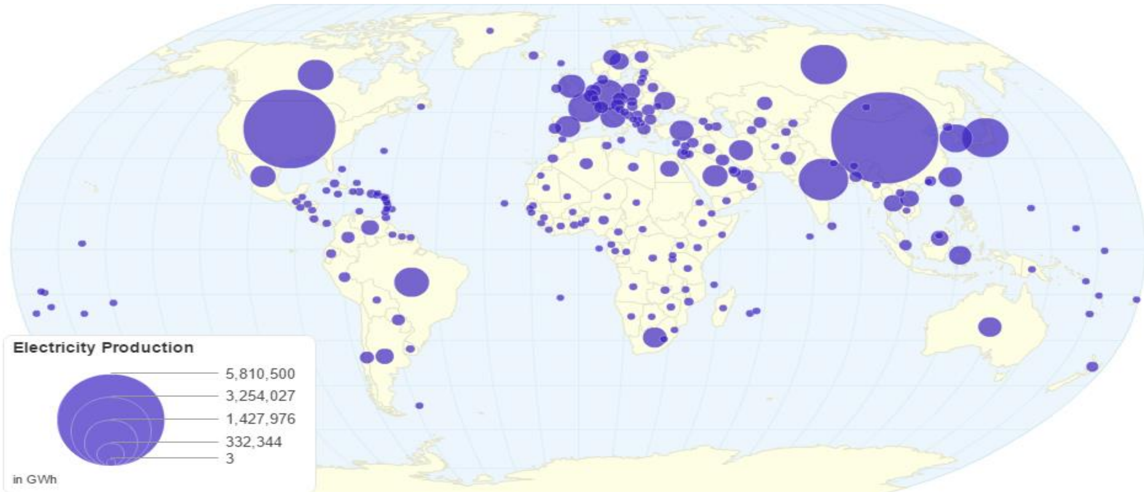


Figure 1.10: Electricity production per country in 2016 [24]

Algeria has one of the biggest solar power in the world with 2000 hours in the whole nation land per year and more than 3900 hours in highlands and Sahara. The global horizontal irradiation is 3000Wh/m^2 every year in the north and more than 5000 Wh/m^2 yearly in the south of Algeria (Sahara) [6].

Algeria has also an important wind resource in the south with wind speed that varies between 4m/s to 8m/s [6], and wind power resource is estimated to 35 TWh every year in whole country [25].

Despite all these resources, Algeria is the last country using renewable energy in the world with1,5% out of global electrical production (classified 131th in the world) [18], but government has designed a strategy for the development of renewable energies 2011 -2030, that consists of the establishment of a program to meet national market requirements over the period 2015-2030 of 22000 MW.

Achieving this program will allow reaching by 2030 part of renewable of about 27% of the national report of electric production [26]. The division of this program by the technology sector appears in figure 1.11

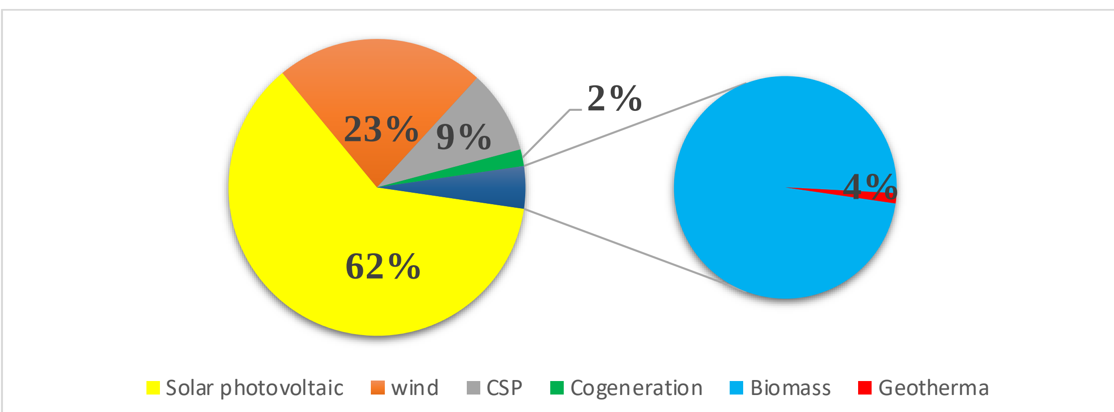


Figure 1.11: Division of renewable energy program by technology sector [26]

I.5 Hybrid systems

I.5.1 Definition

Professor Herbert Girardet (director of programs World Future Council) and Miguel Mendonça (the World Future Council's Research Manager.) in their book "A Renewable World" define the hybrid system in a simple sentence and said; "Typical hybrid systems combine two or more energy technologies." [27]

Hybrid renewable energy system (HRES) is described as an electric energy system, composed of one renewable source and other one or more sources. These sources may be conventional or renewable or mixed, and this system can work on the grid or standalone (off-grid) [11].

Professor Muhammad H. Rashid put complementary energy generation system as a condition in the combination of different systems and wrote in the same book "Combination of different but complementary energy generation systems based on renewable or mixed energy (renewable energy with a backup biofuel/biodiesel generator) is known as renewable energy hybrid systems".[10]

I.5.2 Classification of hybrid systems

There are many proposed classifications for hybrid systems, and the most frequently used is the classification based on three criteria; connection to the power grid, the method of integration and the last one is based on elements inside hybrid system [28].

- **Classification based on power grid connection**

According to installed objective and capacity, hybrid systems can be connected to power grid like enforced global production, or stand-alone for supply to the rural village. [28]

- **Classification by the integration method**

This classification is based on interconnection inside hybrid systems, and this connection may be directs current bus (DC), alternative current bus (AC)or both them (AC and DC) named hybrid bus. Next table summarized the advantages and drawbacks of interconnection methods [28].

Table 1.1: Classification of hybrid systems [28, 29]

Connection methods	Advantages	Drawbacks	Installation Field
DC bus	Reduce loss Simple use	Poor power quality Larger number of converters	Low power application
AC bus	Simple operation Reduce internal loss	Poor power quality Complexity and high cost	Medium and high production
Hybrid bus	Reduce power converters	Complex control in operating on two different networks	High production

- **Classification by integrated elements**

Classification of hybrid systems, according to integrated elements, is in three different system elements; generators (solar photovoltaic, wind turbine, diesel generators…etc), storage systems (fuel cell, battery, super capacity…etc) and demand (telecommunication, residences, power grid connection…etc). [28] This classification is summarized in figure 1.12.

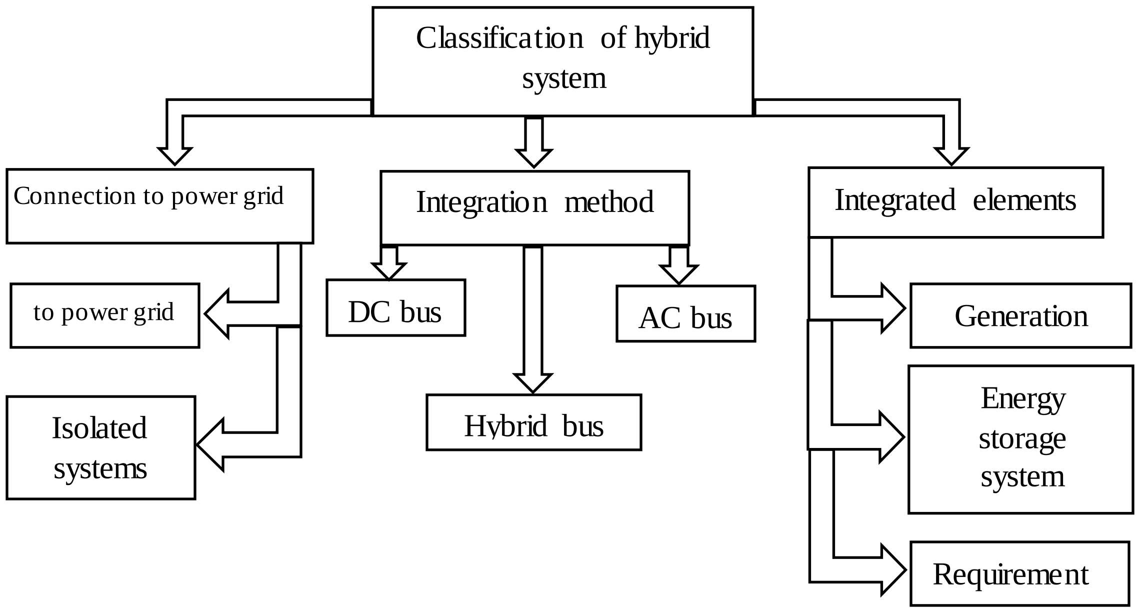


Figure 1.12: Classification of hybrid systems [28]

Doctor Ludmil Stoyanov, in his thesis, simplified the previous classification into two categories; classification based on operating regime and classification based on the structure of systems (figure 1.13) [30].

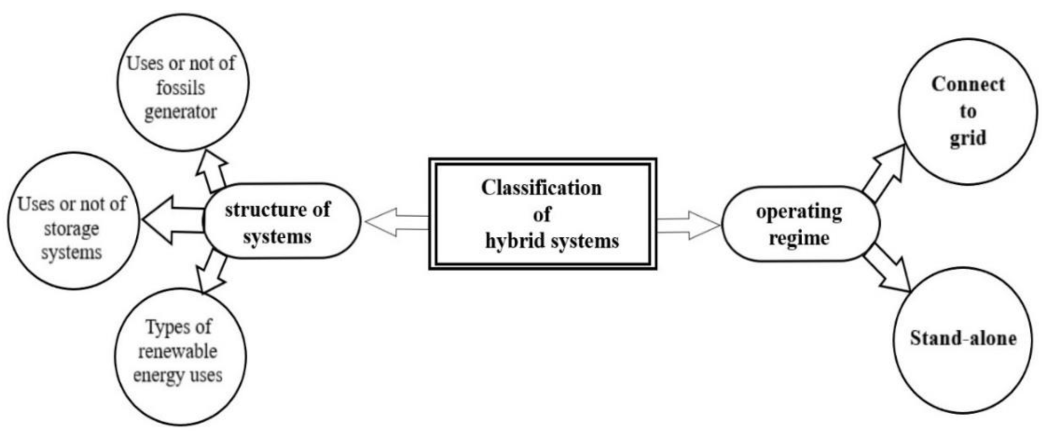


Figure 1.13: Classification of hybrid systems [30]

- **Classification based on the operating regime**

The hybrid system is classified in two groups; hybrid system connected to power grid uses for high capacity of systems and has the ability to meet a large requirement. The second group is a hybrid system in stand-alone mode and uses for meeting only small and medium demand in the rural and isolated village.[30]

- **Classification based on the structure of systems**

This classification is characterized by three conditions:

- Use or not fossils generator like a gas turbine, diesel generator (author considers the connection to the power grid as a fossils source).
- Use or not storage systems like a lithium-ion battery, super capacity…etc.
- Types of renewable energy are used in hybrid systems; this condition is based on energetic potential available on site. [30]

Another classification for hybrid systems is based on installed capacity (varies from few kW to hundreds of kW), and that less than 5 kW can be considered as small systems. Generally, these systems are used to supply for remotely located home or a telecommunication relay system. Medium systems are used for the capacity of more than 5 kW and less than 100 kW, these systems in major cases work in stand-alone mode (sometimes connect to the utility power grid). These systems are used to meet small rural villages' power demand. The last systems are able to cover the power demand of a region, of more than 100 kW; being a large system. These systems are generally connected to the power grid and enable the power exchange between the power grid and system in case of excess or deficiency. [31]

Table 1.2: classification of hybrid systems based on capacity [31]

Size of systems	Capacity variation	Field installation
Small	< 5 kW	Telecommunication, individual home
Medium	≥5 kW and <100 kW	Rural village
Large	≥100 kW	Connected to grid

In this work, on propose another classification of hybrid systems is based on power sources used in systems (hybrid systems use one types of power or hybrid systems use two types of power).

- **Hybrid systems use one types of energy**

Major energy resource used in hybrid systems is a renewable energy, a combination of two renewable energies gives a system of high performance with low cost better than using one resource [32]. In hybrid systems, one type of energy is used, on distinguished two configurations; hybrid systems of conventional sources and hybrid systems of renewable energy.

- **Hybrid systems based on conventional sources**

The combination of two or more conventional sources in the same system was not used in producing electrical power because the main objective of hybridization is combining with the other generator to meet the power demand [10]. However, there are some systems integrated in ships for generating power, named Integrated Electric Propulsion (IEP) and use diesel generator with a gas turbine to eliminate mechanical connection (gearbox), reduce noises …. etc [33,34]. These hybrid systems use in warships like Royal Navy Type 45 destroyer (United Kingdom) [34] or passenger ships like Royal Mail Ships Queen Mary 2(United Kingdom) [35].

- **Hybrid systems based on Renewable energy**

Due to the limited capacity of a single system based on renewable energy (intermittent in nature, costly and low production), the combination of different renewable energy resources in one hybrid system results in a system of high capacity and better quality of power supply and minimize storage capacity [36]. This system can be connected to the power grid or be combined with storage systems to be used in stand-alone mode [37].

A- Hybrid systems use two types of energy

The major hybrid systems used for the researcher or installed in worldwide is hybrid system combined fossils generator (diesel, gas, storage systems) with renewable energy (solar thermal or photovoltaic, wind turbine, hydropower…etc) due to high flexibility, the reliability of power supply, low emission and cost. [28, 36, 38, 39]

I.5.3 Various configuration of hybrid systems

In this part, and in every hybrid system, the below elements are explained:

- The integrated elements
- Methods of interconnection
- Advantages and drawbacks
- Installed central in the world.

A. Hybrid system Diesel generator/Gas turbine

A.1 Elements of the system [33, 34]

- Two gas turbines connected to generators.
- Diesel generators.
- Power system control or Switchboard
- Converters
- Load (motors).

A.2 Methods of interconnection

For instance, in the warships Royal Navy Type 45 destroyer (figure 1.14), the installed gas turbine in this system is Rolls Royce type WR-21 brand, combined with generator producing together power equal to 20 MW and combined with two diesel generators produces 2 MW. The diesel generator is used only for low power demand, and hybrid systems provide control using platform management for easy remote machinery control, monitoring and damage control and so also detection. [34]

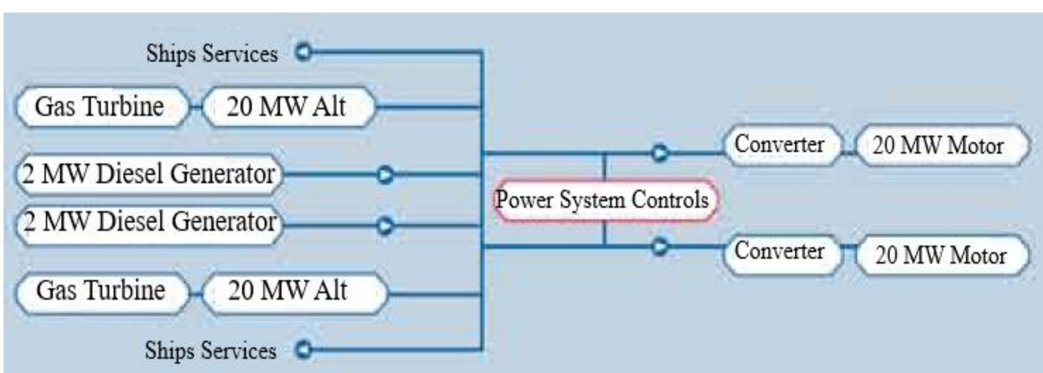


Figure 1.14: Power system diagram [34]

A.3 Advantages and drawbacks

- ✓ improved efficiency
- ✓ reduced cost of maintenance
- ✓ higher flexibility
- ✖ High cost and risk
- ✖ Difficult to manage common voltages modes
- ✖ Incompatibility with current standards

A.4 Central installed in the world

Until now, this hybrid system was only used in electric ships, as mentioned above, and in passenger ships or warships

B. Hybrid systems PV/wind turbine with or without storage systems

B.1 Elements of systems

The main elements of any hybrid system, using wind turbine and photovoltaic solar, are solar photovoltaic, wind turbine and converters. The types of used converters in systems depend on used configuration (AC bus, DC bus or Hybrid bus), the use of storage systems or not and installed load in the systems (alternative load, direct current load or both of them), figure 1.15 illustrates all elements those may installed in this systems. [28]

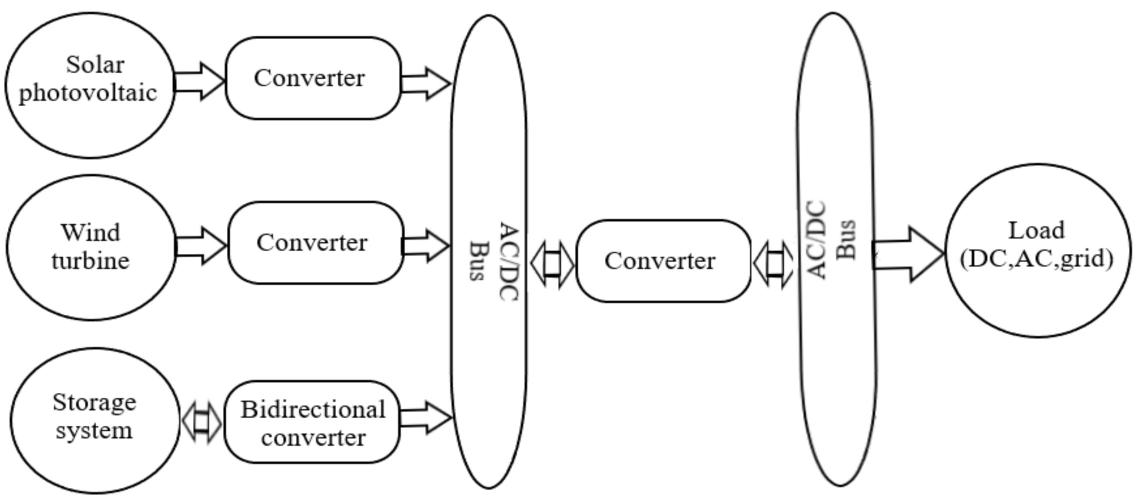


Figure 1.15: Main elements of PV/WT hybrid system

B.2 Methods of interconnection [28]

They are three methods of connecting elements to systems:

- *AC Architecture*

In this configuration, solar photovoltaic is combined with the inverter for supply AC load or connected directly to storage systems (or DC load if they used). The wind turbine was connected directly with AC load or with bidirectional for supply storage systems (or DC load if available) (figure 1.16).

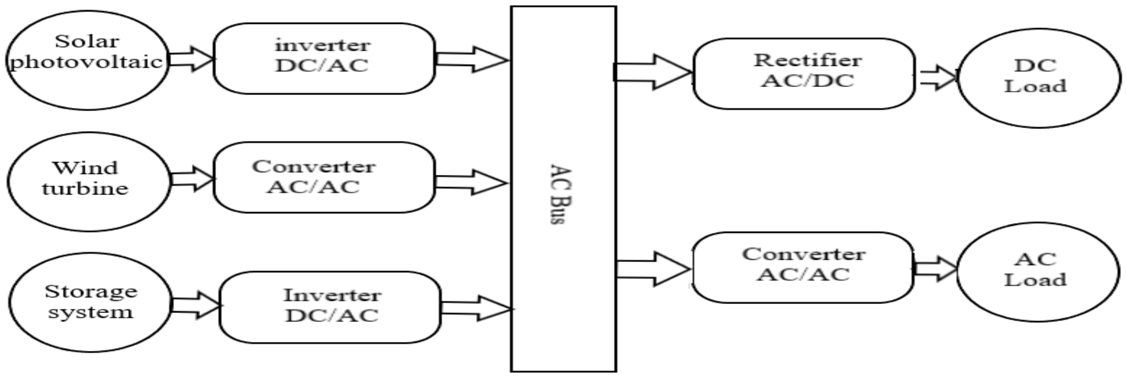


Figure 1.16: AC architecture for hybrid PV/WT system

- *DC Architecture*

This configuration is used for supply DC load or storage systems and the only installed converter is the rectifier connected to the wind turbine to convert AC output to DC for load supply or for storage systems (figure 1.17).

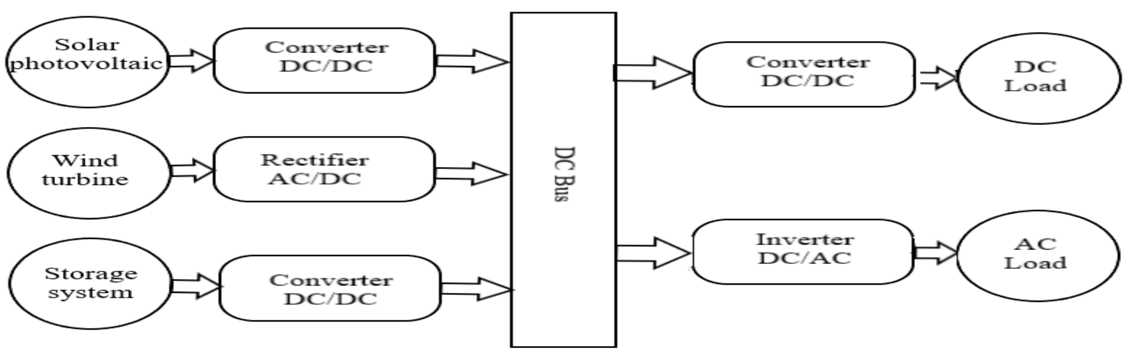


Figure 1.17: DC architecture for hybrid PV/WT system

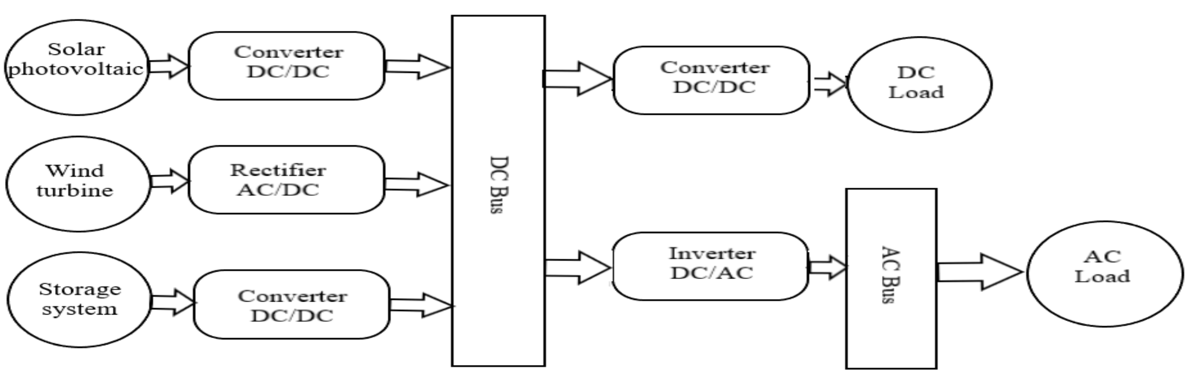


Figure 1.18: Hybrid architecture for hybrid PV/WT system

- *Hybrid architecture*

This configuration is used in case of two load types; DC and AC, and a bidirectional converter between AC load and storage systems were installed inside systems. For the generator, AC architecture and DC architecture are used for solar photovoltaic and wind turbine respectively (figure 1.18).

B.3 Advantages and drawbacks [40,41-44]

- ✓ Solar and wind energy is the most ubiquitous energy source in the world
- ✓ Produces power simultaneously in sequential mode and produces electricity alternatively.
- ✓ Low variation of power output
- ✖ Systems can't cover load all the time using just two renewable resources without conventional source or storage systems
- ✖ Unpredictable and sometimes unable to meet the high demand
- ✖ Very expensive

B.4 Installed central in the world

Major hybrid central PV/wind turbine installed in the world is not connected to power grid [28]. For example, the largest European PV wind hybrid system is located on the Pell worm Island in Germany (1.1 MW PV/WT) [40], Zhangbei National Energy Storage and Transmission Demonstration Project in China (210 MW PV/WT/Battery) [45].

C. Hybrid systems PV/ Diesel generator with or without storage systems

C.1 Elements of systems

Generally, this system of the diesel generator is connected directly to AC load or to the converter in case of DC load supply and solar photovoltaic is connected to DC/AC converter or to the bidirectional converter, in case of storage systems (fig 1.19).

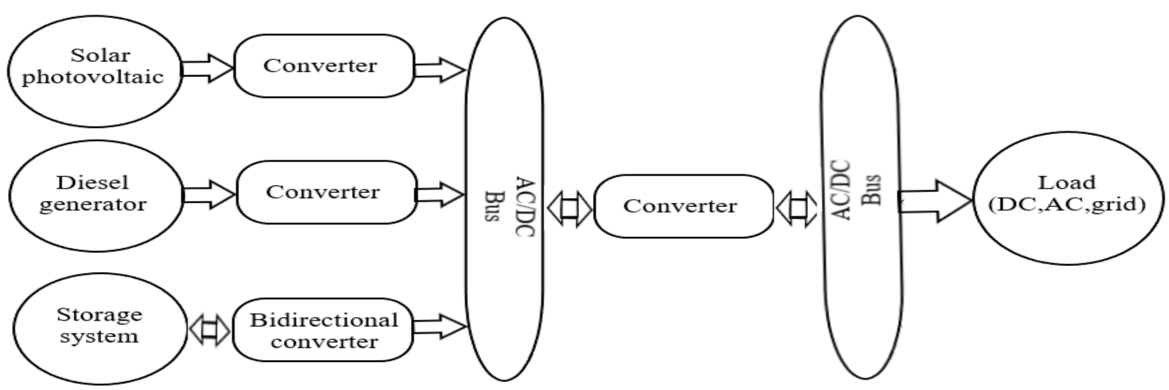


Figure 1.19: Essential elements of the system

C.2 Methods of interconnection

According to installed load in the system, there are three configurations for hybrid systems based on solar photovoltaic and diesel generator; series connection, commutation connection and parallel connection. After comparison between these three architectures, a summary table was made below:

Table 1.3: Comparison between different connections of hybrid systems [30]

Connection methods	Advantages	Drawbacks
Series	- Simplicity of system - Suitable frequency	- Low efficiency - Larger capacity of battery
Commutation	- High efficiency - High quality of power	- Complex system - Larger capacity of inverter
Parallel	- High efficiency - Reduced number of installed converter	- Impossible synchronization between generator of system - Difficult control of DC bus

All these connections are summarized in the below figure:

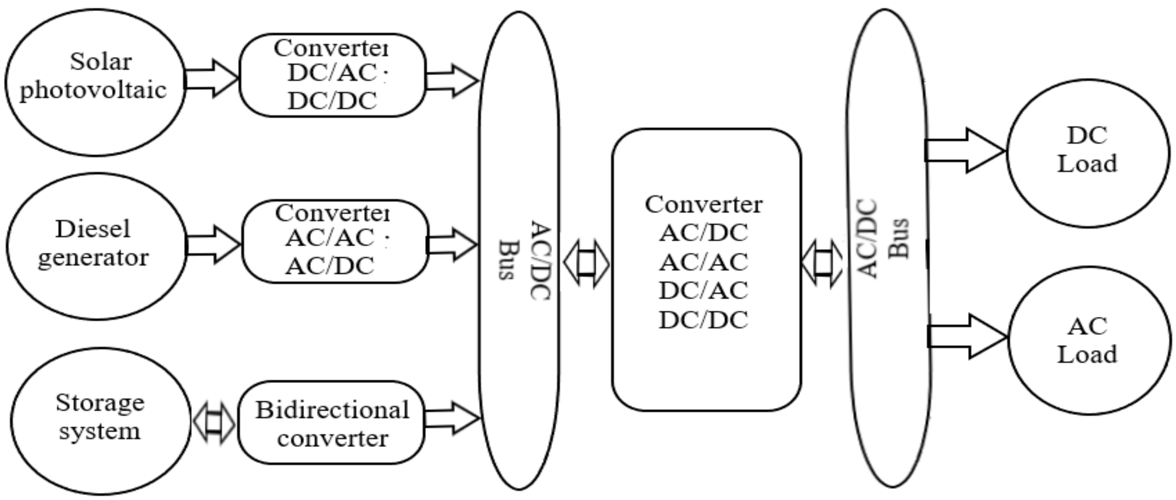


Figure 1.20: Possible configuration for systems

C.3 Advantages and drawbacks [30, 46-48]

- ✓ Best systems for zone characterized by high temperature
- ✓ Reduce maintenance of diesel generator
- ✓ Cover the load demand
- ✖ Complexity of systems
- ✖ Regulating the load voltage
- ✖ Inverter optimal operation

C.4 Installed central in the world

In Africa and exactly in Burkina Faso, hybrid system PV/DG is installed in a small village named Bilgo. This system is composed of 31 kWc solar photovoltaic field and three diesel generators (two generators of 18 kW and one 27 kW)[49]. Another hybrid central is installed in France since 1983 of 100 kW solar photovoltaic field, in addition to two diesel generators of 83 kW and battery of 12500 kW for power supply to a rural village named “Kaw”[50].

D. Hybrid systems based on hydro energy

D.1 Elements of systems

They are many hybrid systems based on hydro like solar photovoltaic with hydropower and wind turbine with hydropower [51]. According to installed hybrid systems, the essential element in any hybrid systems is based on hydropower as stated below:

- Solar or wind turbine or both
- Hydropower
- Converter
- Load DC, AC or both

D.2 Methods of interconnection

Hybrid systems based on hydropower, solar photovoltaic and wind turbine with or without storage system is characterized by two configurations; DC configuration and hybrid configuration. [52]

- *DC configuration*

This configuration is distinguished by using just DC bus and for AC generators (wind turbine and hydropower), the converter was installed to connect these generators with DC bus. The DC load is connected to DC/DC converter at the stabilized voltage and integrates an inverter for AC load (figure 1.21). [53]

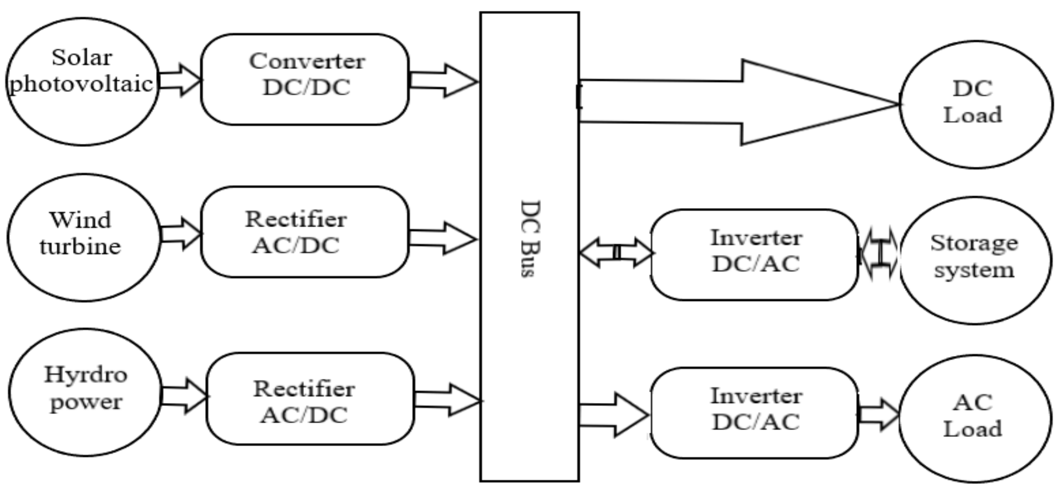


Figure 1.21: DC architecture of the system

- *Hybrid architecture*

In this architecture, all DC generator and load are connected to DC bus through DC/DC converter (bidirectional converter is used in storage systems, if available), and for AC bus, AC generator and AC load are also connected without any converter, between AC and DC bus, besides, an inverter is integrated for supply to storage systems or load (AC or DC). Next figure illustrates the component and interconnection between them.[52]

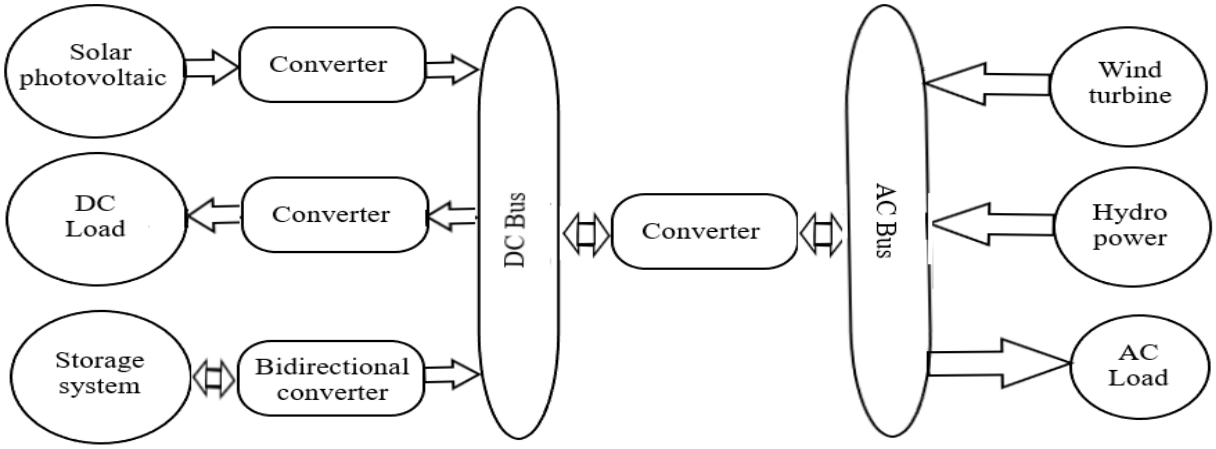


Figure 1.12: Hybrid architecture of the system

D.3 Advantages and drawbacks

- ✓ Lower cost in Hybrid connection
- ✓ High power efficiency
- ✓ Reduce loss of converter in hybrid connection
- ✖ In DC architecture and in case converter has failed, the systems can't supply the load
- ✖ Complex control
- ✖ Complex power management

D.4 Installed central in the world [51]:

The largest hybrid system, based on solar photovoltaic and hydropower, was installed in China. This system has 320 MW solar park connected to 1280 MW hydropower. For hybrid system based on wind turbine and hydropower, a station of 11MW is installed in El Hierro (Canary Islands) in Spain.

E. Hybrid systems based on concentrator solar photovoltaic

E.1 Elements of systems

They are many possible combinations between concentrator solar photovoltaic CSP and other generator fossils or renewable. The main elements of any hybrid system are based on CSP as below:

- CSP
- Another generator such as gas turbine, solar photovoltaic, diesel generator…etc, or storage systems (fuel cell, battery…etc)
- Electronic interface
- Load

E.2 Methods of interconnection

They are two ways to connect between CSP and other generators; non-compact and compact methods. The first method is based on independently working of generators (figure 1.23) [54,55] and the second method aimed to make full use of solar energy and mostly use in CSP/CPV hybrid systems (figure1.24) [56].

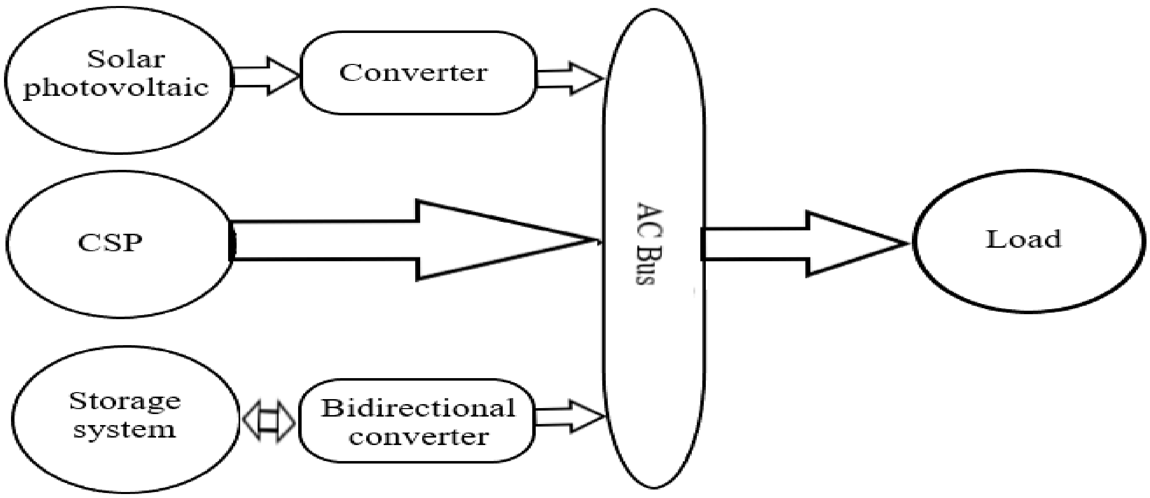


Figure 1.23: Non-compact method connection between CSP and solar photovoltaic [57]

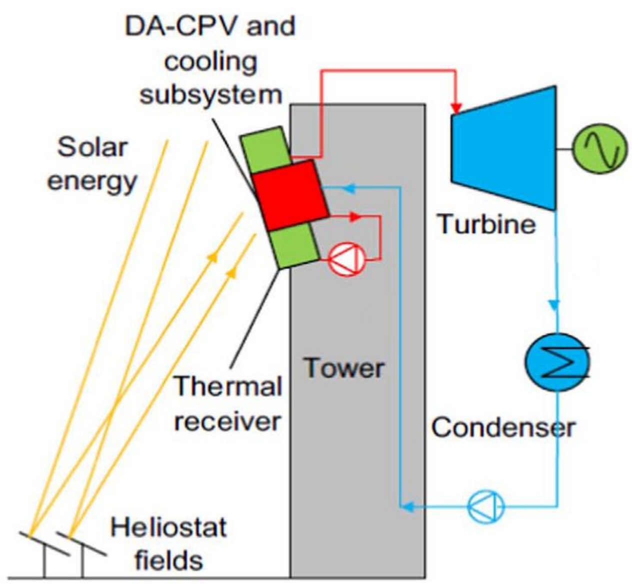


Figure 1.24: Compact method connection between CSP and solar photovoltaic [58]

E.3 Advantages and drawbacks [59,60]

- ✓ Good power quality
- ✓ Long-term stability
- ✓ Suitable to develop large-scale solar power plants
- ✖ Limitation of the PV operating temperature
- ✖ Power source cannot be distributed
- ✖ High temperature solar technology still requires development

E.4 Installed central in the world

In South America and exactly in Chile, mega hybrid system uses CSP (110 MW) and PV (100 MW). This hybrid system is under construction and uses molten salt for storage [61,62]. In Algeria, there is another type of hybrid system based on CSP (30 MW) and natural gas (120 MW). This centre is connected to the power grid and reduces 33000 tons of dioxide carbon emission every year [63].

F. Hybrid system wind turbine with a storage system

F.1 Elements of systems

They are many possible combinations between wind turbine and other generators (biomass, micro hydropower…etc) or storage systems (battery, fuel cell…etc). The essential elements of any hybrid system are used in wind turbine as stated below:

- Wind turbine
- Converter
- Fossils generators (diesel generator, gas turbine…etc), renewable generator (PV, CSP...etc) or storage systems (battery, fuel cell…etc)
- Load

F.2 Methods of interconnection

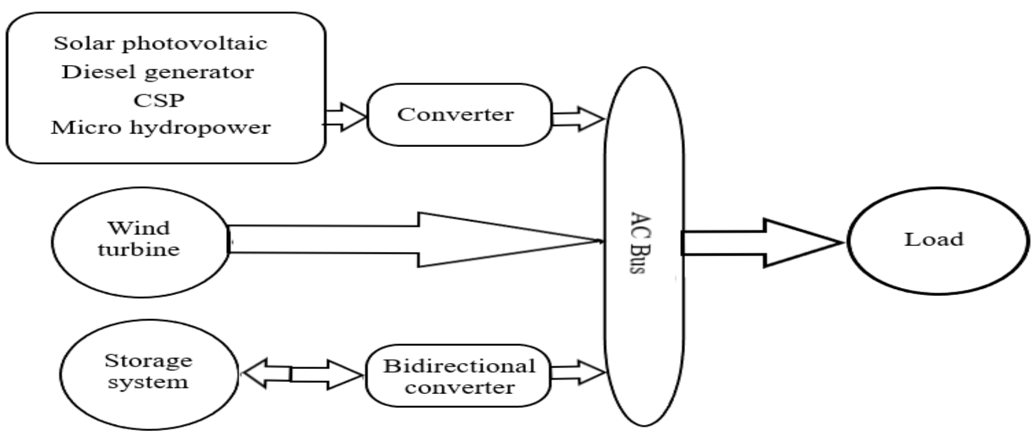


Figure 1.25: AC configuration for hybrid system based on wind turbine

- *AC architecture*

Generally, this architecture is the main configuration used in hybrid system based on wind turbine because the most output of wind turbine is AC. For DC load supply or storage system, a converter was integrated inside hybrid system to convert power from AC to DC or inverse in case of storage systems [64-66] (figure1.25)

- *Hybrid architecture*

In this configuration, DC component is required in hybrid system, and this element may be generator, load or storage system. Between AC and DC bus, bidirectional converter is installed for conversion between these two types of power [66] (figure 1.26).

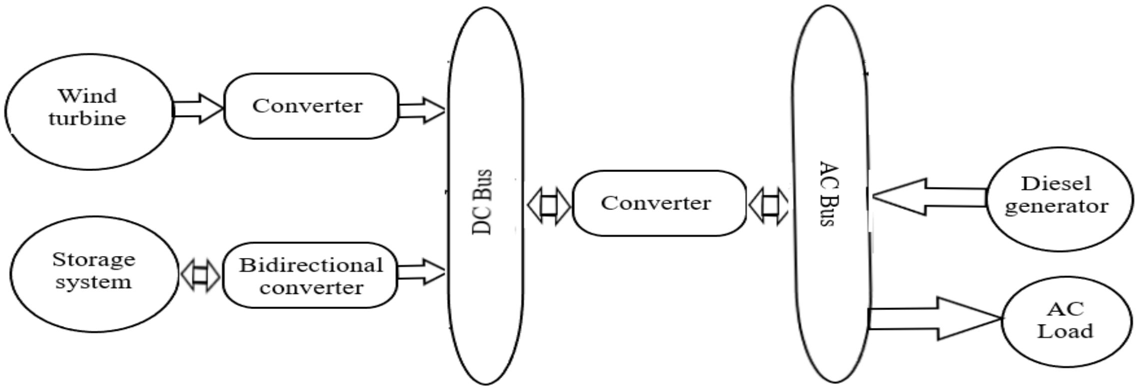


Figure 1.26: Hybrid configuration for hybrid system based on wind turbine

F.3 Advantages and drawbacks [66,67]

- ✓ Reduce dioxide carbon emission compared to system using an only diesel generator
- ✓ Decrease the cost of the diesel generator system
- ✓ Low cost of power.
- ✖ Backup storage requirement due to high uncertainty in wind availability.
- ✖ Large backup requirement.
- ✖ The wind has high intermittency.

F.4 Installed central in the world

In United State of America and exactly in "Saint Paul" (capital of Minnesota). Hybrid system was installed and composed of two diesel generators (2*150 kW) and one wind turbine (225 kW), this system was built in June 1999 to cover airplane and industry requirements [65].

In Africa, another hybrid system is built in South Africa, composed of 10 wind turbines (10*1 kW), 500 kW of biogas and 600 batteries of 1156 Ah [68]. Similar hybrid system is built in Germany with high capacity and is composed of three wind turbines of 2 MW, 1MW biogas with hydrogen storage of 500 kW. This centre is connected to the power grid and produces hydrogen (for hydrogen car), electrical and thermal power [69]

I.6 Conclusion

In this chapter, a short study of the hybrid system was made. This chapter is composed of four sections, the first one is on scientific terms used in this chapter, and the second one is on energy condition (use and production) in the world and in Algeria.

The third section is an analysis of renewable energy status in the last twenty years in the world and in Algeria. The fourth section starts with definition of the hybrid system, followed by classification of this system. Next part is on hybrid system and several combinations of hybrids systems, combination elements, interconnection, advantages and drawbacks and so also electrical central installed in the world.

Chapter II
Literature review

This chapter covers the last and main research published on the hybrid system. This chapter is divided into four sections; a review of sizing methods, a review of optimization methods, a review of control methods and a review of management methods

II.1 Introduction

As defined in the first chapter, hybrid Renewable energy system is every system combined from more than renewable source with or without storage system that can be the battery, fuel cell or diesel generator.

In this chapter, a review of the last study is carried out on in sizing, optimizing or control of hybrid system. This chapter is classified into three sections:

1. The first one is a review of sizing method
2. The second one is a review of optimizing methods
3. The third section is a review of control methods
4. The last one is a review of some management methods uses in hybrid systems.

In the end of each section, a full comparison between methods was achieved.

II.2 Classification of the review article in hybrid Renewable energy system

Every year, many published reviews on the hybrid system in the world by the researchers are the latest articles. Major reviews are on sizing [70], optimization [71] and control [72].

Some reviews contain a comparison between hybrid systems like R.K. Akikur using solar energy with battery and another hybrid system with or without conventional source [94]. Sonali Goel et al. compared the performance of connection mode for the solar photovoltaic hybrid system [95].

The configuration of hybrid systems also has a considerable review like Chauhan in the comparison between different configurations (AC, DC and hybrid) of hybrid systems (figure 2.1) [76]. In [77], authors use different configurations for the general hybrid system without a specific generator and summarized the three configurations (AC, DC and hybrid) in one table by mentioning the advantages and drawbacks of each configuration. Mohammad Junaid Khana et al. focuses on the analysis of hybrid system aspects technically and economically [96].

II.3 Review of used sizing method for hybrid system

Sizing of the hybrid system is an important step in defining the capacity of each system generator. There is a big risk in sizing under-sized or over-sized systems considering the difficulties in the evaluation of real load time of many fluctuations (in time and use), however, most researchers take average hours, days or months as time of use. [84]

There are two categories of sizing method; the first one is by using software and the second one is by using traditional method (figure2.2).

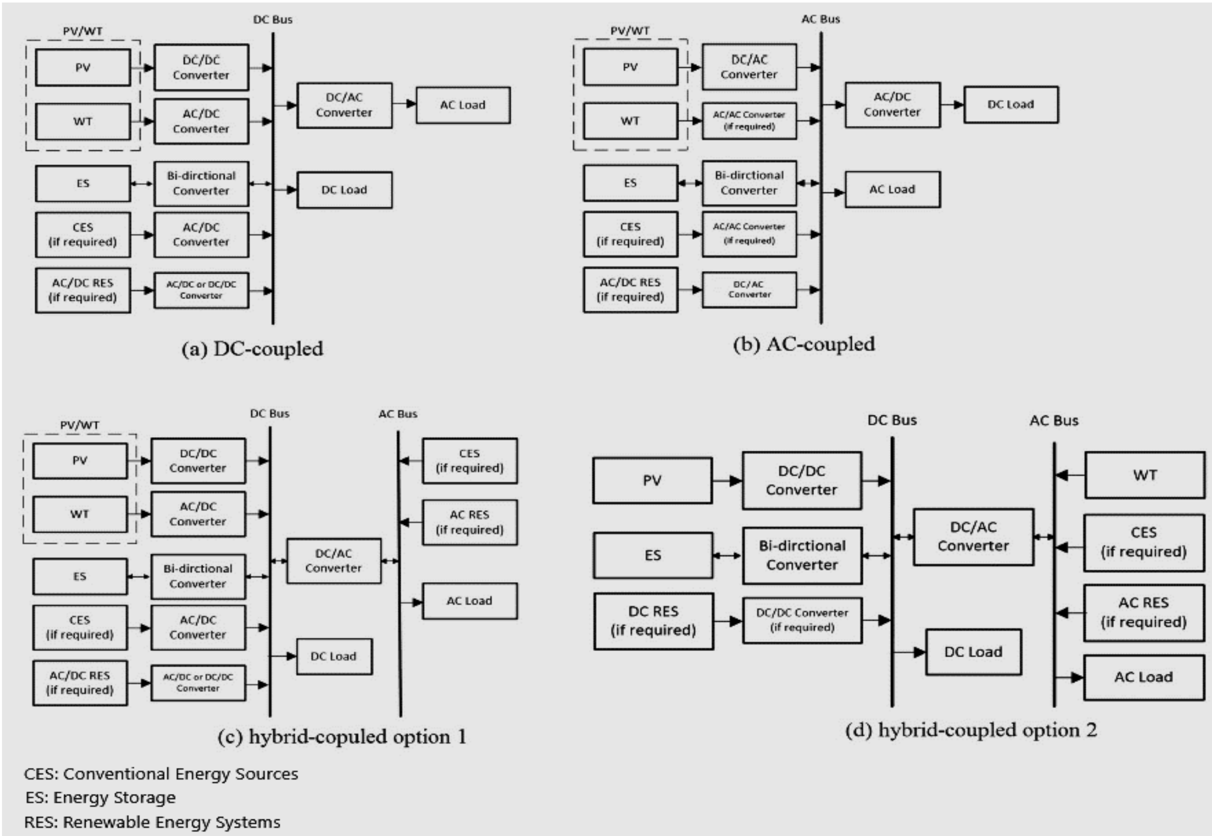


Figure 2.1: hybrid energy system configurations [70]

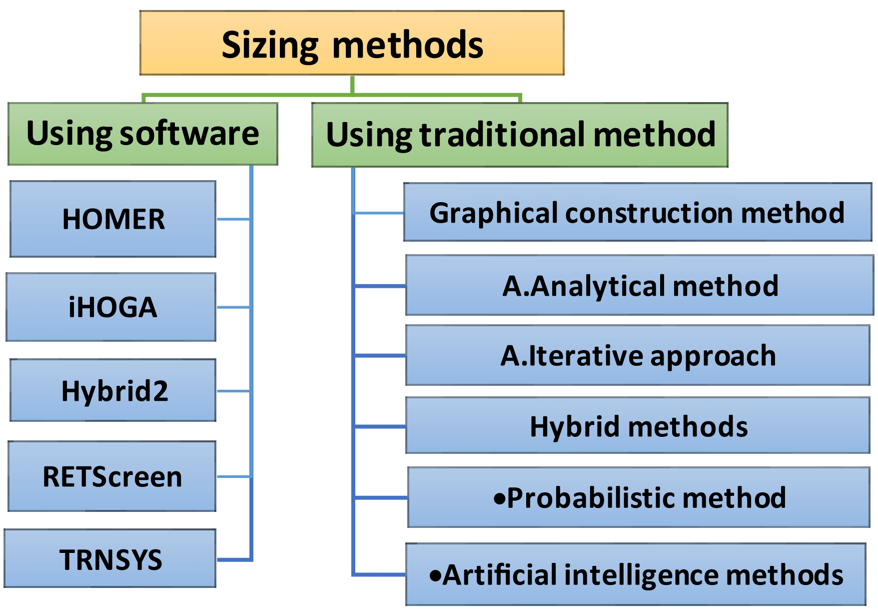


Figure 2.2: Sizing methods of hybrid system

II.3.1 Sizing hybrid system using software

Many commercial applications are available for sizing hybrid system, and most of these applications use windows as computer platform with the programming language visual C++ as RET Screen (figure 2.3.a), iHOGA (Hybrid Optimization by Genetic Algorithm) (figure 2.3.b), INSEL (Integrated Simulation Environment Language), HOMER (Hybrid Optimization Model for Electric Renewable) (figure 2.3.c) and other programs [97]

Bentouba et al. use HOMER software for size hybrid system based on solar photovoltaic, wind turbine and diesel generator in Timiaouine (Algeria). The objective of this study is cover consumption of this rural village using hybrid system. After simulation, the best economic result is 0,176 $/kWh. [98]

Using iHOGA software, Fadaeenejad et al. size hybrid system use two renewable generators (solar photovoltaic and wind turbine) and two conventional generators (diesel generator and battery) in Kampung Opar in Malaysia for supply to the rural village. [99]

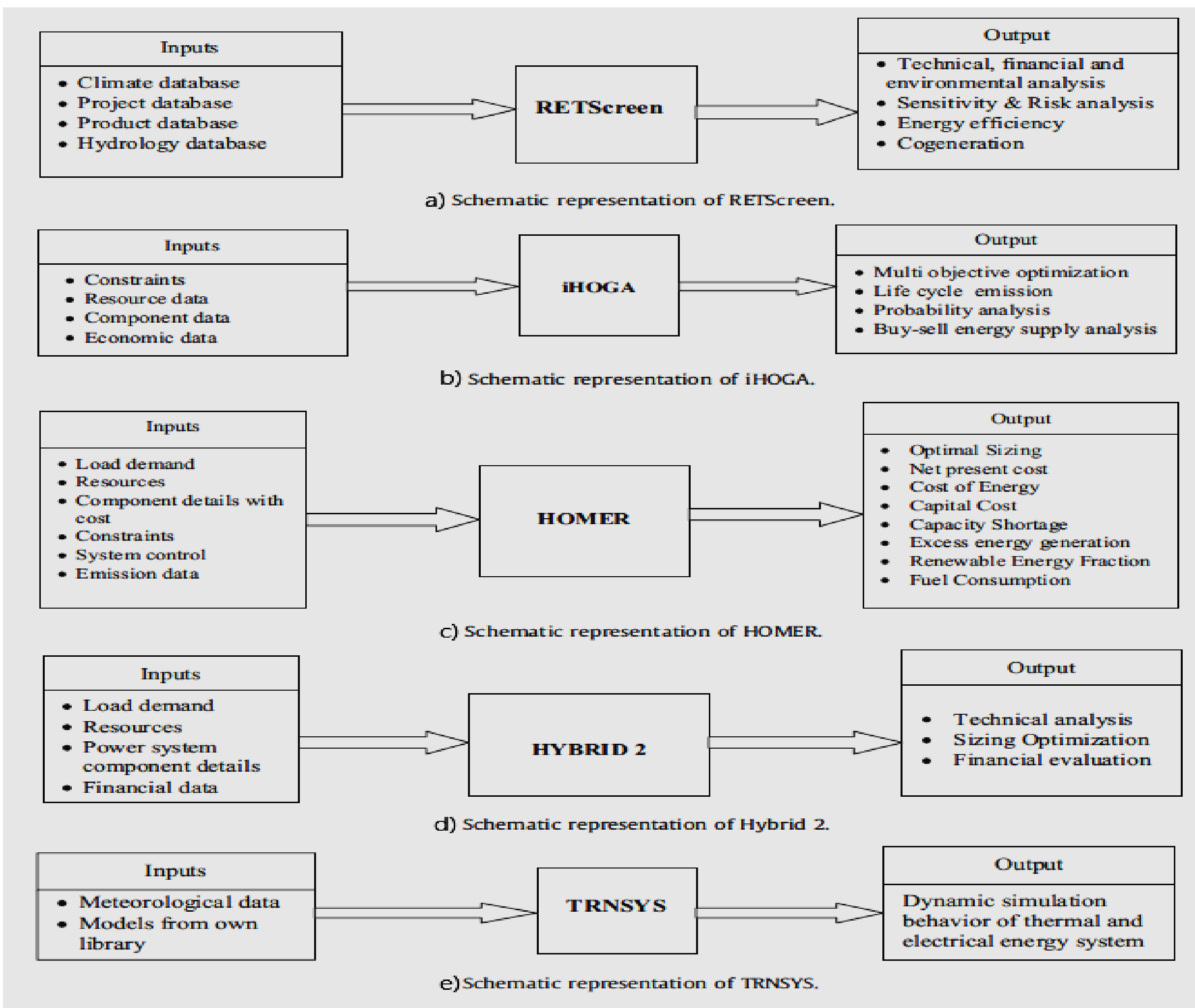


Figure 2.3: Schematic representation of commercial application [97]

Hybrid2 is a developed software by Renewable energy Research Laboratory (RERL) of the University of Massachusetts, USA with support from National Renewable energy Laboratory [97] (figure 2.2.d). Mills et al. use this software for size solar/wind/fuel cell hybrid system in Chicago (USA), and after simulation, the location choice for plotting systems shows sufficient renewable resource to cover load profile and possibility doesn't need a fuel cell. [100]

In 1998, the Ministry of Natural Resources in Canada develops software for sizing and optimization called "RET Screen" that simulate systems in different sections; technically, financially, in environmental analysis, power efficiency…etc [76]. Liqun et al. simulate their study using Canadian software for solar photovoltaic, wind, diesel generator with battery hybrid system in Shanghai (China). The results show a reduction in greenhouse gas emission because the hybrid system is basically based on Renewable energy (more than 99%) [101].

The University of Wisconsin in Madison (USA) develops "TRNSYS" (figure 2.2.e), where main software is used for the simulate thermic system [76]. This software is used to modulate and simulate solar photovoltaic and thermic hybrid system [102], and results show that hybrid system is technically and economically better than used system for solar photovoltaic.

Below table is a summary of advantages and drawbacks of each software:

Table 2.1: Comparison between different software [97,76]

Software	Advantages	Drawbacks
HOMER	- Plot results in efficiency graph - Easy to understand	- Uses first degree linear equations - Can't import time series data
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
RET Screen	- 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

II.3.2 Sizing hybrid system using the traditional method

They are five essential traditional sizing methods:

- Graphical construction method
- Analytical method
- Iterative approach
- Hybrid method
- Probabilistic method
- Artificial intelligence methods

A- Graphical construction method

This method is based on one condition; the average value of demand must be covered with multiplied average values of the potential generator (solar radiations, wind speed) by the size of the generator. [74] Markvart used this method to size economically hybrid system based on solar photovoltaic and wind turbine, and the obtained results are that wind potential is more powerful than solar potential as size of wind turbine equal five times the size of solar photovoltaic (figure 2.4) [103].

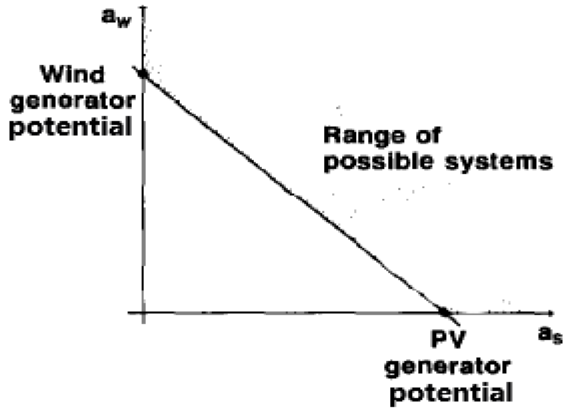


Figure 2.4: The range of hybrid PV/wind energy systems that satisfy the load [103]

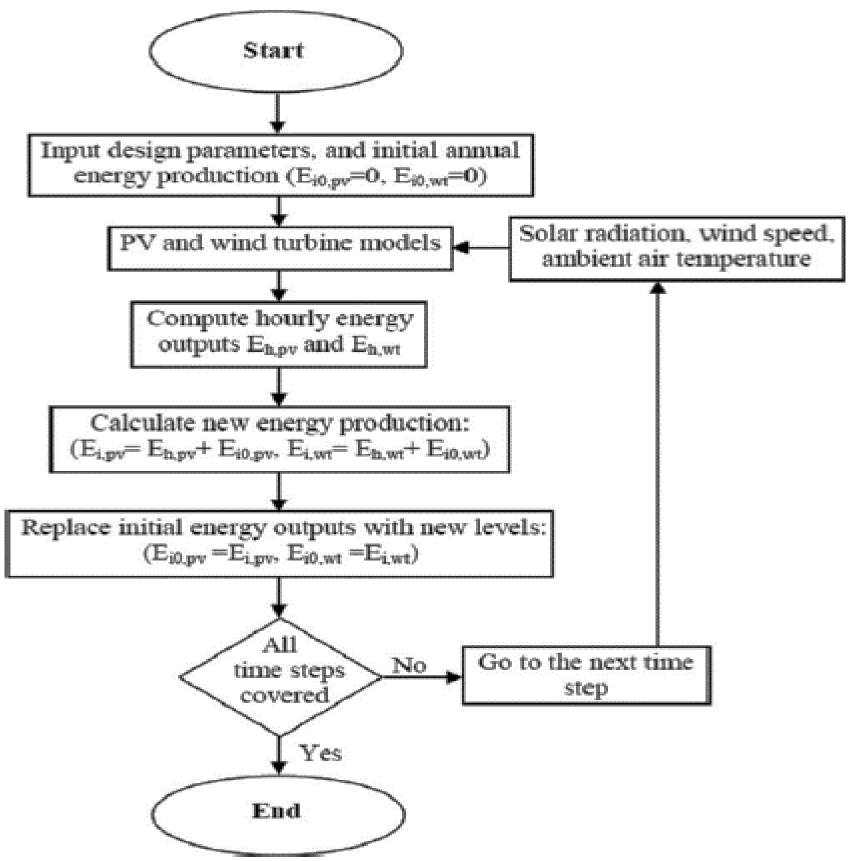


Figure 2.5: The range of hybrid PV/wind energy systems that satisfy the load [105]

B- Analytical method

This method considers the hybrid system as means of a computational model and describes the hybrid system size as a function of feasibility [104]. Amos Madhlopa et al. published in 2015, a study for a hybrid system using analytical method (figure 2.5), where the components of the hybrid system are solar photovoltaic and a wind turbine in South Africa. The objective is investigating water efficiency optimization of the hybrid system. The obtained results show that hybrid central generates 100000 MWh every year,0,97€/kWh and 75000 m^3 of water yearly [105].

C- Iterative approach

This method is an algorithm program based on recursive process, ending when the optimum system design is attained [74,76]. Camargo et al. use this method for size stand-alone hybrid system based on solar photovoltaic, wind power with batteries for supply to a rural village in Brazil (figure 2.6). The objective of this study is to produce a system with minimum cost and high reliability. After simulation, the optimum configuration for hybrid system is 0,5 kW of solar photovoltaic, 3 wind turbines (0,6 kW for each one) and 5 batteries (each one has 1,2 kWh). The total cost of this system is 25672.01R$ (Brazilian real is the official currency of Brazil) with levilized cost1.044 R$ /kWh[106].

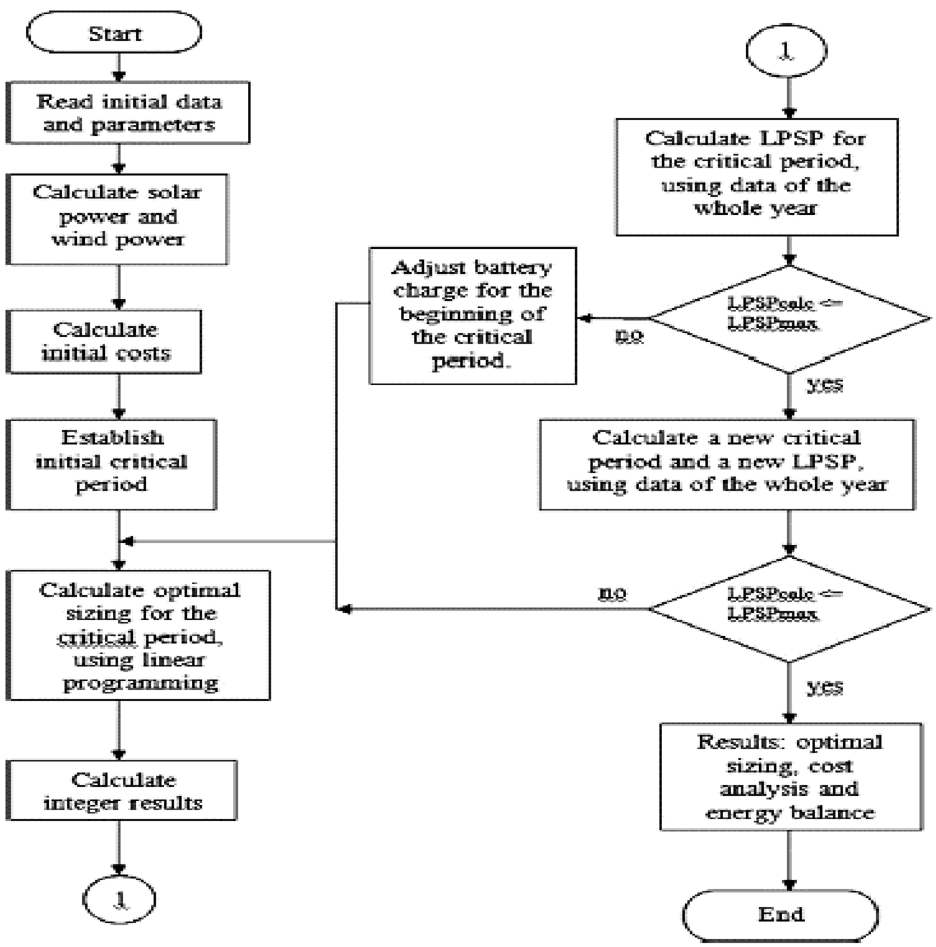


Figure 2.6: Flowchart for the energy system optimal sizing [106]

D- Hybrid method

Hybrid method is defined as a combination of two or more different techniques, using the advantages of these techniques in obtaining optimal result [74]. Sharafi et al. use hybrid method to size hybrid system based on solar photovoltaic, wind turbine, diesel generator and for storage systems, they use battery and fuel cell. The results show that this technical reduces the cost of systems and dioxide carbon emission [107].

E- Probabilistic method

Probabilistic approaches for sizing an integrated system considers the effect of the insulation and changes in wind speed for system design [106]. This method is one of the simplest used sizing methods but results show that it may not be appropriate to find the best possible solution [74].

Lujano Rojas uses an algorithm for sizing solar photovoltaic/wind turbine/diesel generator and battery hybrid system using probabilistic method, considering the uncertainty of solar radiation, wind speed, fuel prices and battery bank lifetime. The result shows minimization in economic and technical parameter [108].

F- Artificial intelligence methods

Subho Upadhyay defined artificial intelligence in his review article "A review on configurations, control and sizing methodologies of hybrid power systems" and wrote exactly in simple sentences: "Artificial intelligence is a term that in its broadest sense would mean the ability of a machine or artifact to perform similar kinds of functions that characterize human thought" [74].

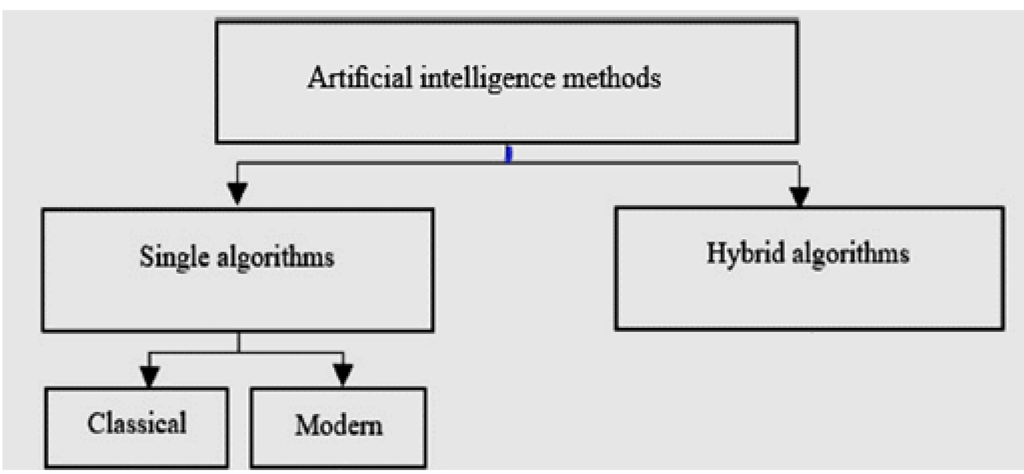


Figure 2.7: Artificial intelligence methods for sizing hybrid systems [109]

Several types of genetic algorithm are used by researchers to find optimum sizing for hybrid system (figure 2.7) like genetic algorithm [109], adaptive genetic algorithm [110], non-dominated sorting genetic algorithm (NSGA-II) [111], mine blast algorithm (MBA) [112], Particle swarm optimization (PSO) [113], multi-objective line-up competition algorithm (MLUCA) [114], Ant colony optimization (ACO) [115], and preference inspired coevolutionary algorithm (PICEA) [116]. A new algorithm biogeography based on optimization (BBO) is used for sizing by Bensal et al. [117], cuckoo search (CS) [118], discrete harmony search (DHS) [119], and discrete harmony search simulated annealing (DHSSA) [120], Artificial bee swarm algorithm [121], Improved fruit fly algorithm (IFFA) [122], A-Strong [123], bacterial food algorithm [124], Artificial neural network (ANN) [125], fuzzy logic [126]. Next two tables summarize sizing methods and characterize of each one:

Table 2.2: A summary of recent optimal sizing studies

Sizing methods	**System components**	**Objective functions**	**Ref.**
Graphical construction method	PV/WT	Hybrid generator cost	103
Analytical method	PV/WT	Levelized cost of energy (LCOE)	105
Iterative approach	PV/WT/Battery	Loss of power supply probability (LPSP)	106
Hybrid method	PV/WT/DG/Battery/ fuel cell (FC)	Minimizing the total cost of the system, the total CO_2 emissions and loss of load probability (LPP).	107
Probabilistic method	PV/WT/DG	Net present cost (NPC)	108
Generic algorithm	PV/WT/DG/Battery	Minimize LCC (life cycle cost), total CO2 emissions (E) and net dump load (D)	109
Adaptive genetic algorithm	PV/WT/Battery	Minimize installation costs	110
Non-dominated sorting genetic algorithm (NSGA-II)	PV/WT/Battery	Minimize total cost (TC) and deficiency in power supply probability (DPSP)	111
Mine blast algorithm (MBA)	PV/WT/DG/FC/ hydrogen tank (HT)	Minimize annual total cost (TAC)	112
Particle swarm optimization (PSO)	PV/WT/Battery	Minimize LCC	113
Multi-objective line-up competition algorithm (MLUCA)	PV/WT/DG/Battery	Minimize TAC and greenhouse gasses (GHG) emissions	114
Ant colony optimization (ACO)	PV/WT/DG/Battery	Minimize TAC	115
Preference inspired coevolutionary algorithm (PICEA)	PV/WT/DG/Battery	Minimize ACS, LPSP and fuel emissions	116
Biogeography based on optimization (BBO)	PV/WT/Pico hydro plant/Battery	Minimize cost function	117
Cuckoo search (CS)	PV/WT/Battery	Minimize the TC	118
Discrete harmony search (DHS)	PV/WT/DG/Battery	Minimize the TAC	119
Discrete harmony search simulated annealing (DHSSA)	PV/WT/Battery	Minimize TAC	120

Artificial bee swarm algorithm	PV/WT/FC	Minimize the cost and LPSP	121
Improved fruit fly algorithm (IFFA)	PV/WT/DG/Battery	Cost and emissions	122
A-Strong	PV/WT/Battery	Cost and reliability	123
Bacterial food algorithm	-	Cost and emissions	124
Artificial neural network (ANN)	PV/WT	Minimize weighted mean absolute error and normalized mean absolute error	125
Fuzzy logic	PV/WT/FC	fuel cell power requirement	126

II.3.3 Comparison between sizing methods

Table 2.3: Comparison between different sizing methods used in hybrid system [74,84]

Method	Advantages	Drawbacks
Graphical construction method	Easy to use	Ignore some important parameters like higher wind turbine or slope angle of solar photovoltaic
Analytical method	Rapidly [127]	Low flexibility
Iterative approach	Easy to use	Ignored some important parameters like higher wind turbine or slope angle of solar photovoltaic
Hybrid method	The best method to solve multi objective problem	Complex method
Probabilistic method	Easy to uses	Cannot present a dynamic performance of hybrid system
Artificial intelligence methods	Solve complex and multi objective problem	Complex method

II.4 Review of Optimization method used for the hybrid system [77,80,84]

There are many objectives in a hybrid system that needs optimization like sizing, control, management …etc [71]. In this part, a note is taken for the most optimization method used in last years. The classified optimization methods are in three categories; classical methods, artificial methods and hybrid methods (figure 2.8).

II.4.1 Classical methods

The classical method is described as the method using the differential calculation in such a way to achieve optimum solution [77, 128]. Due to their limited space optimization, these techniques were rarely used by the researcher. However, there are many classical optimization methods like linear programming model (LPM) [129], multi objective goal programming (MOGP) [130], multi-objective evolutionary algorithms (MOEA) [131], multi-input linear programming (MILP) [132], dynamic programming (DP) [133] and nonlinear programming (NLP) [134].

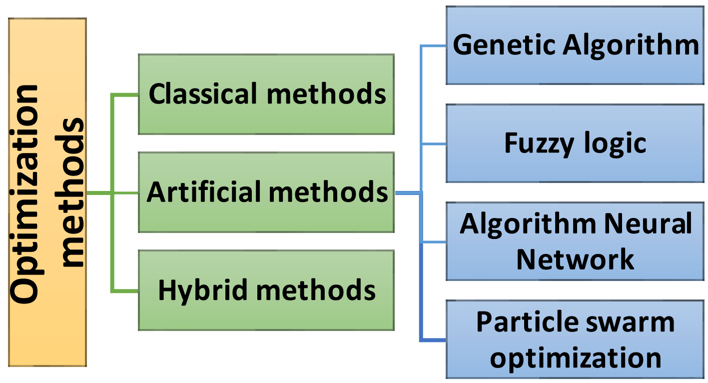


Figure 2.8: Optimization methods of hybrid system

II.4.2 Artificial methods

Most artificial methods, previously mentioned in sizing review, are used for optimization but concentration, in this part, is made just on methods generally and recently used by the researcher.

A- Genetic Algorithm

Genetic algorithm (GA) is a search process (computer programs) that simulates the process of natural selection (biological evolution) like inheritance, mutation, selection and crossover. Today, in researchers, the term "genetical algorithm" is used to describe something very far from the creator of the genetic algorithm (John Holland) [135-137].

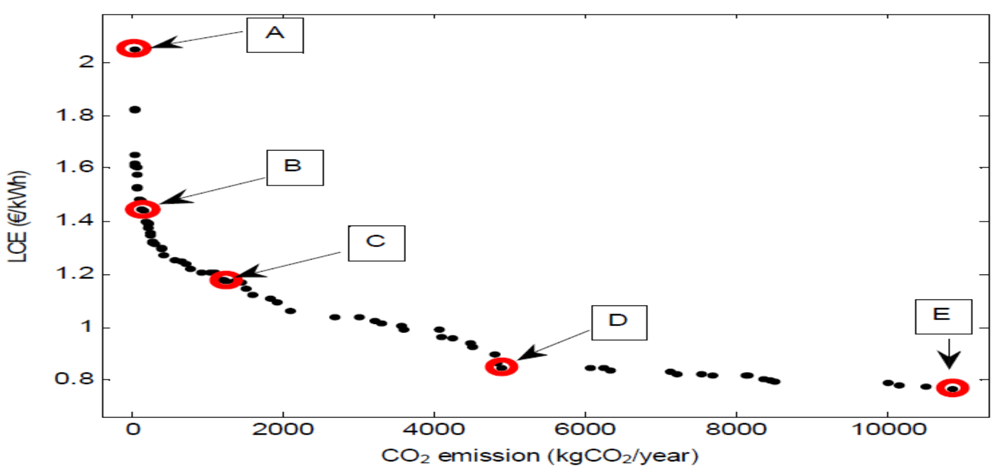


Figure 2.9: Evolution of optimal hybrid PV/wind/diesel/battery system [138]

Bilal BO et al. use a genetic algorithm to design and optimize hybrid system solar photovoltaic/wind turbine/diesel and storage system (battery) for supply to isolated areas in Senegal. This study has two objectives (economic and environmental). The first is minimizing levelized cost of the system and the second is reducing dioxide carbon emission. The results show an inverse relation between levilized cost and CO_2 emission, that mean when levilized cost increases from 1,22€/kWh to 2,05€/kWh, the dioxide carbon decreases from 762.08kg/year to 11.89kg/year (figure 2.9) [138].

B- Fuzzy logic

Fuzzy logic is a mathematical theory of fuzzy sets, which is a many but as One. [139-141], Suganthi et al. define fuzzy logic in a simple sentence and wrote: "Fuzzy logic deals with reality and it is a form of much valued logic" [78].

For Michael and Warne; the authors of "Electrical Engineering Reference Book", fuzzy logic is an important way to represent the experience of humanity on the digital processor and wrote: "It is essentially a method of readily representing human expert knowledge on a digital processor in particular where mathematical or rule-based expert systems experience difficulty". (figure 2.10) [142].

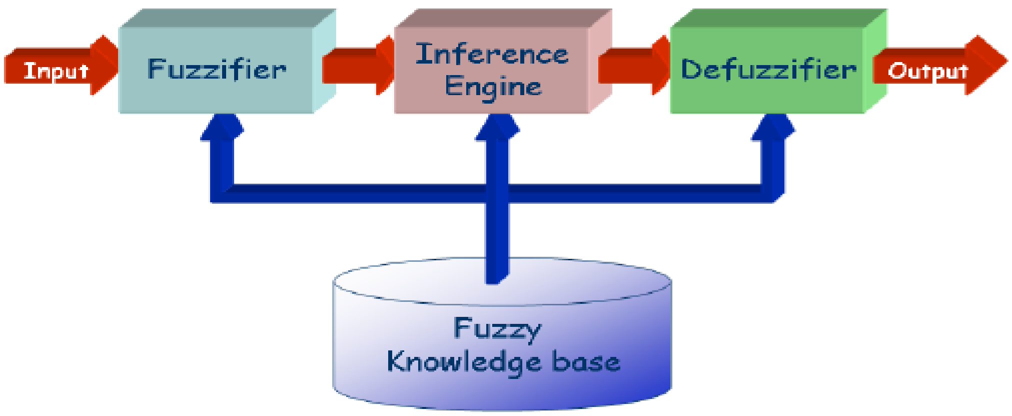


Figure 2.10: Overview diagram of a fuzzy system [141]

Mukhtaruddin et al. used fuzzy logic with two other algorithms to optimize the combination of a hybrid system with solar photovoltaic, wind turbine and battery for supply of isolated areas in Malaysia. The obtained results show a minimization in economic parameter (total cost) and technical parameter (power excess) and maximum reliability of the system [143]

It is noted that there are many types of fuzzy logic algorithm such as adaptive neuro-fuzzy inference system (ANFIS) [144], fuzzy analytic hierarchy process (AHP) [145], A fuzzy analytic network process (ANP) [146], fuzzy clustering [147], fuzzy genetical algorithm [148], fuzzy TOPSIS [149], fuzzy particle swarm optimization [150], fuzzy honey bee optimization [151], Quantum behaved Particle Swarm Optimization [152]…etc.

C- Algorithm neural network

Michael and Warne described algorithm neural network generally like the structure of the human brain but many experts opinion is that resemblance is very superficial (figure 2.11). Technically, authors explain the importance of algorithm neural network is the training for performing an essential action and wrote; "In engineering terms, what is important is that the ANNs can be trained to perform' a required action" [142].

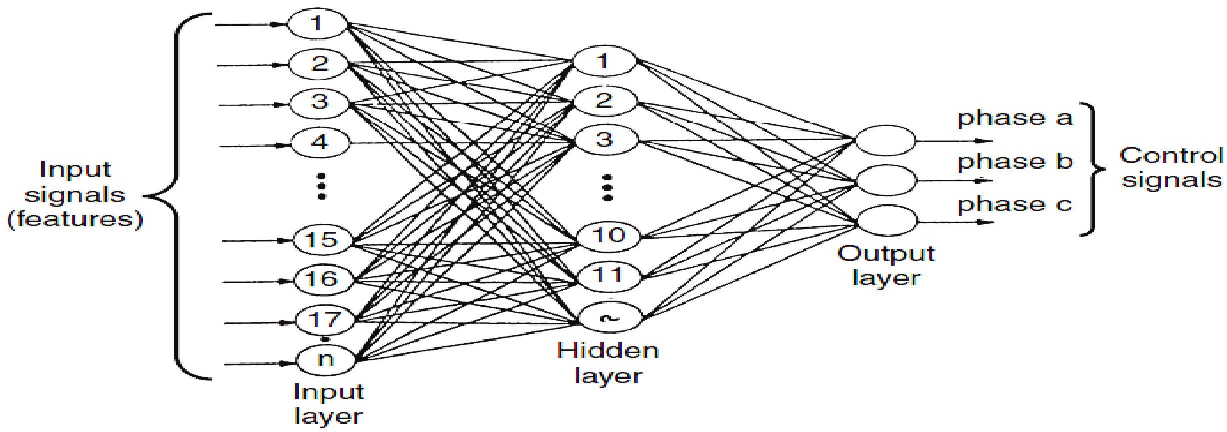


Figure 2.11: Artificial neural network (ANN) topology [142]

They are many ways to use ANN in optimization. Sinha and Chandel use ANN to predict meteorological data (solar and wind), and the results show that the obtained results are close to measured or estimated data [153].

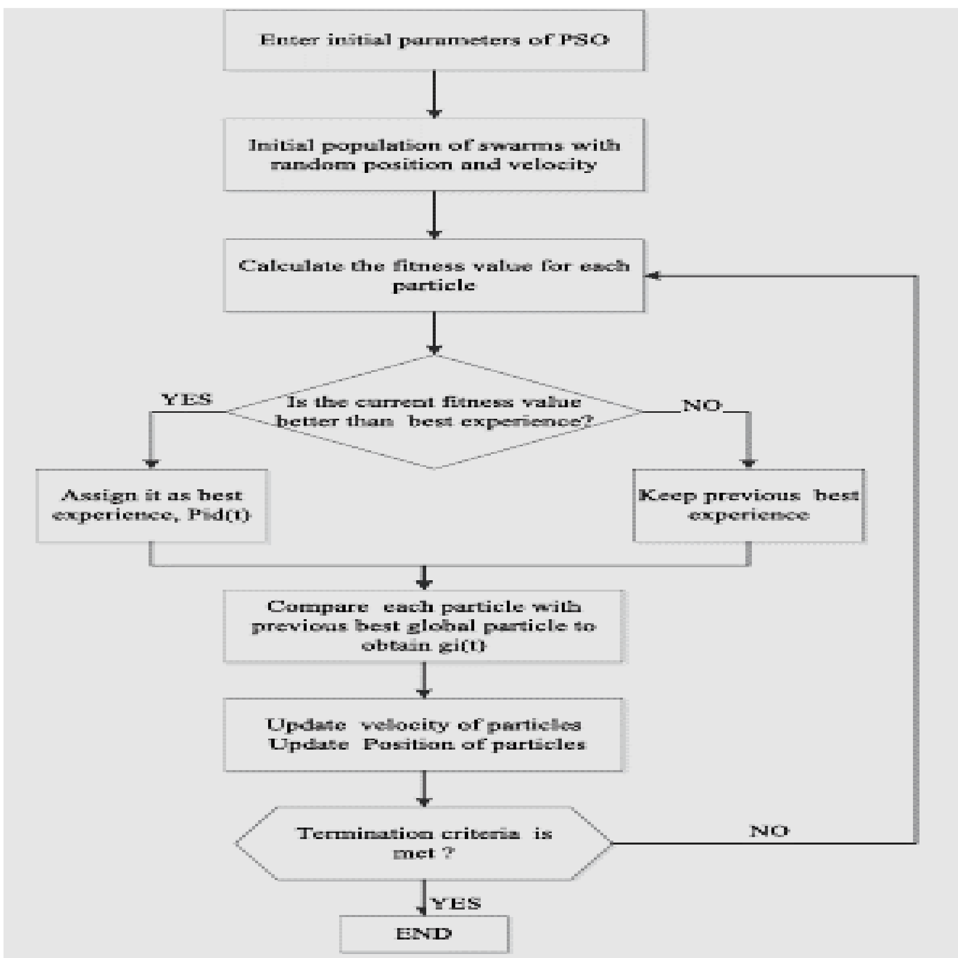


Figure 2.12: PSO algorithm flowchart [156]

D- Particle swarm optimization (PSO)

This method is based on collective movement of birds or fishes and uses this movement simultaneously in three-dimensional space with continuously changing position and speeds, where each particle (or animal) represents a possible solution [154,155]. Considering simplicity and fast convergence, this method was one of the most popular and used algorithm [70]. Sharafi et al. used this algorithm to optimize hybrid system based on solar and concentrator photovoltaic, biomass, wind turbine and heat tank for the storage system (figure 2.12). The obtained results show economic (total cost of the system) and ecologic (dioxide carbon emission) optimization higher than in another used method [156].

II.4.3 Hybrid methods

A hybrid method is every combined method with two or more algorithms methods, that use the advantage of these methods to overcome a single algorithm [84]. In recent years, a lot of hybrid methods are developed to optimize hybrid system like simulated annealing hybrid and Tabu Search (SA-TS) [157], DCHSSA (discrete chaotic search, harmony search and simulated annealing [120], Monte Carlo simulation-PSO [158], hybrid iterative- algorithm genetic [159].

In addition, they are an artificial neural network/algorithm genetic and Monte Carlo simulation [160]; simulating annealing particle swarm optimization (SAPSO) [161], Iterative-Pareto-Fuzzy (IPF) [162], multi objective genetic algorithm (MOGA) [163] and many other hybrid methods. Next table summarizes all optimization methods and the characterize of each one:

Table 2.4: A summary of recent optimization methods

methods	System components	Objective of study	Ref.
Genetic algorithm	PV/WT/DG/Battery	Minimized LCE and the CO_2 emission	138
Fuzzy logic	PV/WT//Battery	Minimize TC	143
Adaptive neuro-fuzzy inference system (ANFIS)	Fossil fuel/nuclear/ PV/WT/hydropower	Best combination between renewable resource Minimize TC	144
Fuzzy analytic hierarchy process (AHP)	solar, hydropower, geothermal, wind energy and biomass	Select best renewable resource based on five criteria; quality of the energy source, socio-political, economic, technological and environmental	145
Fuzzy analytic network process (ANP)	PV/WT	Best hybrid system in these criteria: Performance Economic Social and environmental	146
Fuzzy clustering	PV/WT/FC	Power losses Voltage deviation Cost Emission	147

Fuzzy genetical algorithm	WT/PV/microturbine/Battery	Minimizing the annualized cost of the system Maximum energy captured from the wind turbine/solar array	148
Fuzzy TOPSIS	PV/WT//Battery	Minimizing LEC, unmet load and fuel consumption	149
Fuzzy particle swarm optimization	Microturbine/FC/Battery	Optimizing the operation of a micro-grid with renewable energy sources.	150
Fuzzy honey bee optimization	PV/WT//FC	Minimize the electrical active power losses, the voltage deviations, the total electrical energy costs and the total emissions	151
Quantum behaved particle swarm optimization	PV/FC//Battery	Optimize performance of the hybrid system	152
Algorithm neural network	PV/WT	Predict solar and wind data	153
Particle swarm optimization (PSO)	PV/WT/Biomass	Minimize cost and CO_2 emissions and maximize renewable energy	156
Simulated annealing hybrid and Tabu Search (SA-TS)	PV/WT/DG/FC/Battery	Minimizing LEC	157
Monte Carlo simulation-PSO	PV/WT/Battery	Minimize the cost	158
Hybrid iterative-algorithm genetic	PV/WT/Micro-grid	Cover the load demand with minimum cost	159
Artificial neural network/algorithm genetic	PV/WT/DG/Battery	Optimum load management strategy to minimize energy.	160
Simulating annealing particle swarm optimization (SAPSO)	PV/WT//Battery/Supercapacitor	Minimize investment and operation costs	161
Iterative-Pareto-Fuzzy (IPF)	PV/WT/Battery	Minimum cost and maximum reliability	162
multi objective genetic algorithm (MOGA)	PV/WT	Minimize cost and CO_2 emissions	163

II.4.4 Comparison between optimization methods

Table 2.5 Advantages and drawbacks of each optimization method [77,84]

Method	Advantages	Drawbacks
Classical method	Enable solution for multi objective problem Useful for investment decision Requires less time	Limited space optimization Linearity in the relation to variables Method needs discrete and continuous probability
Artificial method	Maximum efficiency level Good calculation accuracy High convergence speed	Complex solving process Required long term memory space Several changes are required.
Hybrid method	Require less time Most robustness Quick convergence	Complexity in designing the system. Extended solutions Difficulty to provide code

II.5 Review of Control method used in hybrid system

Generally, the parameters that should be controlled in every hybrid system are [164-167]:

1. Stability: this means the voltage and frequency of the system
2. Protection: observing of power flow
3. Power balance: optimal load distribution.

Some authors classified control of hybrid systems in three essential categories; centralized (figure 2.13.a), distributed (figure 2.13.b) and hybrid control (figure 2.13.c) like Chauhan and Saini in [76]. However, for Eneko and Jon, the control of hybrid system is classified in another three categories; primary local, secondary local and tertiary [88]. In all cases, each generator requires owned control or global control [74]. Moreover, there is another classification made by Chong L.W et al., classifying control methods in two types; classical control and intelligent control [168]. For wind turbine, they are a lot of parameters requiring control using MPPT (Maximum power point tracking) based on quantum neural network (QNN) [100], selection of voltage vectors on the rotor side converter based on direct power control (DPC) and direct virtual torque control (DVTC) algorithms [170], pitch control [171] …etc.

For solar photovoltaic, many control methods were applied to optimize the performance of solar panel like MPPT, based on the neural network [172], algorithm neural network for estimating the power of solar photovoltaic [173], using fuzzy logic to control power generated from solar photovoltaic [174] …etc.

For diesel generator, major researches of control focus on network voltage [175], voltage and current [176] or active and reactive power [177].
However, there are a lot of other methods controlling hybrid Renewable energy system like centralize control [178], distributed control [179], hybrid control [180] (figure 2.14), and so also classical control methods (figure 2.14) such as rule-based control (RBC) [181] (figure 2.15), filtration-based control (FBC) (figure 2.16) [182]. The classical methods are intelligent methods like algorithm neural network [183], fuzzy logic controller [184], particle swarm optimization

(PSO) [185], and adaptive neuro-fuzzy inference system (ANFIS) [186]. Next table summarizes the essentials categories of control:

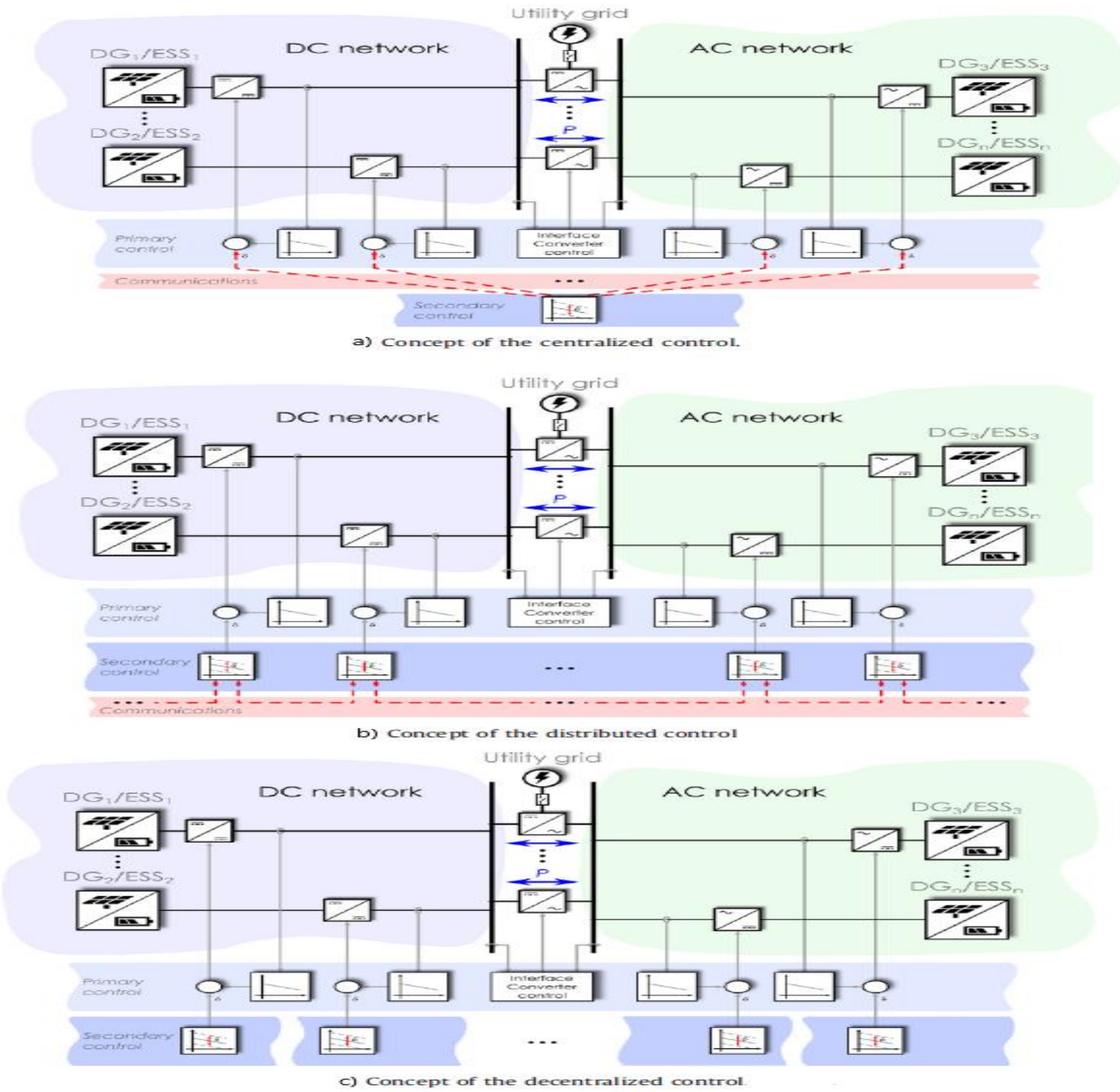


Figure 2.13: Concept of hybrid system control [88]

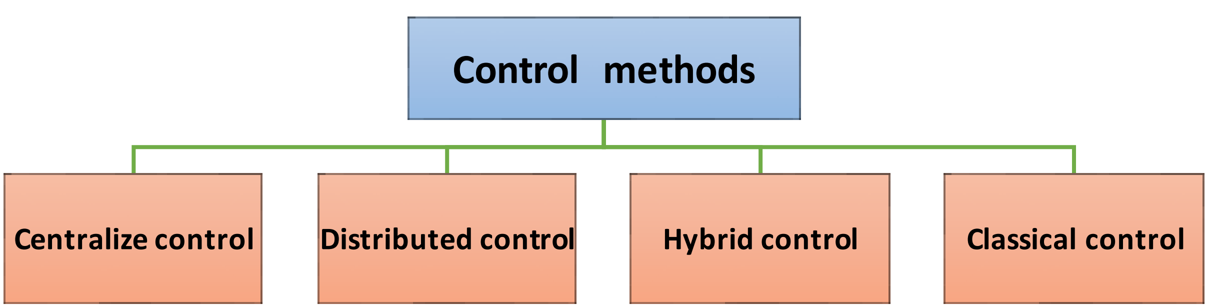


Figure 2.14: Control methods of hybrid system

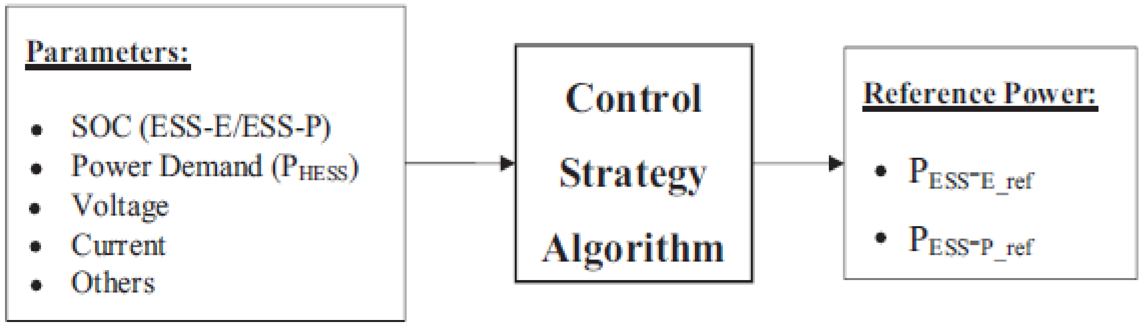


Figure 2.15: Concept of the control strategy for the hybrid system [181]

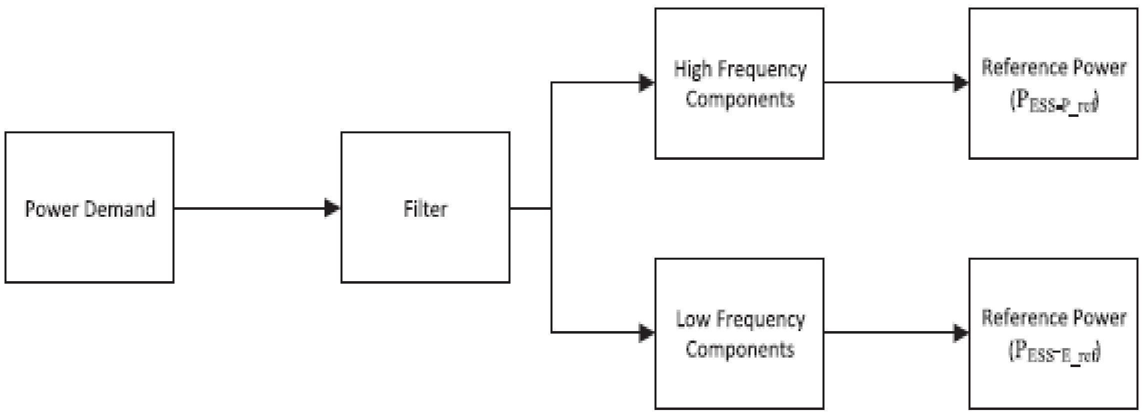


Figure 2.16: FBC algorithm [182]

Table 2.6: Comparison of each method used in control methods [74,76,88]

Method of control	Advantages	Drawbacks
Centralize	Minimization of power costs Can achieve global optimization.	Use a system based on one central control
Distributed	Low possibility of system failure Achieve low and medium use	Complex connection inside system Mostly suboptimal solutions
Hybrid	Local optimization is achieved through centralized control Low use in local controllers	Complex control Complex potential in connection inside system

II.6 Review of management methods

Management of hybrid system ensures high system efficiency and high reliability with least cost [79] to enable system supply throughout the year, an increase of lifetime of the elements, reduction of the economic parameter (global cost, levilized cost …etc) and as a result, maximize system performance (figure 2.17) [90].

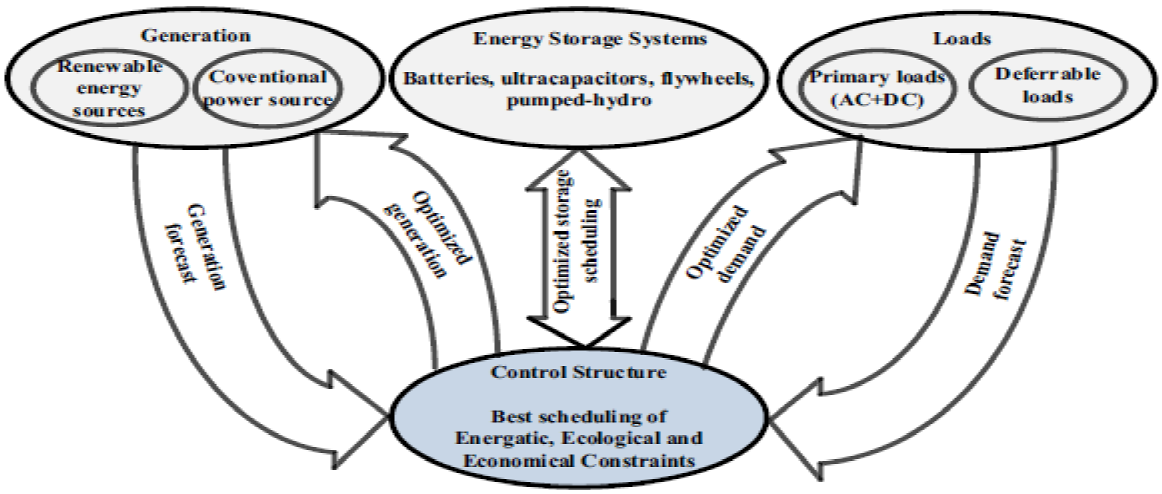


Figure 2.17: Intelligent energy flow management [76]

Management methods are classified in three categories due to objective strategy (figure 2.18) [90]:

- Technical objective strategy
- Economic objective strategy
- Techno-economic strategy objective

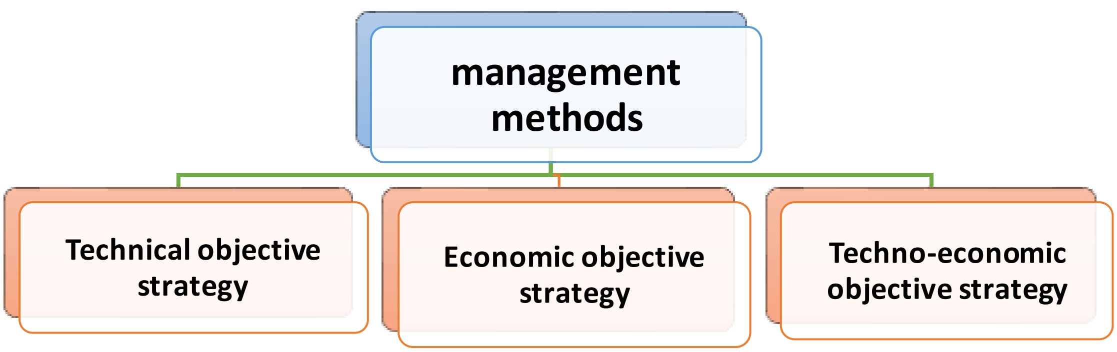


Figure 2.18: Control methods of hybrid system

II.6.1 Technical objective strategy

The main objective of this strategy is to take into account the technical parameter of the hybrid system to cover the demand of load [187], increase equipment lifetime [188], increase performance [189], stability of system [190], increase lifetime of storage system (battery, fuel cell, super capacity…etc) [191] and many other parameters characterizing every hybrid system due to their generators (figure 2.19). These parameters manage using different algorithms like predictive control [192], flow chart [193], fuzzy logic [187], dynamic real-time optimization [194] and artificial neural network controller [195], TRNSYS software [196]

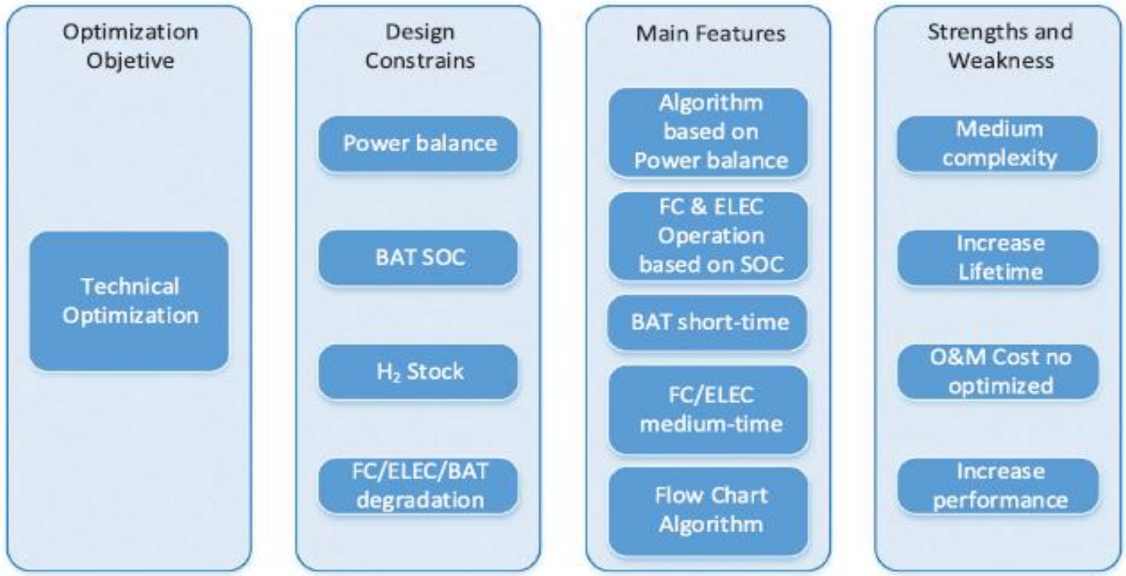


Figure 2.19: Main characteristics of technical objectives strategies [76]

II.6.2 Economic objective strategy

The economic objective is every strategy taking into account some parameters influx in the economic state of the system regardless of the technical situation of the system (stability, the performance of system…etc) (figure 2.20) [90]. Major published studies in economic strategy include two main objectives; coverage of demand and reduction of system cost, through different algorithm as generic algorithm [197], differential evolution algorithm [198], model predictive control [199], mixed-integer linear programming [200], flow chart [201], fuzzy logic [202], interior search algorithm [203] and also commercial software like HOMER [204] …etc.

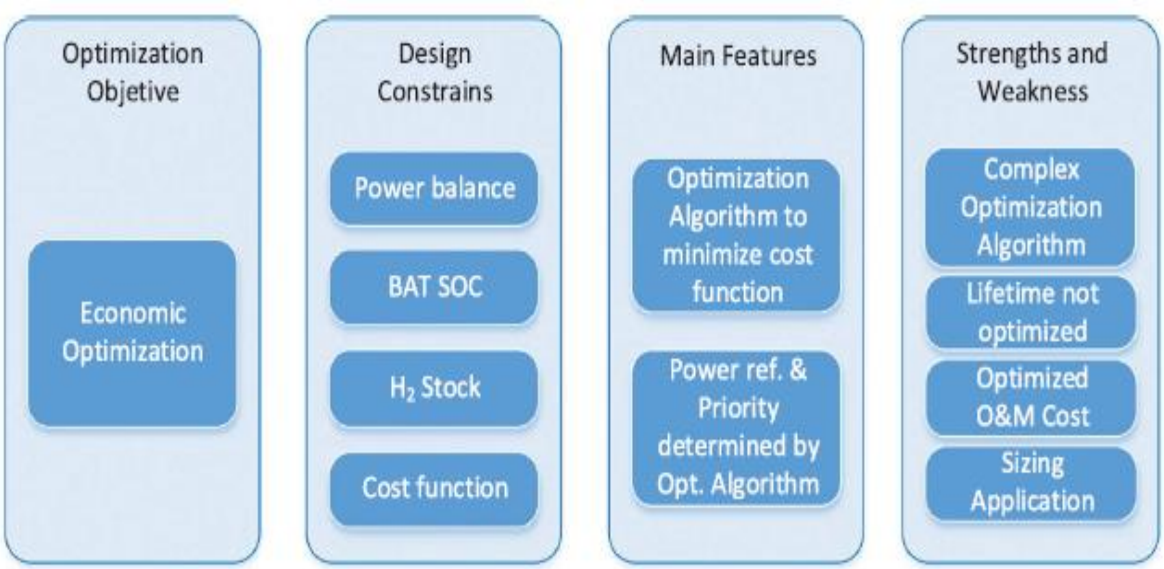


Figure 2.20: Main characteristics of economic objectives strategies [76]

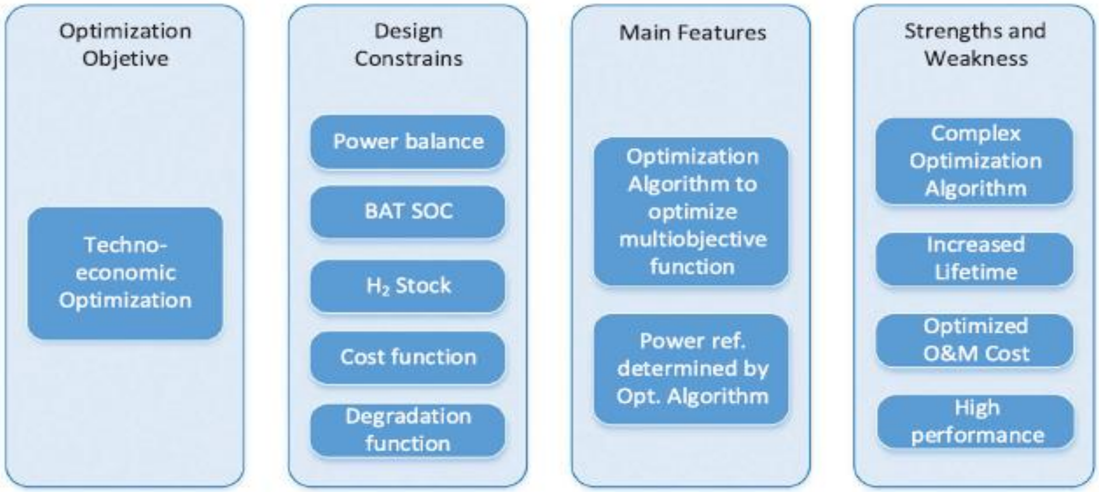


Figure 2.21: Main characteristics of techno-economic objectives strategies [76]

II.6.3 Techno-economic objective strategy

This strategy is based on nonlinear optimization to solve multi objectives function and includes the technical and economic parameters. The advantage of this strategy is to increase the technical parameter like performance and lifetime of the component through the decrease of economic parameter like global cost (figure 2.21) [90]. The main used methods in this strategy are based on algorithms such as fuzzy logic [184] and particle swarm optimization (PSO) [205]. However, many other methods are used in this strategy like flow chart [206] and linear Programming [207], HOMER software [208]. The table below descript in details management methods uses for the hybrid system.

Table 2.7: Management methods review

System components	Optimization objective	Algorithm uses	Ref.
Technical objective			
PV/WT/FC/Battery	Ensure demand Improve lifetime	Fuzzy logic	187
WT/FC	Ensure demand Improve lifetime	Flow chart	188
PV/WT/Battery	Ensure Demand Increase Performance Increase lifetime	Flow chart	189
PV/WT/FC	Ensure Demand Stability	Differential Flatness Based Control	190
PV/FC/Battery	Ensure Demand Maximize H_2 generation	Fuzzy logic	191
PV/WT/FC	Ensure demand Improve lifetime	Model Predictive Control	192
PV/WT/FC/Battery	Ensure demand Improve lifetime	Artificial Neural Network Controller	193
PV/FC/Battery	Increase Performance	TRNSYS	194

	Increase lifetime		
Economic objective			195
PV/WT/FC	Ensure demand Cost reduction	Receding Horizon Optimization	197
PV/WT/FC/Battery	Ensure demand Cost reduction Sizing	Differential evolution algorithm	198
PV/FC/Battery	Ensure demand Cost reduction	Model Predictive Control	199
PV/WT/FC/Battery	Ensure demand Cost reduction	Mixed-Integer Linear Programming	200
PV/FC/Battery	Ensure demand Cost reduction	Flow Chart	201
PV/WT/FC/Battery	Ensure demand Cost reduction	Fuzzy logic	202
PV/WT/FC	Ensure demand Cost reduction	Interior Search Algorithm	203
PV/WT/FC	Cost reduction	HOMER	204
Techno-economic objective			
PV/WT/Battery/hydrogen	Cost reduction Optimal capacity sizing	Fuzzy logic	184
PV/WT/FC/Battery	Ensure demand Cost reduction Increase Lifetime Increase Performance	Particle swarm optimization (PSO)	205
PV/WT/FC/Battery	Ensure demand Cost reduction Increase Lifetime Increase Performance	Flow Chart	206
PV/WT/FC/Battery	Ensure demand Cost reduction Increase Lifetime	Flow Chart and Linear Programming	207
PV/WT/Battery	Cost reduction Increase Performance Ensure demand	HOMER	208

II.7 Conclusion

In the end of this chapter, there are a lot of parameters on hybrid systems requiring optimization of sizing form to control and manage power output; however, the two main used criteria are technical and economic objectives. Recently, the mainly used method by the researcher is genetic algorithm because of the efficiency and the ability to minimize complex problems. With genetic methods, there is also a commercial software for sizing, control and optimizing the hybrid system, including facility and low time in the simulation.

In management methods, most articles published in the last years were focused on an economic and technical objective due to their importance for standalone and connected on grid systems

Next chapter focuses on sizing the hybrid system using two different methods with a full description of a rural village consumption. Also, a full comparison between two sizing methods' results were achieved.

Chapter III

Sizing hybrid system component

The third chapter focuses on sizing the components of the hybrid system. First, description is made on a rural village demand in high and low seasons, then the hybrid system generators are sized using two different methods; the first one is a modified classical method and the second one uses a commercial software. This chapter is finished by a comparison between these methods

III.1 Introduction

Sizing the hybrid system generators is the first step to install any new hybrid system. A lot of methods are used to obtain optimum sizes like genetic methods, commercial software or classical methods. During the last years, sizing hybrid systems by using and comparing different methods, is the most technique used by the researcher to obtain the finest structure with high performance and low cost.

In this chapter the elements of the used hybrid system in this study are described. The size of each element is determined using two different methods; the first method uses commercial software HOMER PRO, the second one is a modified classical method.

This chapter is finished by a technical, economic and environmental comparison made between these two methods.

III.2 Description of hybrid system

III.2.1 Description of load profile

The demand of electricity in a rural village is not high compared to an urban city, because the used power in a rural village is limited to domestic use, agriculture use, community services (schools, administration...etc), small business (blacksmith, food...) and local industry (cold storage, electrical mill…).

In this work we consider the load profile demand of a rural village situated in Algerian-Malian frontier (southwest Algeria) named 'Timiaouine'(figure3.1). 4492 habitant live in this rural village, , 2185 female and 2307 male, the annual growth rate is 0,7% according to 2013 statistics, only 0,4% of the population has a tertiary education [209,210]. Table 3.1 describes this rural village on details:

Table 3.1 Description of Timiaouine city [209]

	Numbers installed in the city
Name	Timiaouine
Latitude	20.9°N
Longitude	1.7°E
Altitude	491 m
Area	12553 km^2
Population	4492
House	450
Primary school	4
Middle school	1
Masjid	1
Administrative building	3
Polyclinic	1

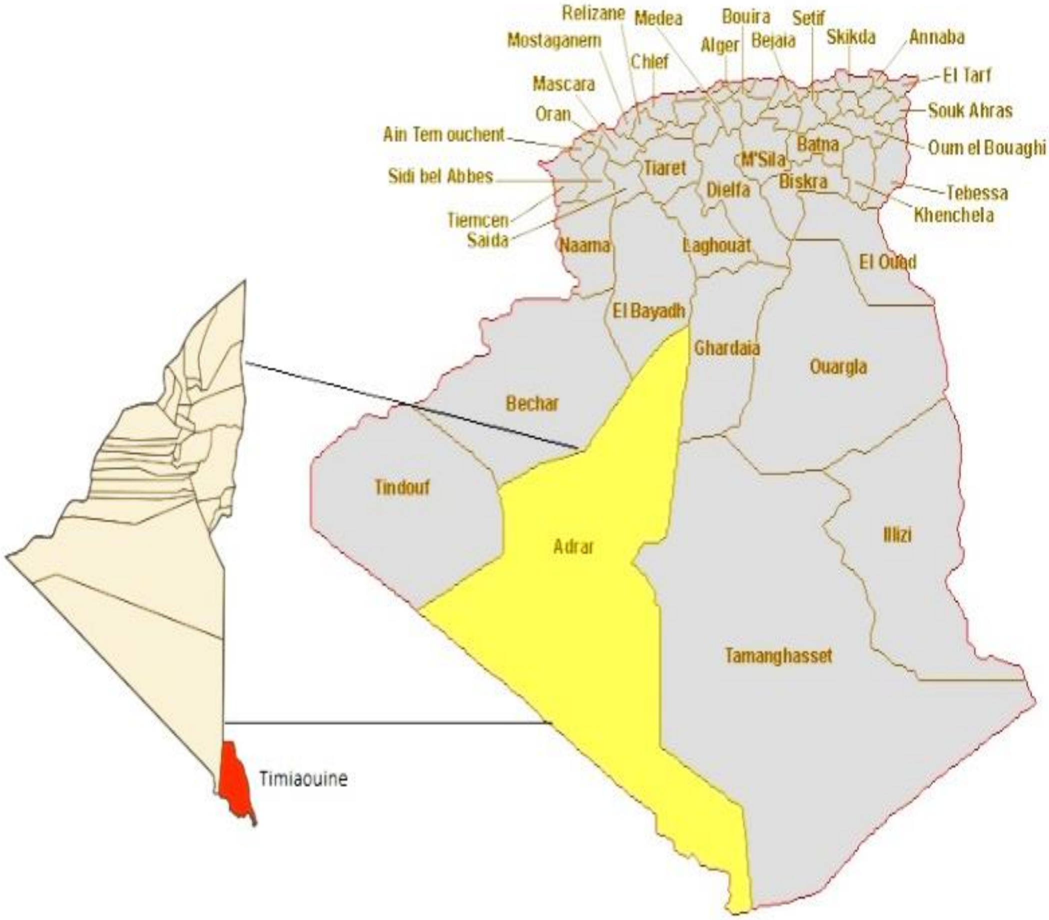


Figure 3.1 Situation of Timiaouine village in Algeria maps [211, 212]

The electrical demand of the rural village was estimated every hour during one year. This estimation is based on a deep sociological, economical and electrical study. The data were obtained from the Algerian Corporation of Electricity and Gas (SONELGAZ) [213]. The demand is divided into two main seasons:

1- Season of low use (Winter season: October to Mars): it is characterized by:
   - Low electrical demand
   - Low fuel demand due to the availablity of the renewable resources to cover power demand what limits diesel generator use.
2- Season of high use(Summer season: April to September): it is characterized by:
   - High pic demand
   - High fuel demand because of a high diesel generator use to cover pic demand.

A- Houses consumption

The considered houses in this study are traditional building installed in Adrar province composed of three rooms, kitchen and two bathrooms. Figure 3.2 shows different faces of house sample installed in the rural village from ASSALAH office for studies and research project-Adrar.

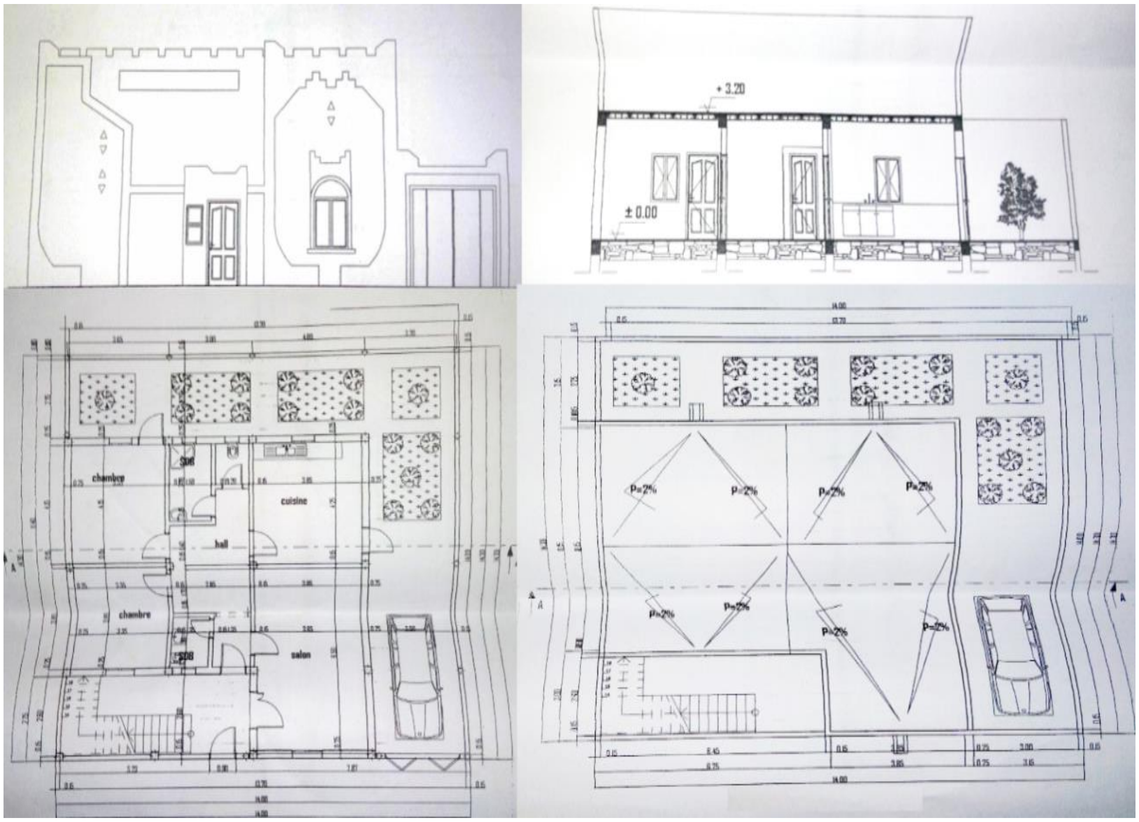


Figure 3.2 Sample of the house installed in a rural village

Table3.2 illustrates the main appliances available in any house and the consumption of each one in both winter and summer seasons.

Table 3.2 Description of appliance uses in house

	Power (W)	Number	Winter season (Hrs./day)	Total consumption (Wh)	Summer season (Hrs./day)	Total consumption (Wh)
Bulb economic	45	6	5	1350	5	1350
Bulb halogen	75	5	5	1875	2	750
Refrigerator 250 L	150	1	24	3600	24	3600
Television + sat reserved	150+ 100	2	4	1000	5	2500
Computer	80	1	3	240	5	400
Ironer	1200	1	1	1200	1	1200
Dryer	1300	1	1	1300	1	1300
Washer machine	2000	1	1	2000	1	2000
Kitchen appliances	800	2	1	1600	1	1600

Pump	1000	1	1	1000	1	1000
Air conditioner (12000BTU)	1300	2	0	0	12	31200
Total	**8050**	**23**	**46**	**16165**	**58**	**44900**

According to the above table, the appliances demand in winter is mainly for light and refrigerator (21% and 24% respectively, figure 3.3). To reduce this consumption, some researchers consider that refrigerator works for 8 hours per day. In summer, the main demand is for air-conditioner due to high temperature (figure 3.4).

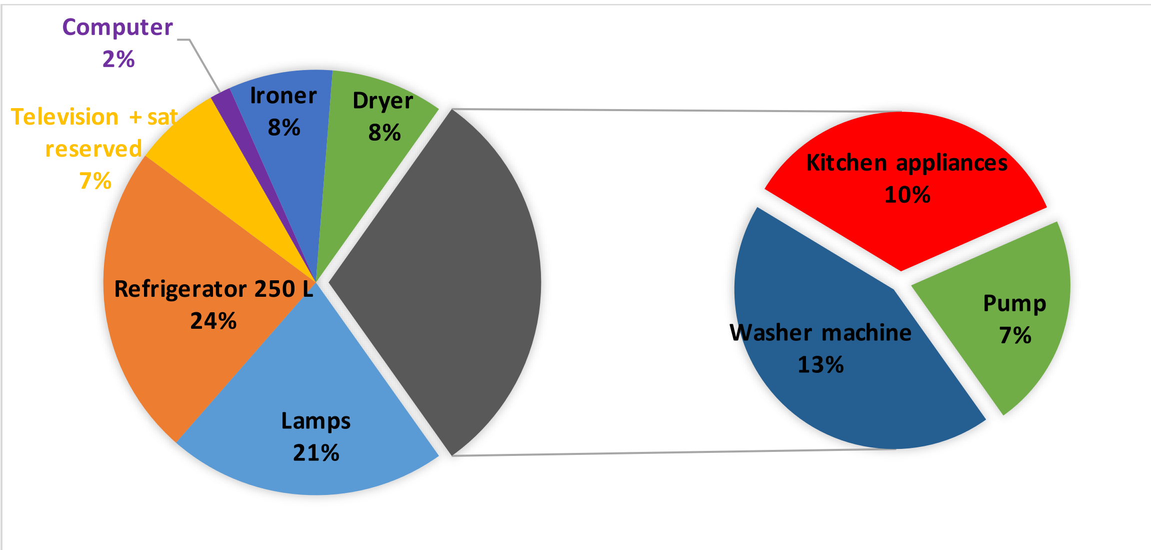


Figure 3.3 Distribution of used appliance in winter

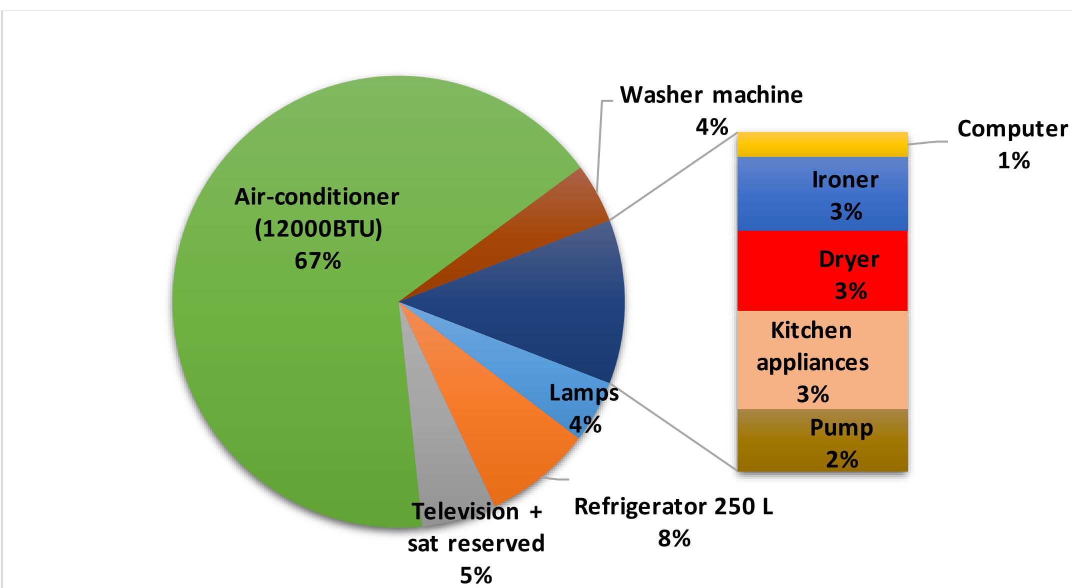


Figure 3.4 Distribution of used appliance in winter

During the winter season, the demand starts one hour earlier than summer season due to the difference in sunrise time between both seasons. Also in winter, demand grows with time and reaches the highest value (2,65 kWh) at 6:00 PM at sunset (figure 3.5).

During the summer season, the demand grows with time and reaches the value of 4,33kWh between 10 PM and 11 PM and the pick value of 4,75 kWh at 16h. This high value resulted from the strong use of air-conditioner due to high temperature noticed at this day time (figure 3.5).

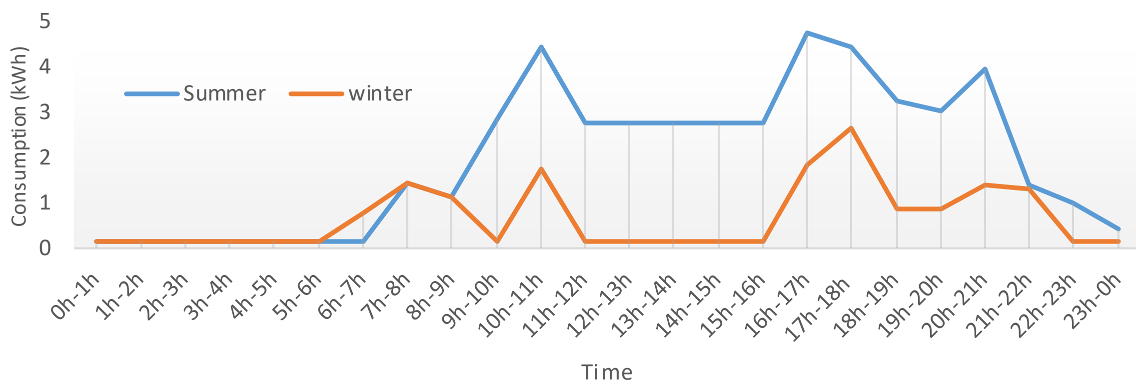


Figure 3.5: House demand per hour both during winter and summer seasons

B- Primary and middle school

In Timiaouine, there are four primary schools with 400 students' capacity including:

- 20 classrooms
- teacher class
- 2 offices
- 2 bathrooms

With a capacity of 900 students, the middle school includes:

- 30 classes
- Teachers class
- 4 offices
- 2 bathrooms
- 2 laboratories
- Computer lab.

All possible installed appliances in schools are listed in the next table:

Table 3.3 Description of used appliances in the school

	Power (W)	Number	Winter season (Hrs./day)	Total *consumption* (Wh)	Summer season (Hrs./day)	Total *consumption* (Wh)
Primary school						
Economic bulb	45	85	5	19125	5	19125
Halogen bulb	75	5	14	4875	10	3750
Computer	80	3	7	1680	5	1200

Photocopy	1600	1	1	1600	1	1600
Printer	950	1	1	950	1	950
Air conditioner (12000BTU)	1300	24	0	0	5	156000
Total	**4050**	**119**	**28**	**28230**	**27**	**182625**
Middle school						
Economic bulb	45	140	7	44100	3	18900
Bulb halogen	75	10	13	9750	10	7500
Computer	80	15	7	8400	7	8400
Air conditioner (12000BTU)	1300	40	0	0	7	364000
Photocopy	1600	1	2	3200	2	3200
Printer	950	1	2	1900	2	1900
Total	**4050**	**207**	**31**	**67350**	**31**	**403900**

In schools, the energy demand increases at study time and decreases during lunchtime and at night (figure 3.6). During the summer season, the school consumption increase in two period and consume more energy compared to winter due to uses of air-conditioner and ventilator. Next figure summarizes the power demand of schools:

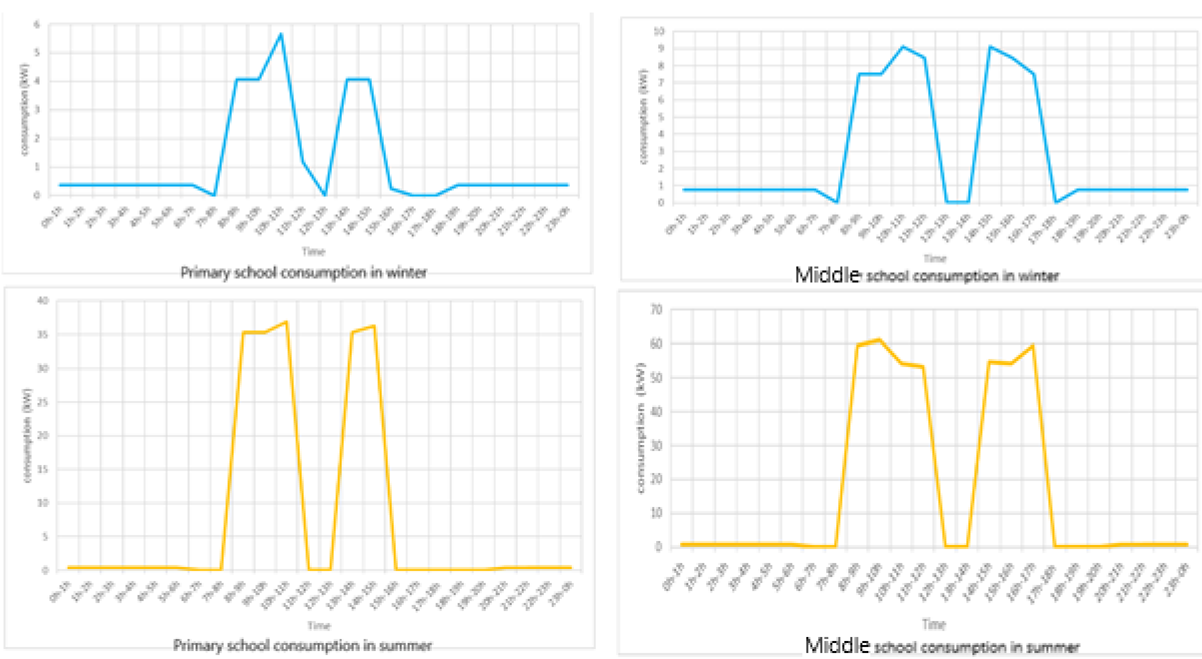


Figure 3.6: Demand per hour of primary and Middle school during winter and summer seasons

C- Masjid

The demand for masjid is high during prayer time (five times per day), during one hour for each prayer, as shown in figure 3.7

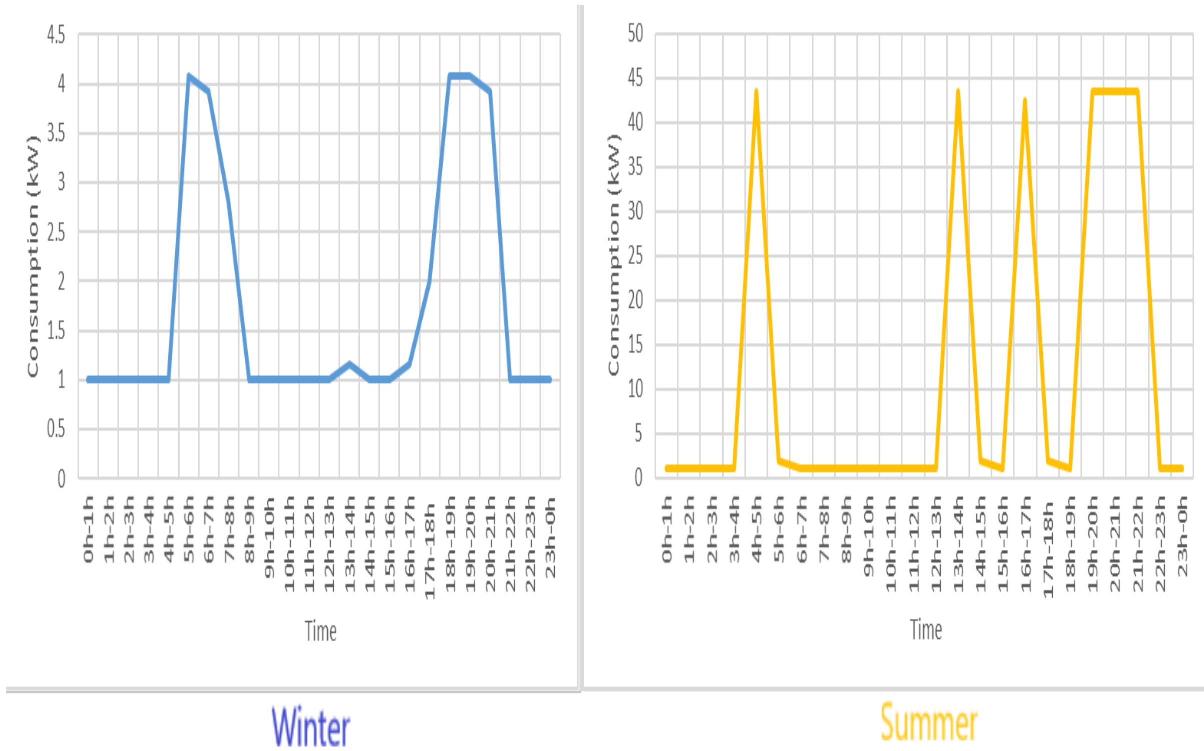


Figure 3.7: Power demand by Masjid per hour during winter and summer seasons

During the winter season, the power demand increases during three periods; after sunrise (Fajr prayer), in middle of the day (Dohre prayer) and begins to increase after Asser prayer up to sunset (Maghrib and Ichaa prayers), reaching more than 4 kWh. During this season, high power demand is noticed at four periods reaching high power values due to the use of ventilator, air-conditioner and fountain. The below listed equipment in the Table3.4 may be installed in masjid:

Table 3.4 Installed equipment in Masjid

	Power (W)	Number	Winter season (Hrs./day)	Total consumption (Wh)	Summer season (Hrs./day)	Total consumption (Wh)
Bulb economic	45	40	6	10800	6	10800
Bulb halogen	75	15	5	5625	5	5625
Sound Amplifier	400	1	2	800	2	800
Pomp	1000	1	1	1000	3	3000
Fountain	100	15	24	24000	24	24000
Air conditioner (18000BTU)	2100	40	0	0	6	189000
Fan	200	10	0	0	6	48000
Total	**3920**	**122**	**38**	**42225**	**52**	**281225**

D- Administrative building

In a rural village there are town halls, post office, SONELGAZ office, youth hall…etc, and all these buildings are small and require the lowest power demand in "Timiaouine" as shown in Figure 3.8.

For previously mentioned users, and during the winter season, the power demand remains low during working period and grows up to the maximum value of 1,6 kW, however during the summer season, this value grows up to 7,28 kW three times per day (figure 3.8) due to high temperature in this area. Many appliances that may be used in any administration building are listed in the table 3.5 below.

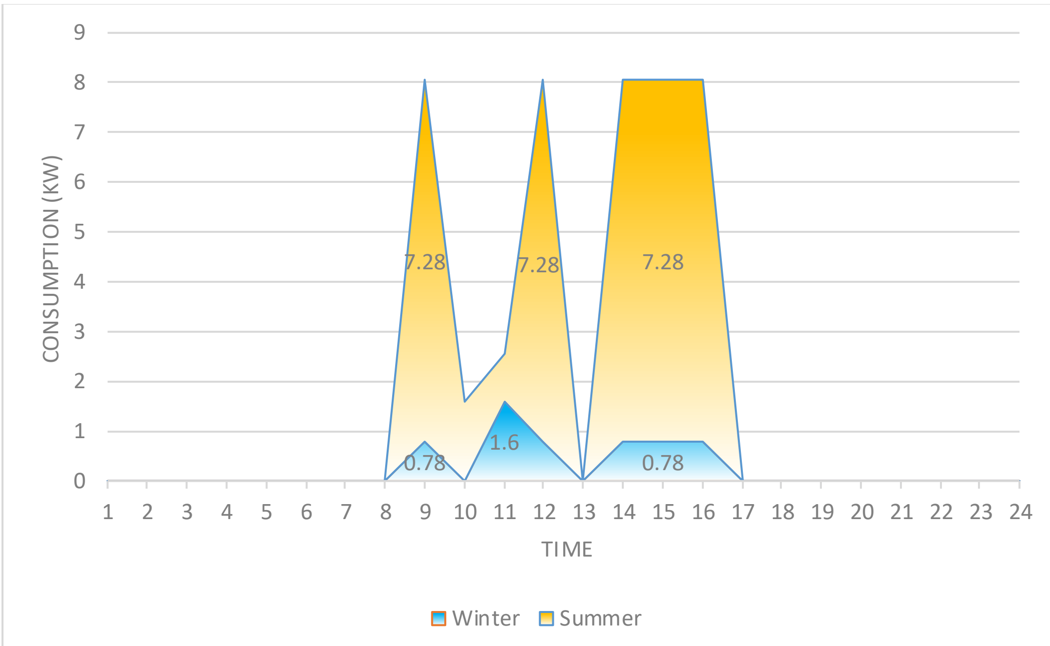


Figure 3.8: Administration building power demand per hour

Table 3.5: Installed equipment in the administration building

	Power (W)	Number	Winter season (Hrs./day)	Total consumption (Wh)	Summer season (Hrs./day)	Total consumption (Wh)
Bulb economic	45	12	7	3780	7	3780
Computer	80	3	7	1680	7	1680
Photocopy	1600	1	1	1600	1	1600
Printer	950	1	1	950	6	950
Air conditioner (12000BTU)	1300	5	0	0	6	45500
Total	**3975**	**22**	**16**	**8010**	**27**	**53510**

E- Polyclinic

Considering the small population, small polyclinic is installed in the rural village. The available appliances are summarized in table 3.6.

Table 3.6: Installed equipment in the polyclinic

	Power (W)	Number	Winter season (Hrs./day)	Total consumption (Wh)	Summer season (Hrs./day)	Total consumption (Wh)
Bulb economic	45	15	7	4725	8	4725
Sterilizer	600	1	2	1200	2	1200
Computer	80	2	3	480	4	640
Air conditioner (12000BTU)	1300	7	0	0	8	72800
Total	**2025**	**25**	**12**	**6405**	**22**	**80040**

F- Town use

After demand estimation, an hourly repartition for all power load profiles is made based on the two points below:

1- Four experience years with consumers in Adrar.
2- The official report from the department of the operating system (OS) in Algerian Corporation of Electricity and Gas (SONELGAZ) [214]

Next table shows general demand in the rural village, at low and high demand season

Table 3.7: Electrical consumption of the rural village

	Number	Winter	Summer	Percentage (%)
		Global consumption (kWh)	Global consumption (kWh)	
Houses	450	7274,25	21105	93%
Primary school	4	112,920	730,5	3%
Middle School	1	67,350	403,9	2%
Masjid	1	42,225	281,225	1%
Administrative building	3	24,030	160,530	0.5%
Polyclinic	1	6,405	80,040	0.5%
Total	-	7527	22761,195	-

In the winter season, the demand increases one hour earlier compared to summer season due to the difference in sunrise time between both seasons. Moreover, in this same season, power demand increases up to 1200 kWh at 6:00 PM, i.e. sunset time. In summer, the power demand increases up to 2250 kWh compared to winter season (figure 3.9), due to the use of cooling devices (air-conditioner, ventilator, fountain…etc).

According to table 3.7 and in the winter season, general power demand in the rural village equals 7,5 MWh per day (low demand season), however, in the summer season, it equals 22,7 MWh per day. We notice that the power houses demand is the highest in “Timiaouine” area with 93%, the second highest demand is the schools demands with 5% (figure 3.10).

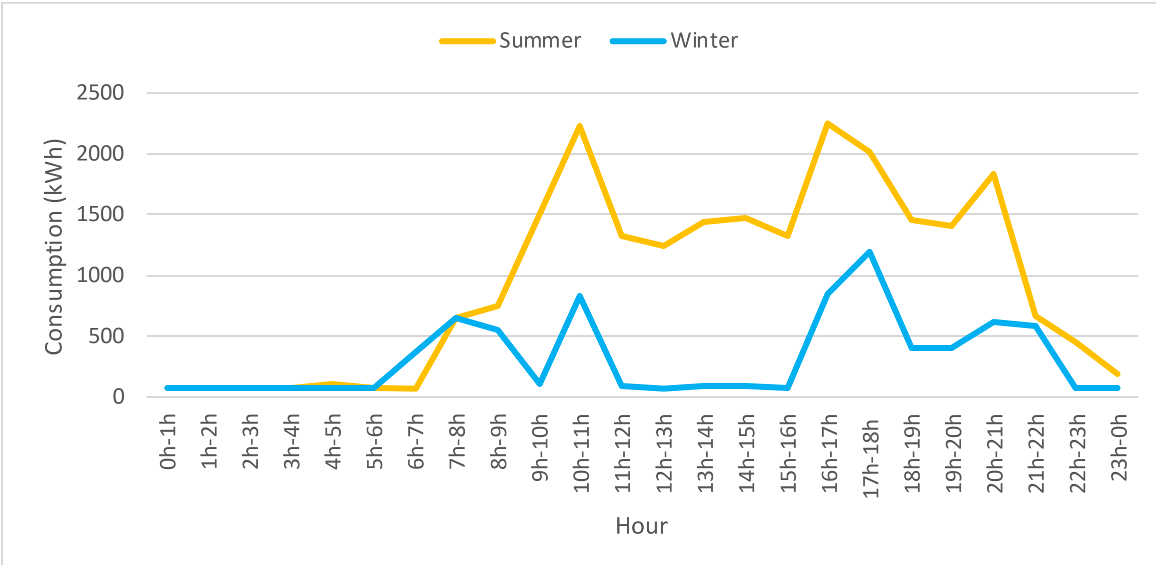


Figure 3.9: Power demand of rural village per hour in summer

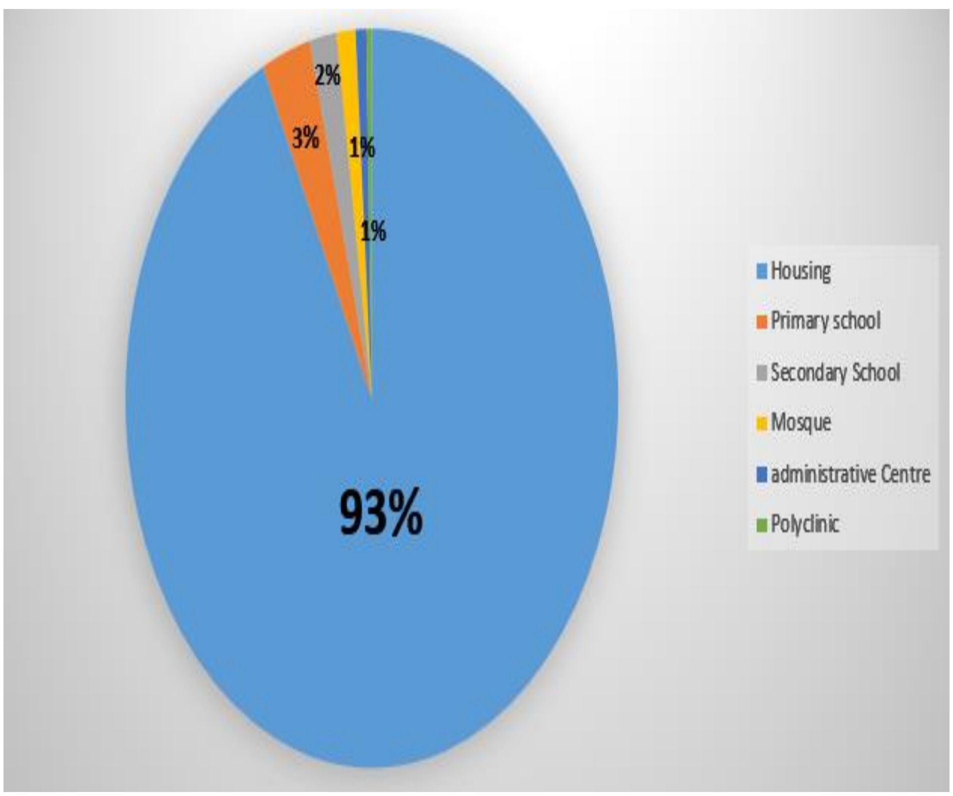


Figure 3.10: Distribution of rural village demand

III.2.2 Weather data

In Timiaouine village location, solar and wind resources data were given by The National Aeronautics and Space Administration (NASA) using METEONORM program. The meteorological data are 12 months hourly average values of considered 22 years (from 1983 to 2005).

In this rural village, the solar potential is characterized by high solar radiation throughout the year (figure 3.11), and high temperature in the middle of the year (Figure 3.1). Wind speed varies from 2m/s to 4,5m/s and reaches the pic value in the middle of the year (Figure 3.13). This makes that sizing the hybrid system is based more on favoring solar photovoltaic than wind turbine.

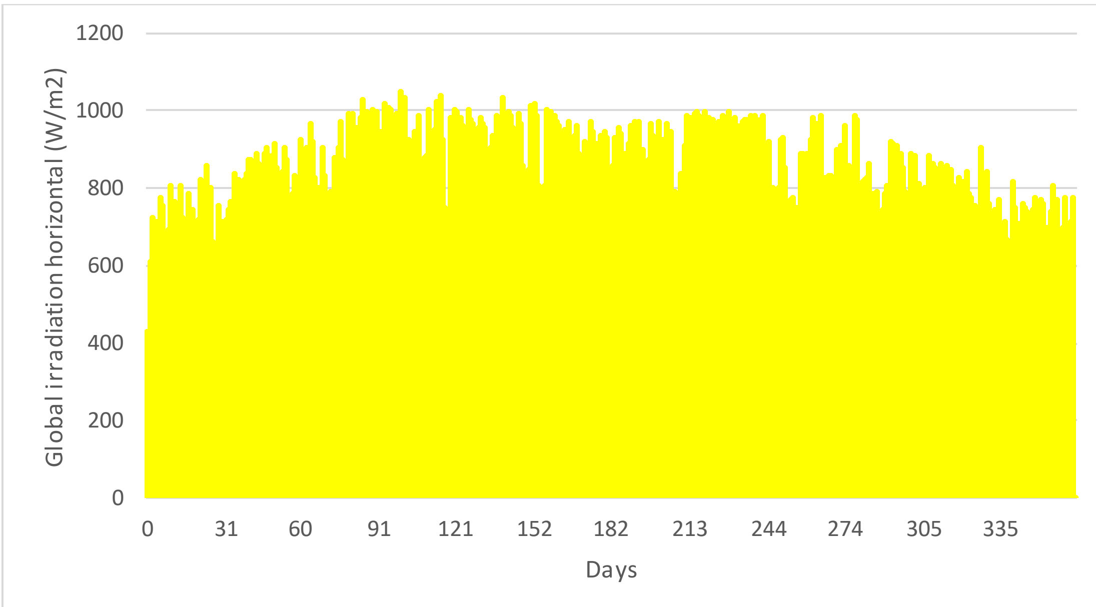


Figure 3.11: GHI in the rural village

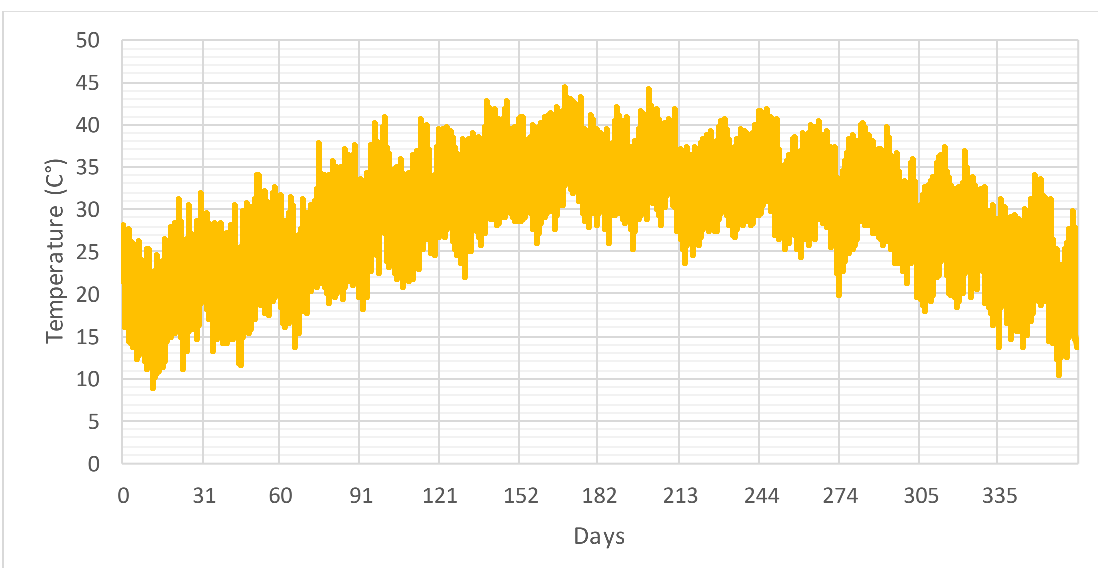


Figure 3.12: Temperature variation in the rural village

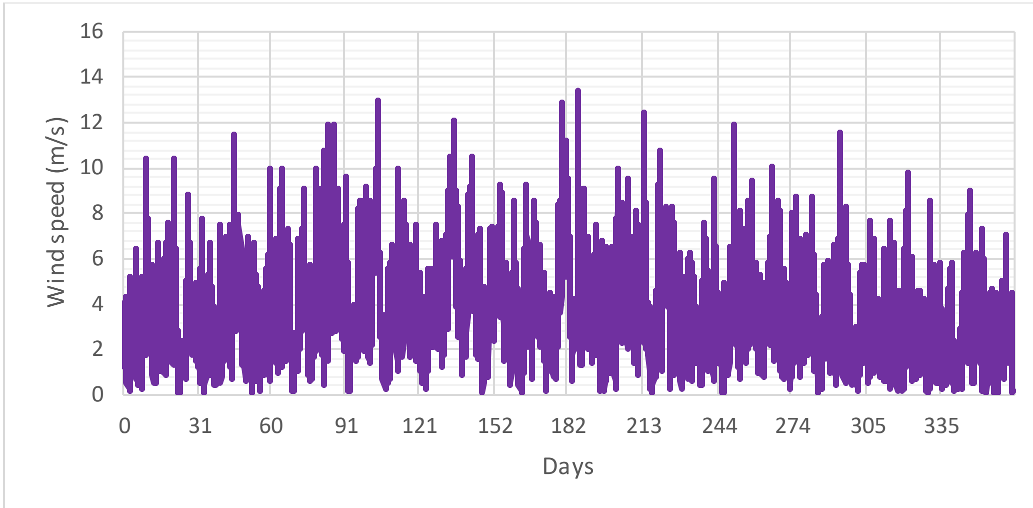


Figure 03.103: Variation of wind speed in a rural village

III.2.3 Generators of hybrid system

In this study, the used hybrid system includes:

1- Solar photovoltaic
2- Wind turbine
3- Diesel generator
4- Converters (inverter and rectifier)
5- As in rural village, only alternative power is used, AC architecture is considered for power supply as shown in the next figure:

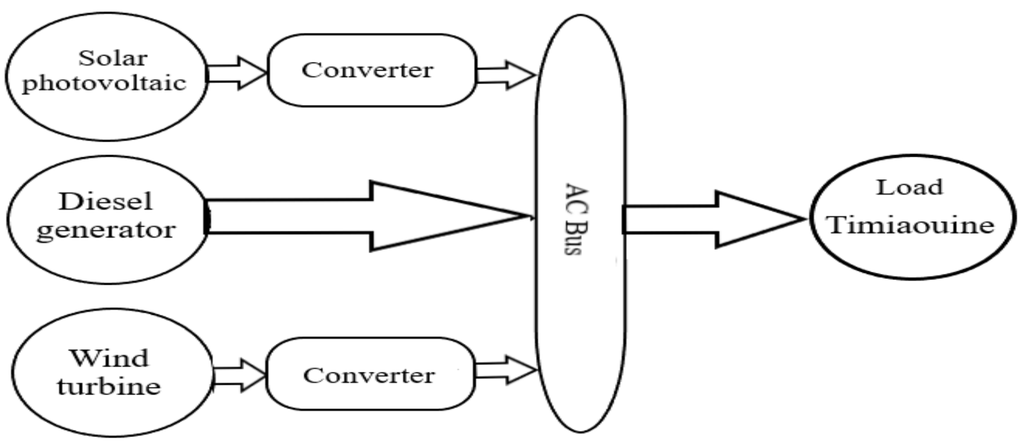


Figure 3.14: Architecture of the hybrid system

III.3 Sizing of the hybrid system

III.3.1 Using classical modified methods

A- Description of methods

In this study, power pic is used to size hybrid generator with two parameters; correlation coefficient (CC) and energy complementarity (R). Figure 3.15 illustrates the used method.

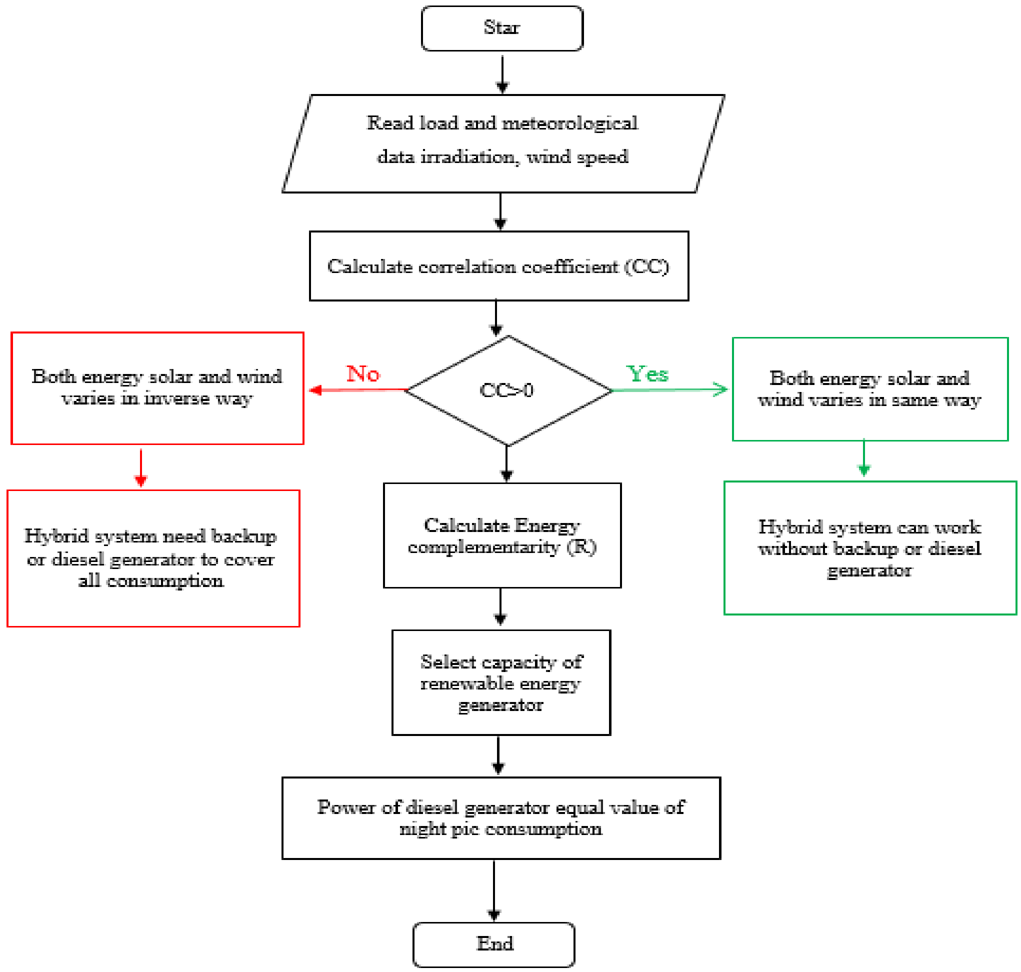


Figure 3.15: Flow chart of the used method in sizing hybrid system

The correlation coefficient (CC)

This is a method that checks the relation that may exist between two quantitative variables (x) and (y) [215]. In this study (x) is the wind energy and (y) is the solar energy. The correlation coefficient is given by:

$$\mathrm{CC} = \frac{\sum_{i=1}^{N}(y_i-\bar{y})(x_i-\bar{x})}{\{[\sum_{i=1}^{N}(y_i-\bar{y})^2][\sum_{i=1}^{N}(x_i-\bar{x})^2]\}^{\frac{1}{2}}} \tag{3.1}$$

Yi: daily average value of the solar energy for ' ' i ' ' months

Xi: daily average value of the wind energy for ' ' i ' ' months

$\bar{y}$: Annual average value of solar energy

$\bar{x}$: Annual average value of wind energy

The value of the correlation coefficient indicates that both solar and wind energy varies in an inverse way. The best value of CC is the nearest to (-1) because when solar potential increases, the wind energy decreases and vice versa which guarantees power source.

The figure 3.16 bellow shows a variation of two renewable potentials based on calculation as detailed in Table 3.8:

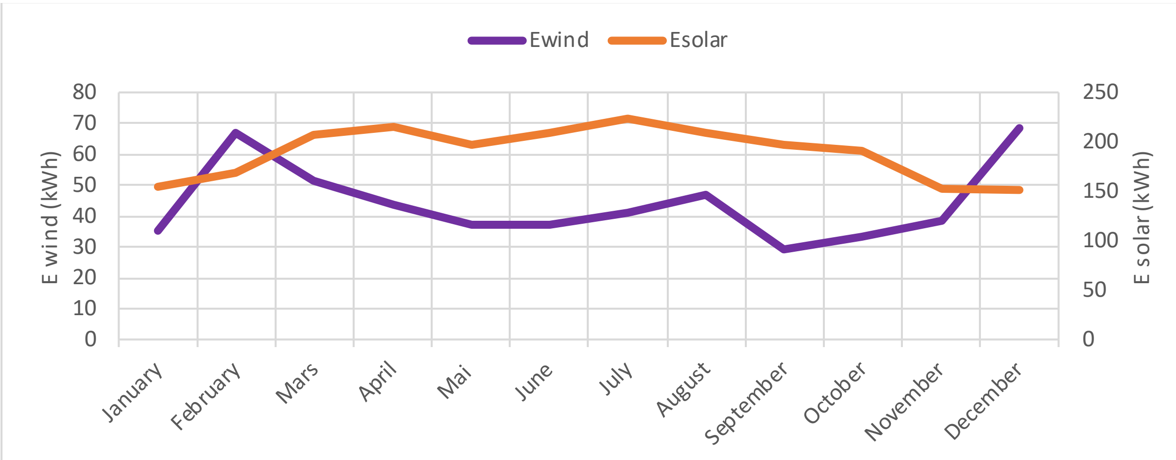


Figure 3.16: Monthly variations for solar and wind potentials

After the calculation of the correlation coefficient, it was noticed that this coefficient value equals (-0,3) and this means:

1- Both solar and wind potentials are available
2- They are an inverse relation between solar potential and wind potential, that ensure one renewable resource produce energy

Energy complementarity (R)

The energy complementarity is a link between the annual average value of wind energy and the annual average value of the solar power. The results are summarized in table 3.8:

$$R = \frac{\bar{E}_{wind}}{\bar{E}_{solar}} \quad (3.2)$$

Table 3.8: Solar and wind potentials values recorded through the year

Month	Power complementarity
January	0.221
February	0.395
March	0.248
April	0.201
May	0.187
June	0.176
July	0.182
August	0.223
September	0.148
October	0.175

November	0.249
December	0.452
Average	0.239

As a conclusion, the solar potential is 4 times powerful than wind potential. This former is used to operate renewable generators being more powerful than wind power. For the diesel generator, the main objective is to cover power demand at night. In case of power pic demand, this helps to meet pic power demand at night. The result of sizing is summarized in the next table:

Table 3.9: Description of hybrid system generator

Generators	Installation capacity (kW)	Percentage
Solar photovoltaic	2250	48%
Diesel generator	1850	39%
Wind turbine	600	13%

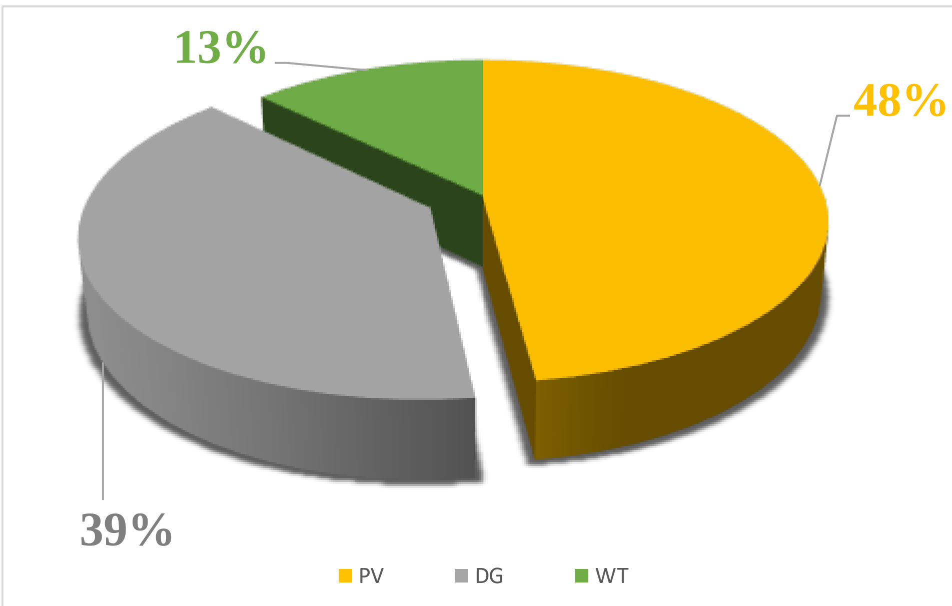


Figure 3.17: Distribution of hybrid system generators

After knowing the capacity of each generator, this specific parameter is used to calculate the number of solar photovoltaic panels (on series and parallel), surface covered by modules, cable section…etc. For wind turbine, we determine three parameters; length of pales, height of turbine and type of generator (PMSG, MADA…etc).

B- Solar photovoltaic:

<u>Orientation and tilt of photovoltaic panels</u>

The first step to be followed in the installation of photovoltaic field is to describe the tilt angle (It is the angle between the panel and the horizon) and orientation direction (to south, north…etc).
There are a lot of used methods to calculate optimal tilt angle like seasonal method [216], monthly method [217], GLADIUS model [218]…etc. The proposed equation to define annual tilt angle is given by [219]:

Optimal yearly tilt angle= Latitude of site+10°=20,9+10=30,9°
For orientation of panels, it is difficult and expensive to make all fields following sun and turn hundreds of square meters. A good compromise is to place the modules towards the equatorial [220].

Power crest of photovoltaic generator

To calculate the number of required panels to be installed for producing more than 2 MW we use the next equation:

$$N_{panels} = \frac{P_t}{P_{panel}} = \frac{2250000}{285} \approx 7894{,}73 = 7895 \qquad (3.3)$$

With:

- P_t: total power of solar photovoltaic field should produce (from sizing result are equal 2250 kW)
- P_{panel}: the power of one panel (equal to 285 kW)

All parameters of the installed panels are given in Appendix A.
The number of panels in series defines the output voltage of the system and the number of panels in parallel gives the output current. If the number of panels in series is high, this means that a chopper is required to increase output current. If the number of the panels in parallel is high, this means that a transformer should be installed to increase output voltage. In our case, we take 24 panels on series to obtain output voltage equal to 864V. we calculate the number of panels in parallel using the next equation:

$$N_P = \frac{N_t}{N_s} = \frac{7895}{24} \approx 328{,}95 = 329 \qquad (3.4)$$

- N_t: total number of panels
- N_s: number of series panels

To produce the nominal power of the solar photovoltaic field 7896 panels are needed; 329 strings and 24 panels each have to be installed (figure 3.18).

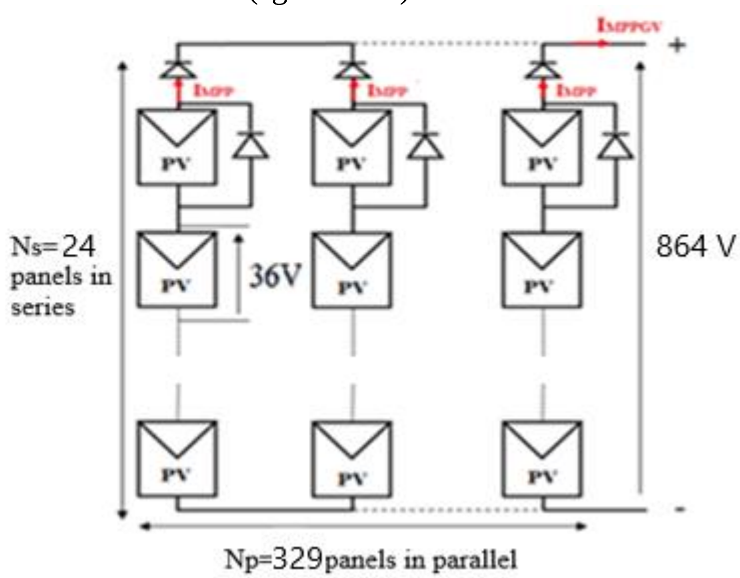


Figure 3.18: Connection of photovoltaic panels

The surface of solar photovoltaic field

The polycrystalline panels are known for their high efficiency and reliability in case of high temperature (appendix A). Next figure illustrates the number of connected cells, inside a panel, either in series or in parallel.

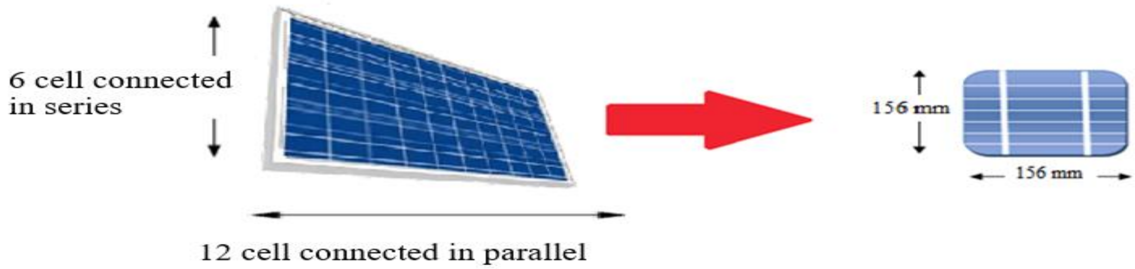


Figure 3.19: Model of the selected panel

The covered surface by one cell is calculated as below:

$$\left.\begin{array}{l} 6 \times 156\text{mm} = 936\text{mm} \\ 12 \times 156\text{mm} = 1872\text{mm} \end{array}\right\} \Rightarrow S_m = 936\text{mm} \times 1872\text{mm} = 1752192\text{mm}^2 = 1.75\text{m}^2$$

With S_m: suthe rface of cell inside one panel.
Hence, the total covered surface by all cells equal:

$$\left.\begin{array}{l} 24 \times 936 \text{ mm} = 22464 \\ 329 \times 1872 \text{ mm} = 615888 \end{array}\right\} S_T = 22464 \times 615888 = 13835.30 \text{ m}^2 \approx 1.38 \text{ Hectare}$$

The total covered surface by panels equal:

$$(1.956\text{m} \times 0.922\text{m}) \times 7896 \approx 14239.90\, m^2 \approx 1.4 \text{ Hectare}$$

C- Wind turbine

1- The first step to follow is to calculate turbine power using the following equation:

$$P_t = \frac{P_u}{\tau_g} = \frac{562,5}{0,8} = 703,125 \text{ kW} \tag{3.5}$$

With:

P_t: turbine power

P_u: utile power

τ_g: Efficiency of wind turbine equals generally 0.8

2- The second step to follow is to calculate the height of wind turbine:

$$V(h) = V(10) \times (\frac{h}{10})^{\alpha}. \tag{3.6}$$

V(h): wind speed at (h) height

V(10): wind speed at 10m

α: roughness coefficient and vertical evolution of wind speed. This coefficient value is between 0.1 and 0.4, as shown in the next table:

Table 3.10: Variation of coefficient roughness according to site location [221]

Nature of site	α
Plate: ice, snow, sea, swamp, short herbs	0.08 à 0.12
Little rugged: field and grazing, culture	0.13 à 0.16
Rugged: wood, little occupied areas (rural village, small vile…etc)	0.20 à 0.23
Very rugged: towns	0.25 à 0.40

Next figure shows the variation of noise according to the height of the wind turbine

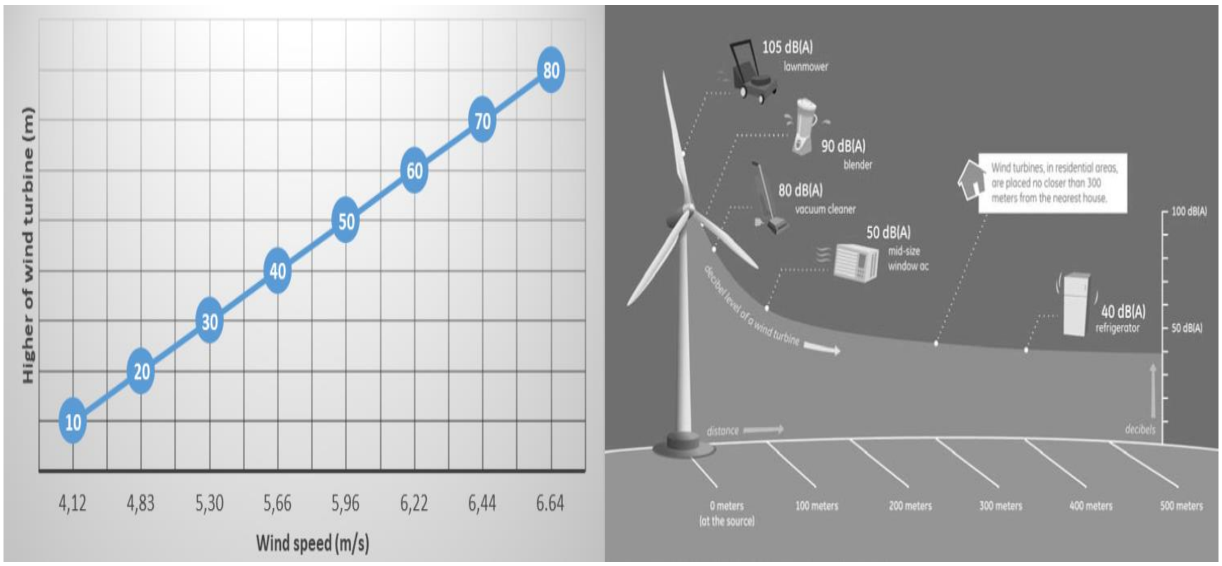


Figure 3.20: Variation of wind speed in left and relation between noise and a high wind turbine in the right [222]

3- The third and last step to follow is to calculate the brushed surface by blades using the equation bellow:

$$S = \frac{P_t}{\frac{1}{2}\times\rho\times C_p\times V^3} = \frac{703{,}125 \times 10^3}{\frac{1}{2}\times 1{,}225\times 0{,}48\times 6.64^3} = 8169{,}22\mathrm{m}^2 \quad (3.7)$$

With:

S= brushed surface by blades

ρ: Air density

C_p: Maximum power coefficient

V: wind speed

The radius of the surface brushed by blades (or length of blades) is given by the following equation:

$$R = \sqrt{\frac{S}{\pi}} = \sqrt{\frac{8169,22}{3,14}} = 51 \text{ m} \tag{3.8}$$

D- Diesel generator

In this study, the used diesel generator is characterized (Appendix B) by power output that equals 1850 kW and covers demand in two cases:

1- No renewable resource (night)
2- Pic demand

In these two cases, renewable generators (solar photovoltaic and wind turbine) will not cover demand. The objective of this strategy is:

- Limiting dioxide carbon emission
- Extending the lifetime of diesel generator
- Limiting the use of fuel by using a renewable resource

E- Converter

The rated power of the inverter should be lower than the pic power of the photovoltaic generator. As sizing system considers pic power demand, calculation of the rated power of the inverter is made by using next the equation [223]:

$$P_{inv} = \frac{P_{pv}}{\eta_{inv}} \tag{3.9}$$

With η_{inv} is the efficiency of the inverter (between 0.9 to 0.95 [224])

There is another method to calculate the rated power of the inverter by using its lower and upper efficiency. This is shown below [225]:

$$(P_{PV} \times 0.9) < P_{inv} < (P_{PV} \times 0.95)$$

III.3.2 using commercial software

Considering simplicity and efficiency, HOMER PRO software is used to size the generator of the hybrid system, the results are compared with the previously obtained results using modified classical methods.

A- Solar photovoltaic

Timiaouine is characterized by high solar potential, according to meteorological data presented previously. HOMER PRO calculates photovoltaic generator for receiving the maximum power, and also covering the power demand. The cost of one kWh, the replacement and the maintenance are approximately 1100 €, 1100 € and 10 € respectively, and the lifetime system is 25 years.

B- Wind turbine

Considering low wind speed, wind turbine presented in Appendix B is used. the acquisition cost of such a turbine is 0,17 M€, which is similar to replacement, however, maintenance costs is 1700€.

C- Diesel generator

A Diesel generator is used additionally in case of weak or absence of energy production from renewable generators (solar or wind). The initial cost for producing one kWh is 500 €, similar to replacement cost, however, maintenance costs is 0.03 €, for 15000 hours lifetime.

D- Converter

Economically, the cost of one kWh is 300 € and the same for replacement after 15 years lifetime. Technically speaking, the converter will be connected only to the solar photovoltaic system, because it is the only generator producing DC power. All sizing results using HOMER PRO software are summarized in the next table:

Table 3.11: Result of sizing using HOMER PRO

PV array parameter	
Technology	Condor polycrystalline
Capital cost	1100 €/Kw
Efficiency	13%
Lifetime	25 years
Power installed	2500 kW
Wind turbine	
Technology	ENERCON-E44
Capital cost	0.17 M€
Power	600 kW
Hub height	65m
Lifetime	14 years
Number of wind turbine installed	13
Diesel generator	
Capital cost	500 €/ kW
Power	2000 kW
Lifetime	15000 Hours
Converter	
Capital cost	300 €/ kW
Power	1600 kW
Lifetime	15000 Hours

III.4 Comparison between sizing methods

After sizing the hybrid system using two different methods, some differences are noted in the obtained results as follows:

- The results show that the size of the renewable generator is higher in HOMER PRO than in classical modified method.
- Classical method design hybrid system to limit use and capacity of the diesel generator, however, this is not found in HOMER PRO.
- It is also noted that the size of the inverter in HOMER PRO is lower than in classical method.

Table 3.12: Comparison between sizing methods

	HOMER PRO	Classical methods
Solar photovoltaic system	2500 kW	2250 kW
Wind turbine	13*600 kW	1*600 kW
Diesel generator	1900 kW	1850 kW

III.5 Conclusion

At the end of this chapter, we conclude that there are many methods for sizing the hybrid system. In this study, two methods are used; the first one is the classical modified method and the second one is by using the commercial software HOMER PRO.

On one hand, the results show that there are differences in the generator capacity of each method that makes the obtained environmental results using commercial software better than those obtained in classical modified methods. On the other hand, and economically speaking, the classical method was better. It is also beneficial in terms of the environment, considering the low capacity of the generator and low used fuel.

In the next chapter, generators and power converters of the hybrid system are defined and described by mathematical models.

Chapter IV Modelling of hybrid system component

After sizing the hybrid system in the previous chapter, we focus in this chapter on describing the hybrid system components starting by the definition of each one, then the definition of different mathematical used equations used in modeling of components

IV.1 Introduction

Modeling of hybrid system components (generators and power converters) makes analysis possible by obtaining simulated values under various meteorological data (temperature and global irradiation). There are various mathematical modeling approaches used for analyzing hybrid power systems (logistic and dynamic), in this hybrid system we use the logistic system because time series of meteorological data change every hour (time-series model).

This chapter was divided on four principal sections:

- Solar photovoltaic
- Wind turbine
- Diesel generator
- Power converter

Also, we describe mathematical models for each component of the hybrid system (generators and converter). These mathematical models will help us in analyzing and understanding generally the hybrid system and so also each part production.

IV.2 Solar photovoltaic system

IV.2.1 Definition

The original photovoltaic term is an action of physics also named "photo effect". It is main power transformation from photon to electron contained inside material [225]. Generally, we define photovoltaic as the use of semiconductors materials to transform sunlight into electricity [7].

IV.2.2 Structure of photovoltaic cell

The basic structure of a photovoltaic cell consists of p-conducting base material and an n-conducting layer on the topside. The entire cell at rear side is covered with a metallic contact, however, the irradiated side is equipped with a finger-type contact system to minimize shading losses. Full cover and transparent conductive layers also are used (figure 1). [225]

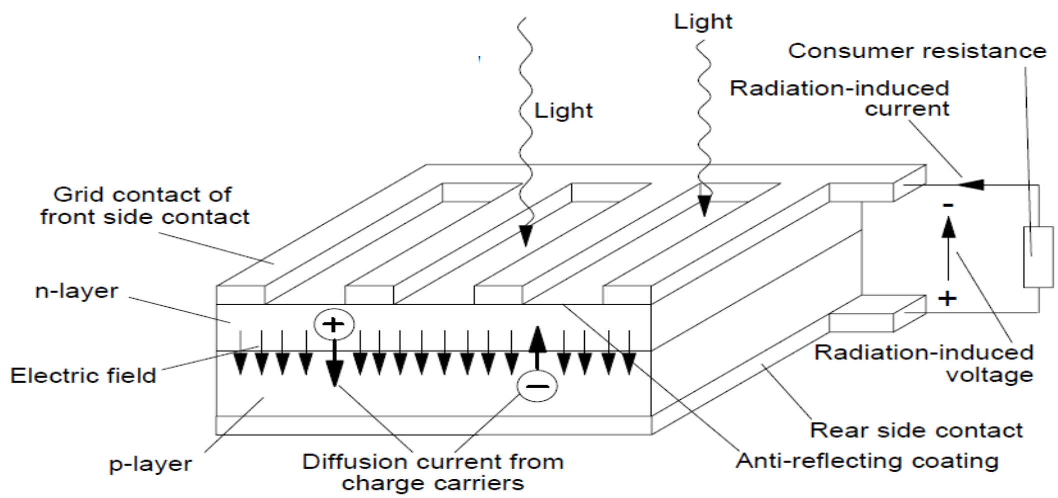


Figure 4.1: Structure of a typical solar cell [225]

IV.2.3 mathematical models

They are many mathematical models for solar photovoltaic. This part summarizes the main used models:

A- First model

The first model is based on the solar irradiation data to calculate solar photovoltaic output power by using the following equation [226]:

$$P_{PV} = \eta H_T A \text{ and } H_T = H_b R_b + H_d R_d + (H_b + H_d) R_r \tag{4.1}$$

With:

P_{pv}: is power output of solar photovoltaic

η: efficiency of solar photovoltaic

H_T: total hourly solar radiation

A: surface area of solar photovoltaic

H_b: the beam part of solar radiation (kWh/m^2)

R_b: tilt factors for beam radiation

H_d: diffused part of solar radiation (kWh/m^2)

R_d: tilt factors for diffused radiation

R_r: the tilt factor for reflected part of solar radiations.

B- ***Second model***

In 2014, Khatib and Elmenreich develop a new method to calculate power output of solar photovoltaic using six parameters (four technical parameters characterize equipment of system and two parameters characterize meteorological data) [227], which are:

1. Power peak of photovoltaic
2. Efficiency of inverter
3. Efficiency of cables
4. Temperature coefficient
5. Global irradiation
6. Ambient temperature

We describe this model using the next two equations as shown below [227, 228]:

$$P_{pv}(t) = \left[P_{peak}\left(\frac{G_t}{G_{stander}}\right) - \alpha_t[T_c(t) - T_{stander}]\right] \times \eta_{inv} \times \eta_{wire} \tag{4.2}$$

$$T(t) = T_{amb}(t) + \left(\left(\frac{NOCT - 20}{800}\right) \times G_t\right) \tag{4.3}$$

C- Third model [*229*]

This model calculates current and voltage of photovoltaic panel and so also solar field using next equations:

$$I_{ref} = I_{sc}\{1 - C_1[\exp\left(\frac{V_{ref}}{C_2 V_{oc}}\right) - 1]\} \quad (4.4)$$

I_{sc} : Short circuit current

V_{oc} : Open circuit voltage

I_{mp} : Maximum current output

V_{mp} : Maximum voltage output

V_{ref} : Referential voltage of the panel

With: $C_1 = \left(1 - \frac{I_{mp}}{I_{sc}}\right) e^{\left(\frac{-V_{mp}}{C_2 V_{oc}}\right)}$ and $C_2 = \frac{\frac{V_{mp}}{V_{oc}} - 1}{\ln(1 - \frac{I_{mp}}{I_{sc}})}$

To make previously cited equations change with different values of temperature and irradiation, we use bellow equations:

$$\Delta T = T - T_{ref} \quad (4.5)$$

$$\Delta I = \alpha\left(\frac{G}{G_{ref}}\right)\Delta T + (\frac{G}{G_{ref}} - 1)I_{sc} \quad (4.6)$$

$$\Delta V = -\beta\Delta T - R_s\Delta I \quad (4.7)$$

Where α and β are temperature coefficient of current and voltage respectively.

For varied temperature and irradiation, we use the new equation of voltage and current as seen below:

$$V_{new} = V_{ref} + \Delta V \quad (4.8)$$

$$I_{new} = I_{ref} + \Delta I \quad (4.9)$$

IV.2.4 Characteristic

- ***Current-voltage characteristic***

The current-voltage characteristics are illustrated in Figure 2. It describes the use of the photovoltaic cell under the influence of weather conditions (illumination level and ambient temperature). The curve of the solar cell I = f (V) is characterized by the below three important points (figure 4.30):

- Short circuit current in point “C”
- Open circuit voltage in point “F”
- Maximum power in point “A”

We note three zones in I(V) curve which are :

1. The first zone is situated between "C" point and "D" point, where the solar cell works as current generator proportionally with irradiation
2. The second zone is "EF", where the solar cell works as a voltage generator
3. The last zone is situated between "D" point and "E" point, which is an optimal zone, where solar cell has high value

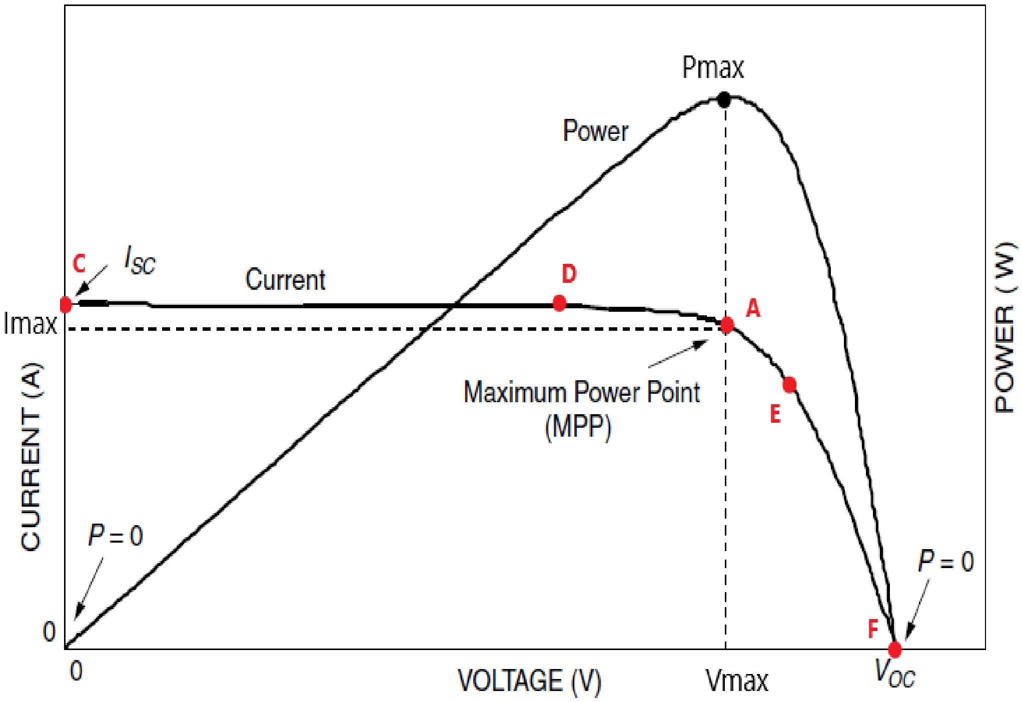


Figure 4.2: I(V) Curve of the solar cell [7]

- ***Efficiencies and losses***

Fill factor is the ratio of the power at the maximum power point level to the product of open circuit voltage **(**V_{OC}**)** and I_{SC} short circuit current as shown in next equation:

$$FF = \frac{\text{Power at the maximum power point}}{P_{opt}} = \frac{I_{max} V_{max}}{I_{sc} V_{oc}} \tag{4.10}$$

Fill factor value is between 70 and 75% for crystalline silicon solar modules and 50-60% for multi junction amorphous-Si modules [7]

Photovoltaic cell performance refers to the power conversion efficiency and is defined as the ratio of the maximum power delivered by the cell to the incident light power as illustrated in the next equation:

$$\eta_m = \frac{P_{max}}{P_{in}}$$

Many technologies were developed in such a way to optimize the efficiency of the solar cell as shown in the next table:

Table.4.1: Efficiencies of solar cells [225]

Material	Type	Efficiency (%)	
		LAB	**Manufacturing**
Silicon	Monocrystalline	24.7	14.0 – 18.0
Polysilicon, simple	Polycrystalline	19.8	13.0 – 15.5
MIS inversion layer (silicon)	Monocrystalline	17.9	16.0
Concentrator solar cell (silicon)	Monocrystalline	26.8	25.0
Silicon on glass substrate	transfer technol.	16.6	8.0
Amorphous silicon, simple	thin film	13.0	8.8
Tandem 2 layers, amorphous silicon	thin film	13.0	10.4
Tandem 3 layers, amorphous silicon	thin film	14.6	21.0
Gallium indium phosphate/ Gallium arsenide	tandem cell	30.3	10.7
Cadmium-telluride	thin film	16.5	12.0
Copper indium di-selenium	thin film	18.4	14.0 – 18.0

IV.3 Wind turbine

IV.3.1 Definition

The wind has been used as a source of power for thousands of years ago in order to fulfill some tasks such as driving ships, grinding, pumping water, and many other tasks. The wind turbine is a necessary part of wind system converting wind energy (or kinetic energy related to wind) to mechanical or electrical energy [10]. Recently, the wind turbine was classified as the fastest developed energy in the world with more than 838 TWh compared to solar photovoltaic with just 247 TWh in 2015 [230].

IV.3.2 mathematical models

They are two mathematical representations of the wind turbine. The first one is by calculating just power output using meteorological data and the second method is by modulating every part of wind turbine alone.

A- First model

This model is based essentially on the meteorological limit output power of wind turbine in defining interval as shown below [231]:

$$P = \left\{ \begin{array}{cc} 0 & (W_S < W_{in}, W_S > W_{out}) \\ \xi(W_S - W_{in})W_n & (W_{in} < W_S < W_{out}) \\ W_{rp}W_n & (W_{rs} < W_S < W_{out}) \end{array} \right\} \tag{4.11}$$

With:

W_s: wind speed

W_{in}: cut-in wind speed

W_{out}: cut-out wind speed

W_{rs}: rated wind speed

W_{rp}: rated power of the wind turbine

W_n: number of wind turbine installed

ξ: slope between W_{in} and W_{rs}

B- Second model

Also in this model, the output power of wind turbine was calculated using a produced characteristic, however in this model (figure 4.31), we used just wind speed as shown in next equation [232]:

$$P = \left\{ \begin{array}{cc} 0 & (W_S < W_{in}) \\ \frac{W_{rp} \times W_S^3}{(W_{rs}^3 - W_{in}^3)} - \frac{W_{in}^3 \times W_{rp}}{(W_{rs}^3 - V_{in}^3)} & (W_{in} < W_S < W_{rs}) \\ P_r & (W_{rs} < W_S < W_{out}) \\ 0 & (W_S > W_{out}) \end{array} \right\} \tag{4.12}$$

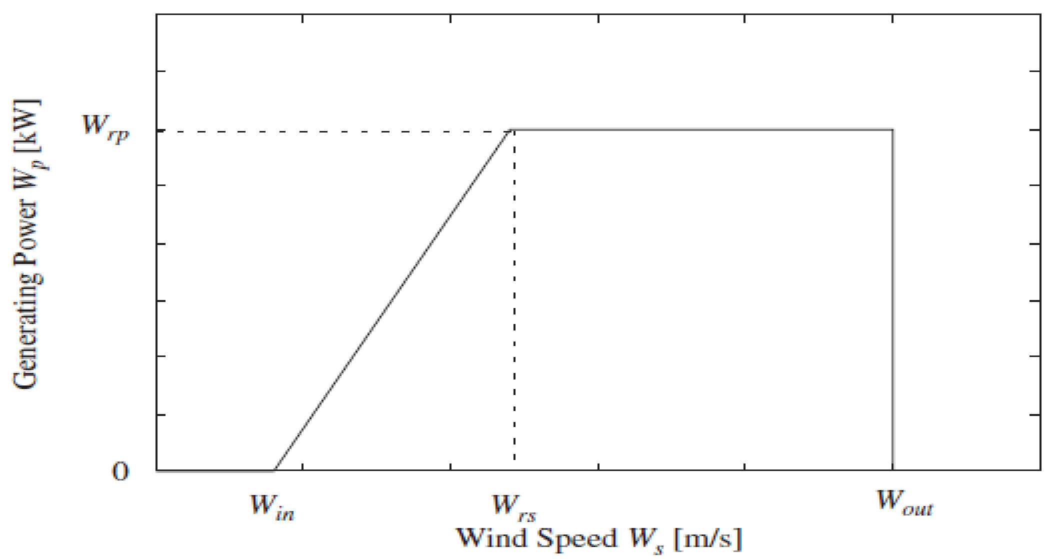


Figure 4.3: Output power characteristic of wind generator [231]

C- Third model [*233*]

In this model, we modulate torque and power wind turbine and so also integrated generator in the nacelle.The power output of the wind turbine was modulated using the next equation:

$$P_t = C_p(\lambda,\beta).\frac{\rho.S.v^3}{2} \tag{4.13}$$

S: wind turbine swept area
v: wind speed
ρ: air density
C_p: power coefficient and calculate using many methods as shown in following equations:

1. **First Cp model**

$$C_p = f(\lambda,\beta) = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\right)\exp\left(\frac{-C_5}{\lambda_i}\right) + C_6\lambda \qquad (4.14)$$

with:

$C_1 = 0.5176, C_2 = 116, C_3 = 0.4, C_4 = 5, C_5 = 21, C_6 = 0.0068$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}$$

β: orientation angle of the blade
λ: tip speed ratio

2. **Second Cp model**

$$C_p = 4a(1 - a)^2 \qquad (4.15)$$

Where "a" is defined as the axial flow interference factor [234].
We calculate tip speed ratio using the next equation:

$$\lambda = \frac{R.\Omega_{turbine}}{v} \qquad (4.16)$$

With:
R: turbine radius
$\Omega_{turbine}$: turbine speed

Generator

There are many types of generators that can be used in wind turbine, but only two types can be used easily for a stand-alone area; permanent magnetic synchronic generator (PMSG) or squirrel cage induction generators. We summarize in the next table some characteristics of generators that can be integrated in wind turbine:

Table.4.2: Characteristic of wind turbine generator [235-239]

Generator	Characteristic
Permanent magnetic synchronic generator (PMSG)	High efficiency, adopted with low wind speed, very expensive
Squirrel cage induction generators (SCIG)	Need three phases ac supply, low cost and work under fixed wind speed
Double supplied indexed generator (DFIG)	High efficiency and reliability, medium cost and work with variable wind speed

Fixed speed inductor generator (FSIG)	Low efficiency, low cost and work under fixed wind speed

According to table 1, PMSG is a good generator that can be used for a standalone area with high efficiency and operating level using low wind speed as wind potential in “Timiaouine”.

The mathematic model of PMSG defined by the different electrical equation, magnetic and mechanical as shown in the following equations [240]:

$$\begin{cases} V_{sd} = R_{ch} i_{sd} + L_{ch} \frac{di_{sd}}{dt} - \omega_r . L_{ch} . i_{sq} & (4.17) \\ V_{sq} = R_{ch} i_{sq} + L_{ch} \frac{di_{sq}}{dt} + \omega_r . L_{ch} . i_{sd} & (4.18) \end{cases}$$

$$C_{em} = \frac{3}{2} * p * \left((L_d - L_q) * i_d + \phi_f \right) * i_q \quad (4.19)$$

$$C_m = C_{em} - f\Omega = J . \frac{d\Omega}{dt} \quad (4.20)$$

C_m: motor torque.

f: coefficient of viscous rubbing.

$f\Omega$: Couple of viscous rubbing.

J: moment of inertia.

IV.3.3 Characteristic

Every wind turbine is characterized by power output curve as shown in the next figure:

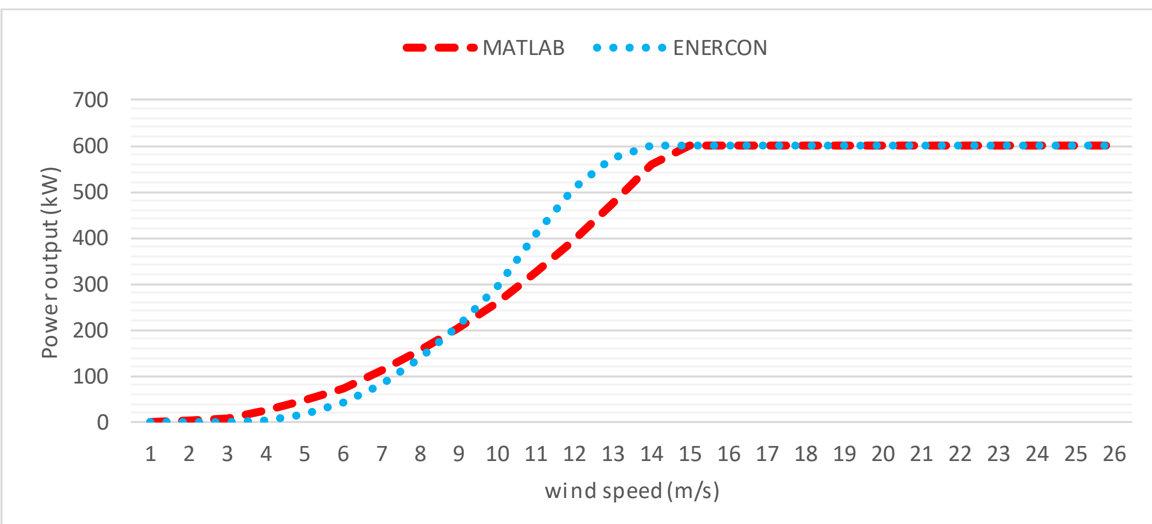


Figure 4.4: Evolution of power output with wind speed

The obtained results from MATLAB show that the wind turbine producing small energy in slow wind speed unlike in output curve obtained from the datasheet of ENERCON wind turbine. Moreover, between 9 m/s to 13 m/s, ENERCON wind turbine produces energy more than MATLAB wind turbine due to the difference of parameters between ENERCON and wind turbine used in MATLAB Simulink.

IV.4 Diesel generator

IV.4.1 Definition

In 1892, Rudolf Diesel invented the first compression ignition engine. The diesel generator is a combination between diesel engine (compression ignition) and generator to produce electrical power [241, 242].

IV.4.2 mathematical models

Many mathematical were suggested to modulate diesel generator but we noticed that bellow two methods were mainly used by the researcher:

A- First method [243,244]

The Diesel generator is divided into two parts, the mechanical part and an electrical generator. In the electrical part, we use the PMSG generator as indicated in Appendix C and modulate mechanical part as seen below

$$T_{DM}(s) = \frac{1}{1+sT_{D1}} z(s) e^{-sT_{D2}} \tag{4.21}$$

With:

T_{DM}: mechanical torque

T_{D1}: the electrohydraulic actuator constant time

T_{D2}: constant time represents the delay of torque change

z(s): The fuel rack position

$e^{-sT_{D2}}$: The transportation delay; $e^{-sT_{D2}} = \frac{2-sT_{D2}}{2+sT_{D2}}$

B- Second method

In this method, we use two differential equations to calculate speed and torque as shown in the following equations [245]:

$$J_{DM}\frac{d\omega}{dt} = T_{DM} - T_{elm} \tag{4.22}$$

$$\tau_1^2 \frac{d^2T_{DM}}{dt^2} + \tau_2 \frac{dT_{DM}}{dt} + T_{DM} = k(\omega_0 - \omega) + T_{DM0} \tag{4.23}$$

J_{DM}: aggregate inertia torque
T_{DM}: diesel motor torque,
T_{elm}: generator's electromagnetic torque

τ_1 and τ_2 is constant time of speed controller
ω: aggregate speed,
ω_0: reference aggregate speed
k: control amplifier
T_{DM0}: diesel motor torque at no-load state.

IV.4.3 Characteristic

The diesel generator is characterized by two operating modes; the first one is transient mode (between 0-3 seconds) where speed, torque and power value increase [240,245]:

- Instantaneous torsional deformations in the driving system of the mechanical fuel injection pump leading to incomplete combustion
- Low values of the flows
- Resistant torque

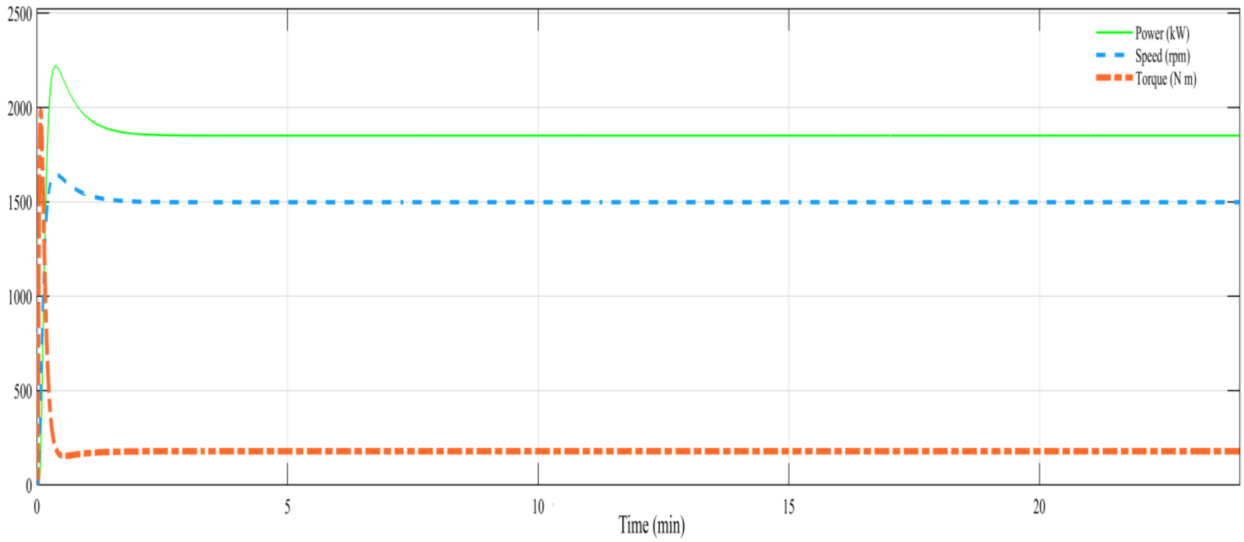


Figure 4.5: Characteristic of diesel generator

IV.5 Power converter

IV.5.1 Inverter

A- Definition

It is the electronic circuit that converts DC power to AC power with commendable amplitude. In Frequency, we notice two types of the inverter; current source inverter and voltage source [246].

Generally, inverter classified on three categories; voltage source, current source and impedance source (figure 4.6) [247]. Also, another classification of the inverter connected to solar photovoltaic due to connection standalone as shown in table 4.3 and figure 4.7 [248,249] or connected to the grid (figure 4.8).

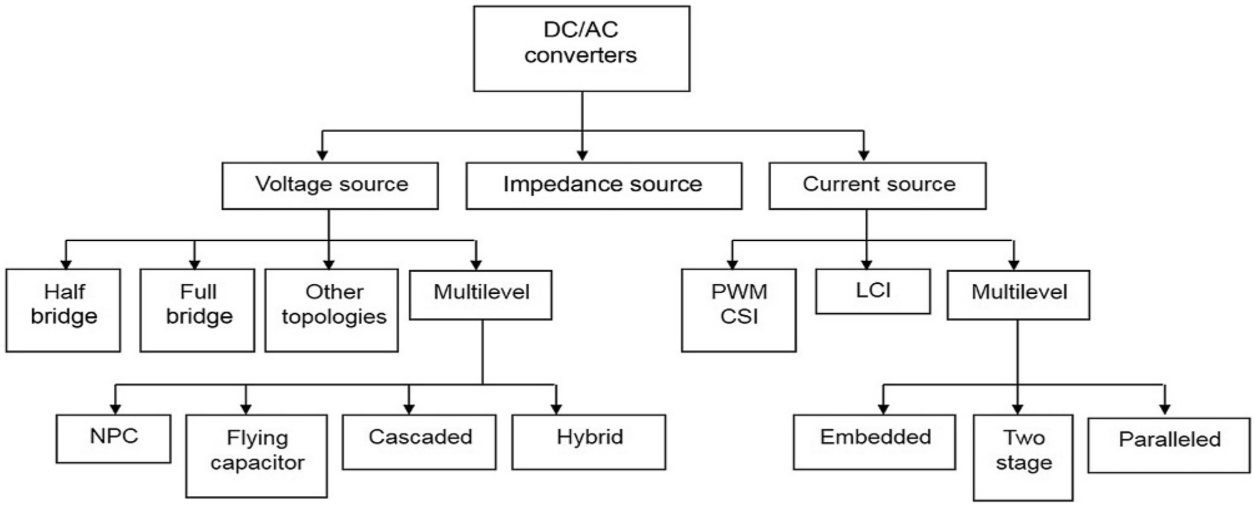


Figure 4.6: Classification of the inverters [247]

Table.4.3: Characteristic of wind turbine generator [248,249]

Topology	Advantages	Drawbacks	Capacity variation
Centralized	Low cost	In case of failure of inverter there is no option of feeding power to the utility grid	30 kW-1 MW
String	Higher system efficiency	Low power output	1 kW-5 kW
Multi-string	Flexible system	The reliability of the system decreased as all the strings are coupled to a single inverter	Maximum 50 kW
AC module	Reduced costs and improved reliability	High cost	More than 500 W

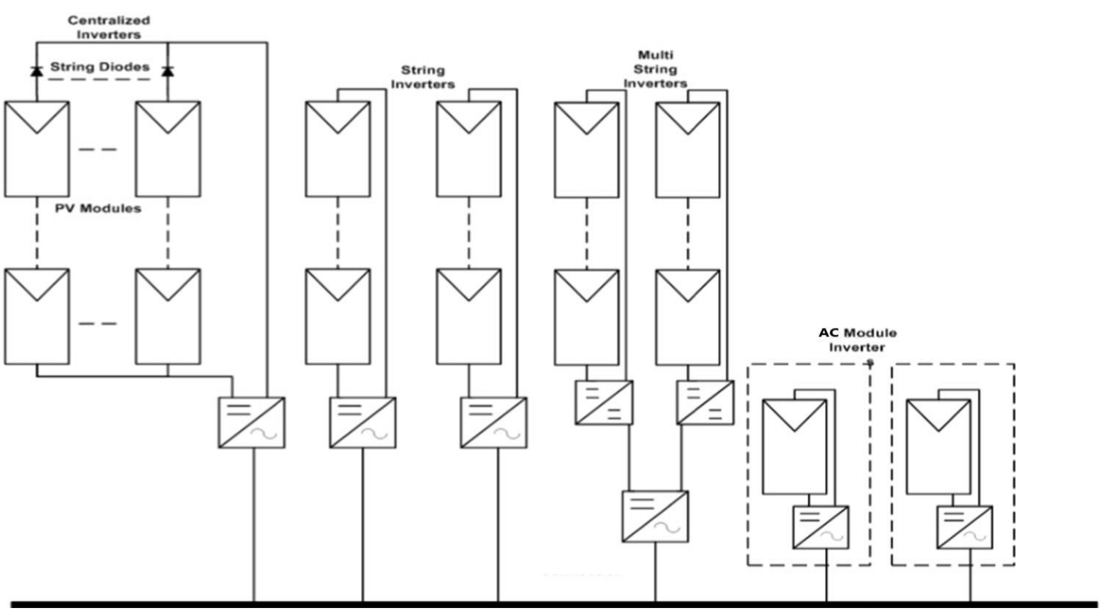


Figure 4.7: Inverter design configurations [250]

B- mathematical model [250]

We define "f_i" function that command every interrupter in the inverter, and this function uses two values; one or zero as shown in the next equation:

$$f_i = \begin{cases} \mathbf{1} & if\ T_i\ is\ close\ and\ T'_i\ are\ open \\ \mathbf{0} & if\ T_i\ is\ open\ and\ T'_i\ are\ close \end{cases} \tag{4.24}$$

The voltage output of the inverter is equal to:

$$\begin{cases} \mathrm{V_{aN}} = \mathrm{F_1 V_{df}} \\ \mathrm{V_{bN}} = \mathrm{F_2 V_{df}} \\ \mathrm{V_{cN}} = \mathrm{F_3 V_{df}} \end{cases} \tag{4.25}$$

Voltage line-line is calculated using the next equations:

$$\mathrm{U_{ab}} = \mathrm{V_{aN}} - \mathrm{V_{bN}} = \mathrm{V_{df}}(\mathrm{F_1} - \mathrm{F_2}) \tag{4.26}$$

$$\mathrm{U_{bc}} = \mathrm{V_{bN}} - \mathrm{V_{cN}} = \mathrm{V_{df}}(\mathrm{F_2} - \mathrm{F_3}) \tag{4.27}$$

$$\mathrm{U_{ca}} = \mathrm{V_{cN}} - \mathrm{V_{aN}} = \mathrm{V_{df}}(\mathrm{F_3} - \mathrm{F_1}) \tag{4.28}$$

According to the last equation, we conclude new equations of the inverter output voltage

$$\begin{cases} \mathrm{V_{aN}} = \mathrm{V_a} = \frac{\mathrm{U_{ab}} - \mathrm{U_{ca}}}{3} \\ \mathrm{V_{bN}} = \mathrm{V_b} = \frac{\mathrm{U_{bc}} - \mathrm{U_{ab}}}{3} \\ \mathrm{V_{cN}} = \mathrm{V_b} = \frac{\mathrm{U_{ca}} - \mathrm{U_{bc}}}{3} \end{cases} \tag{4.29}$$

We write last equations in matrix form:

$$\begin{bmatrix} \mathrm{V_a} \\ \mathrm{V_b} \\ \mathrm{V_c} \end{bmatrix} = \frac{1}{3} \mathrm{V_{df}} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} \mathrm{F_1} \\ \mathrm{F_2} \\ \mathrm{F_3} \end{bmatrix} \rightarrow \mathrm{V_{abc}} = \mathrm{V_{df}}.[\mathrm{T_c}][\mathrm{F}]$$

With:

$$[\mathrm{T_c}] = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ -\frac{1}{2} & 1 & -\frac{1}{2} \\ -\frac{1}{2} & -\frac{1}{2} & 1 \end{bmatrix}$$

T_c: Transfer matrix from continuous type to alternative type.

Figure 4.9 shows all integrated interrupters in the inverter and figure 4.10 represent Simulink model of inverter.

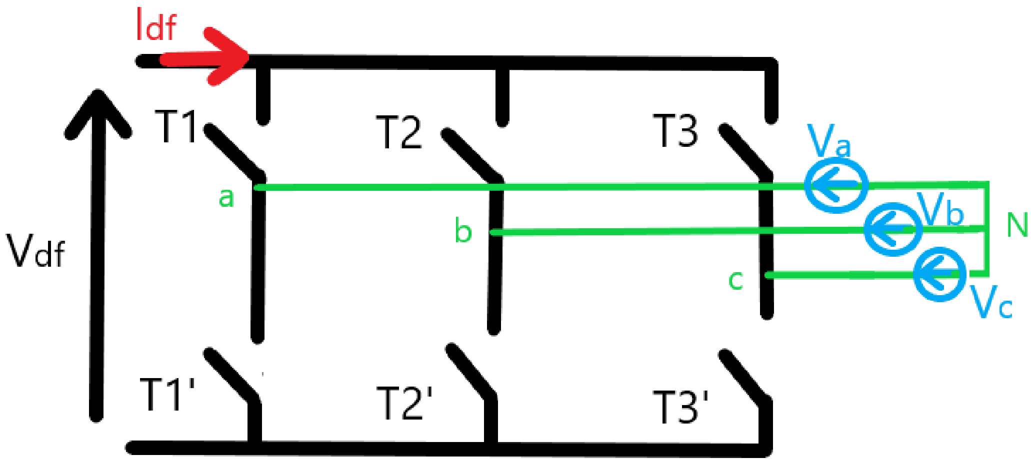


Figure 4.9: Three phase interrupter bridge inverter

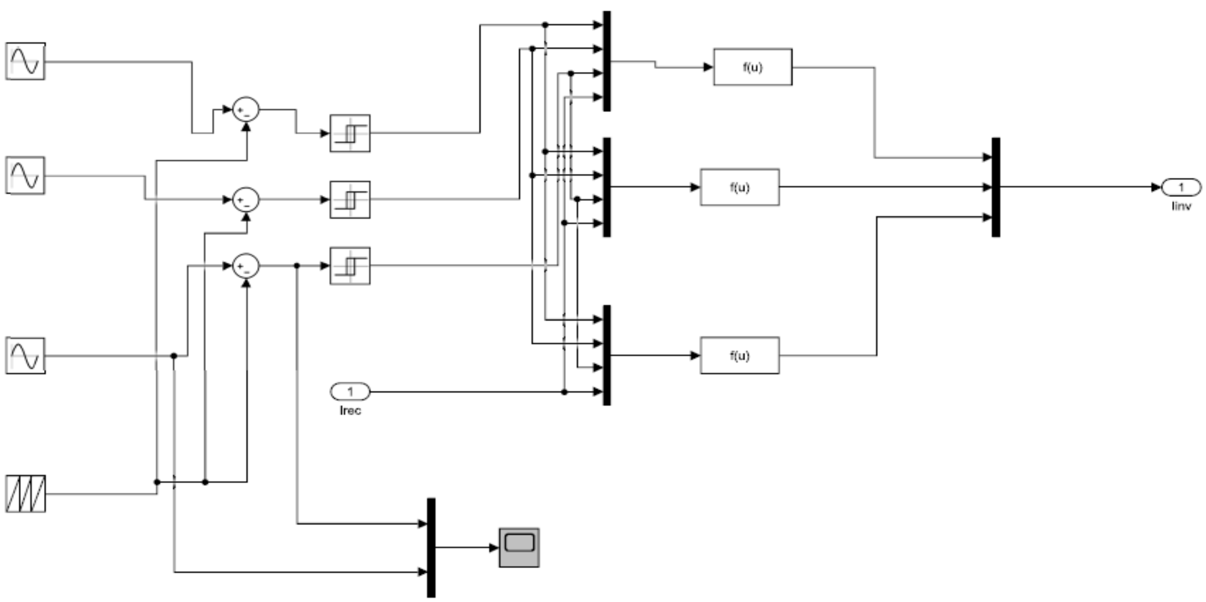


Figure 4.10: Simulink model of inverter

IV.5.2 Rectifier

A- Definition

It is an electronic circuit converting AC power to DC. The rectifier can be controlled (voltage-oriented control [251], voltage-based direct power control [252], virtual flux-oriented control [253], and virtual flux-based direct power control [254]), using a commendable interrupter like thyristor or uncommendable using diode.

Rectifier classified on three types; voltage/current source rectifiers, regenerative rectifiers, hybrid rectifier topologies and Multi-rectifier [256]. Another classification based on semiconductors is summarized in table 4.4 and figure 4.11:

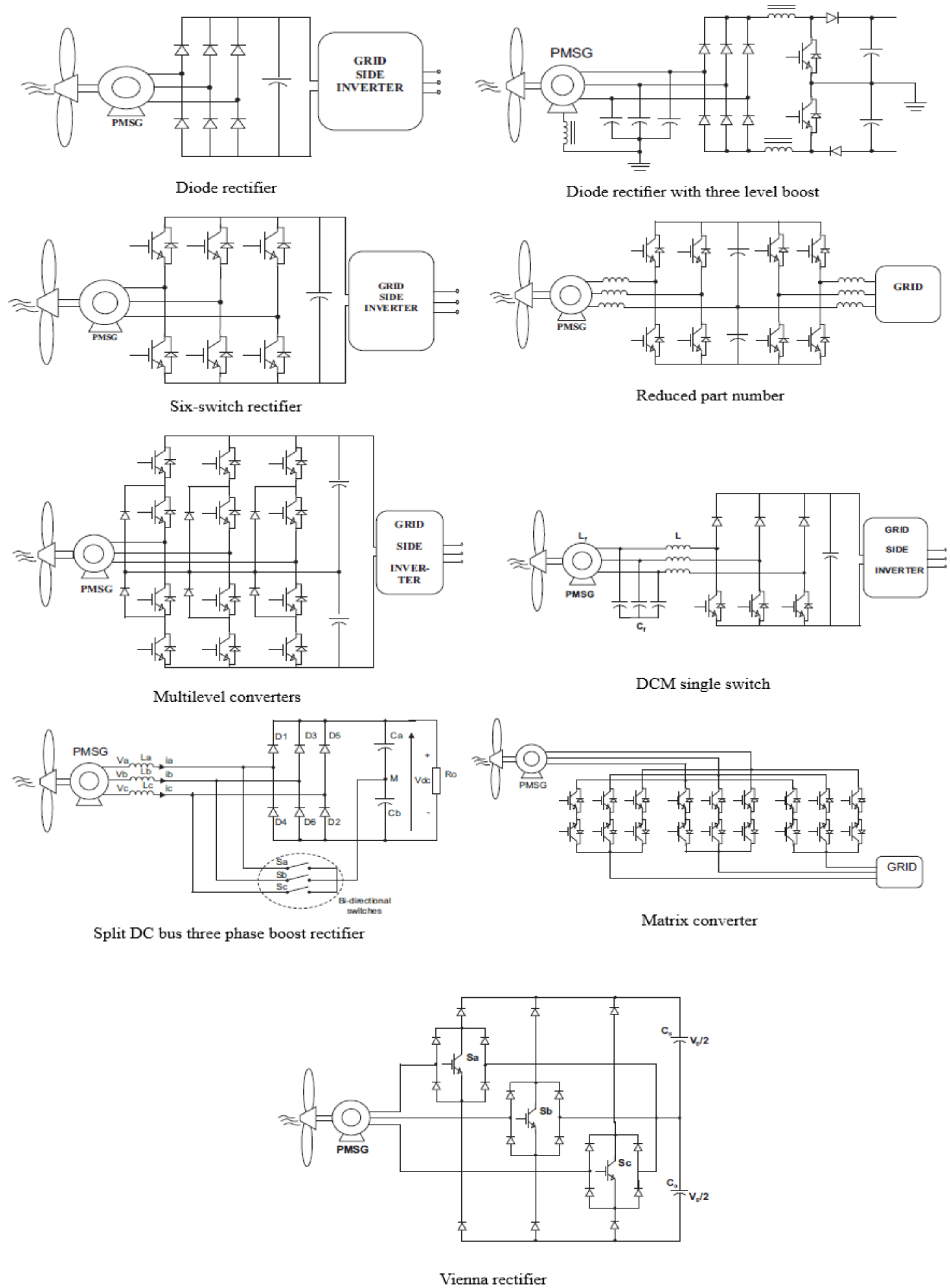


Figure 4.11: Rectifier models [255]

Table.4.4: Characteristic of wind turbine generator [255]

Topology	Advantages	Drawbacks	Semiconductors
Diode rectifier	Low cost	Difficult control	6 Diodes
Diode rectifier with three level boost	High efficiency and low cost	Generator current distortion	8 Diodes and 1 switch
Six-switch rectifier	Active and reactive power control	Expensive with high power losses	6 Switches and 6 diodes
Reduced part number	Fewer semiconductors	Complex control	4 Switches and 4 diodes
Multilevel converters	Lower harmonic distortion	Complex control	12 Switches and 18 diodes
DCM single switch	Simple command	High harmonic content	8 Diodes and 1 switch
Split DC bus three phase boost rectifier	Sinusoidal input current	High semiconductors number	18 Diodes and 3 switches
Matrix converter	Eliminates the dc link stage	High cost	18 Switches and 18 diodes
Vienna rectifier	High input current	High number of diodes	18 Diodes and 3 switches

B- mathematical model [*257*]

Using three-phase balanced voltage (figure 4.12), in the supply of rectifier with V_1, V_2, and V_3, as shown in the following equations:

$$\begin{cases} V_1(t) = V_m sin\omega t \\ V_2(t) = V_m \sin(\omega t - \frac{2\pi}{3}) \\ V_3(t) = V_m \sin(\omega t - \frac{4\pi}{3}) \end{cases} \tag{4.30}$$

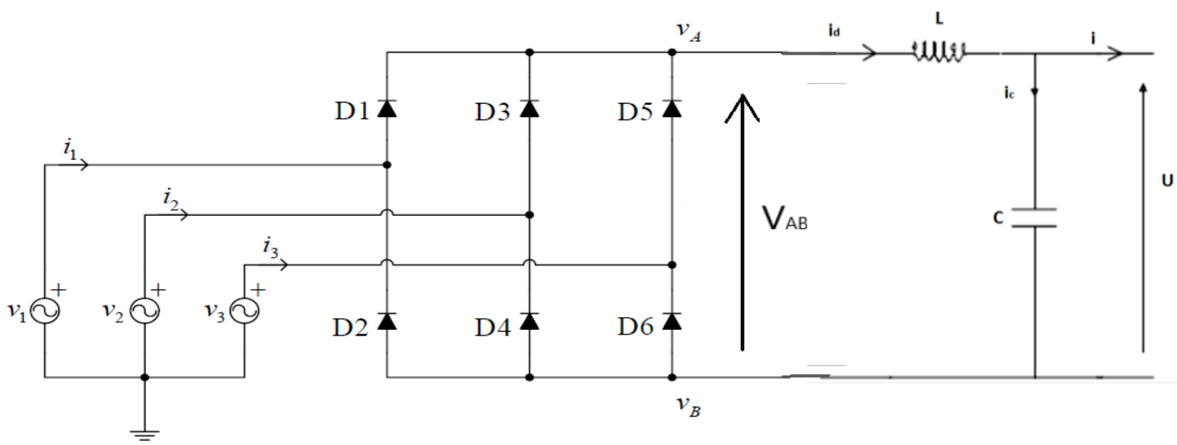


Figure 4.12: Three phase diode bridge rectifier [257]

V_A is the positive output voltage of rectifier and equals maximum phase voltage

V_B is the voltage of the negative output of the rectifier and equals the minimum voltage phase as shown in the below equations:

$$V_A = max(V_1, V_2, V_3) \tag{4.31}$$

$$V_B = min(V_1, V_2, V_3) \tag{4.32}$$

$$V_{AB} = max(V_1, V_2, V_3) - min(V_1, V_2, V_3) \tag{4.33}$$

For rectifier output, we integrate filter to reduce harmonic and perturbation of voltage using the next equation:

$$\frac{U}{V_{AB}} = \frac{1}{LCS^2 + \frac{L}{R}S + 1} \tag{4.34}$$

With:

L,C: Parameter of the filter.

R: equivalent resistor.

Next figure illustrates bloc simulation of rectifier:

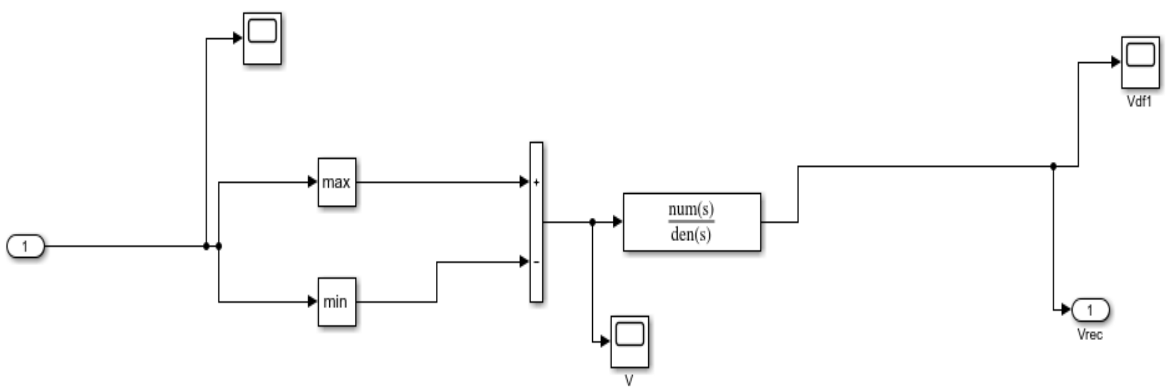


Figure 4.13: Simulink model of the rectifier

IV.5 Conclusion

In the end of this chapter, we conclude that a lot of mathematical models were discovered for each hybrid system component, each mathematical model describes specific physic phenomena. The characteristic of renewable generator shows limitation and progression in the construction of these generators in the way to optimize efficiency. Also, many control models for power converter were noted.

In the next chapter, we will describe Simulink models of hybrid system generators using MATLAB Simulink and compare the results obtained with HOMER PRO results, the comparison will be in technical parameters (total production, unmet load…etc.), economical parameters (investment cost, levilized cost…etc.) and ecological parameters (dioxide carbon emission and fuel consumption).

Chapter V
Simulation of hybrid system

In the last chapter, we evaluate obtained results in chapter three to simulate the hybrid system using two methods. The first one is by MATLAB Simulink and the second one is by using HOMER PRO. In the end of this chapter, we compare between obtained results from two methods. The comparison will be technical, economic and ecological.

V.1 Introduction

Simulation is an operation based on mathematical equations to present a real system in a virtual process. In this final chapter, we evaluate the results of hybrid system sizing using two different programs: MATLAB Simulink and HOMER PRO. After that, we compare these results in three axes; technically, economically and ecologically.

This chapter was divided into three principal sections:

- MATLAB Simulink results
- HOMER PRO results
- Comparison of the two simulation methods

In the first two sections (MATLAB Simulink results and HOMER PRO results), a full description of the hybrid system simulation blocs and results obtained in details for each generator. The last section (Comparison of the two simulation methods) compares between sizing hybrid system using the classical modified method (simulate using MATLAB Simulink) and sizing hybrid system using commercial software (HOMER PRO).

V.2 MATLAB Simulink results

Using obtained results from classical modified sizing method as shown in chapter three and mathematical equations from the previous chapter, we simulate each component of the hybrid system as shown in figure 5.1 below:

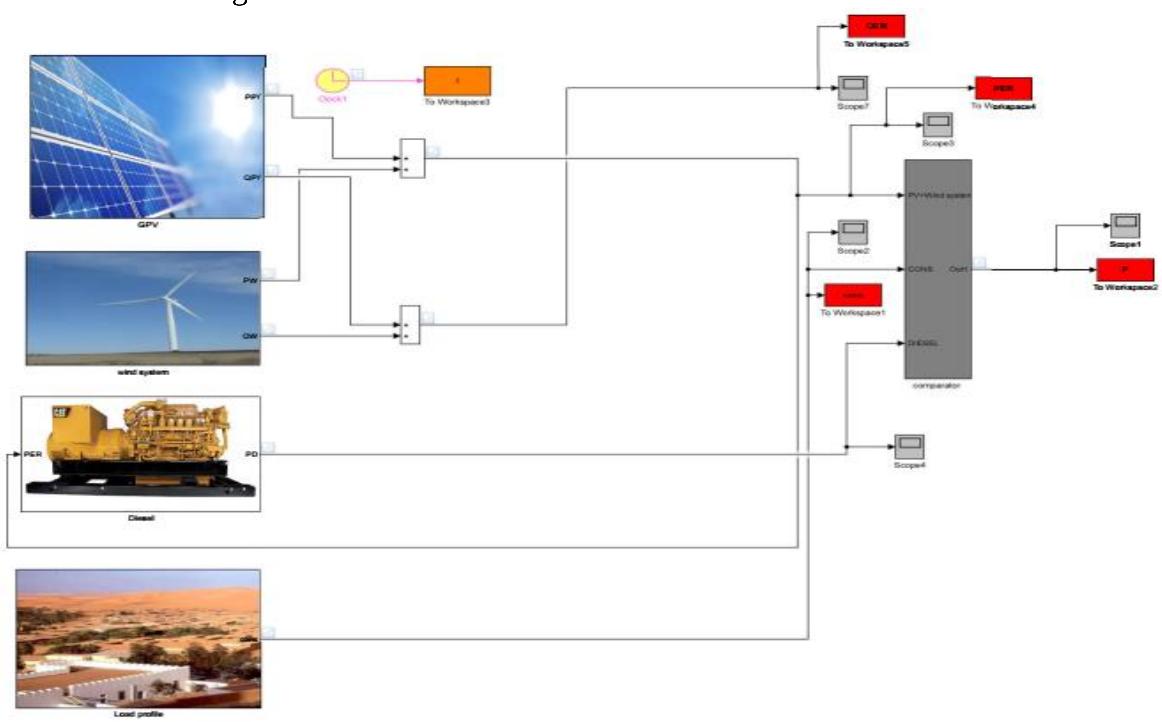


Figure 5.1: Simulation bloc of hybrid system

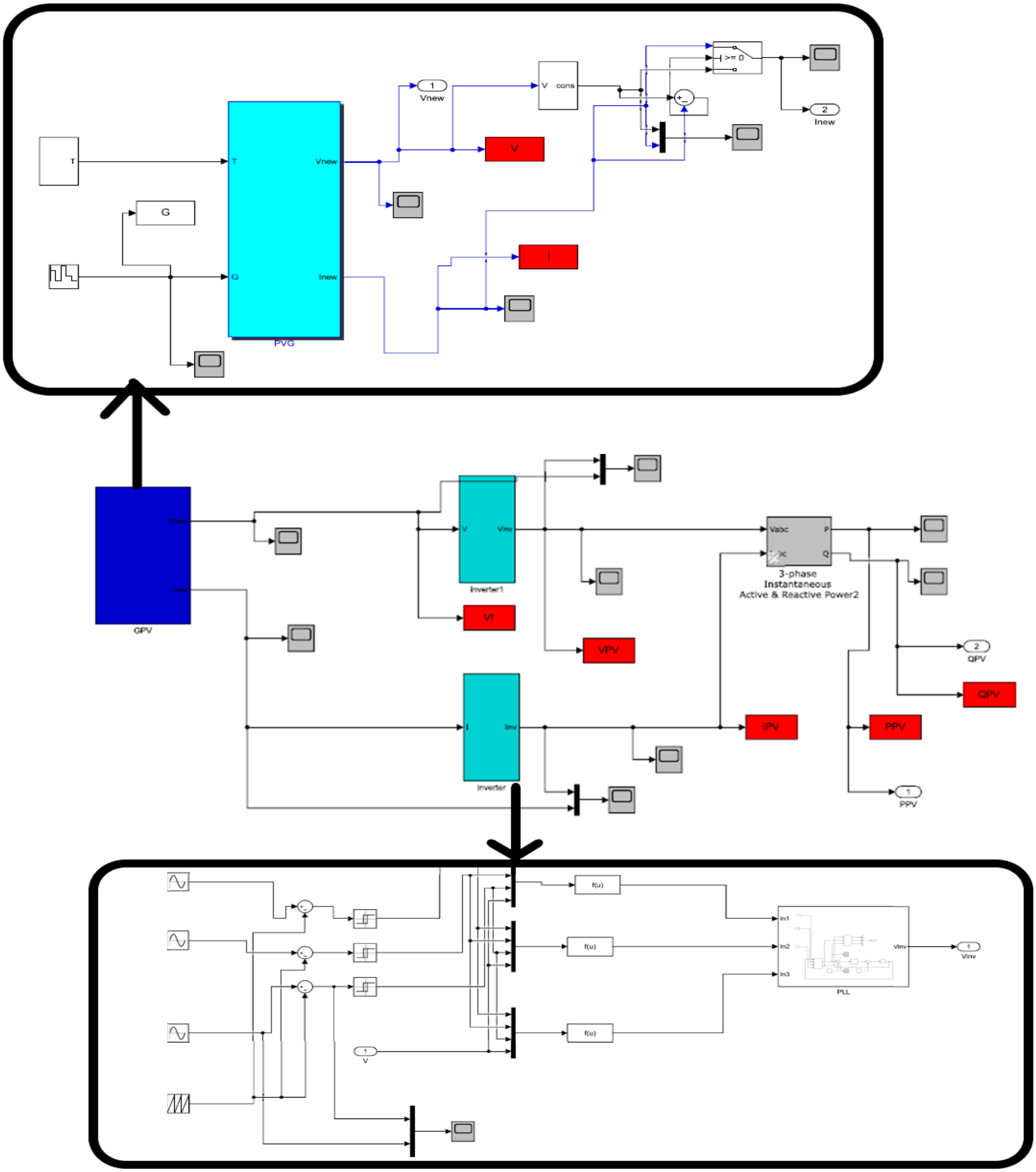


Figure 5.2: Solar photovoltaic field

V.2.1 Simulation of hybrid system generator

In this part, we describe simulation of each generator and the production of each one.

A- Solar photovoltaic

There are a lot of examples of solar photovoltaic fields developed by MATLAB Simulink to simplify the simulation. In our system, we built our solar photovoltaic system by using mathematical equations as shown in figure 5.2. We notice in the same figure that output of solar field was connected to the inverter because the rural village was supplied with just AC power.

The obtained results are shown in figure 5.3. The production of the solar photovoltaic generator represent 48% from global production with 2,56 GWh per year and maximum production of more than 2,2 MWh.

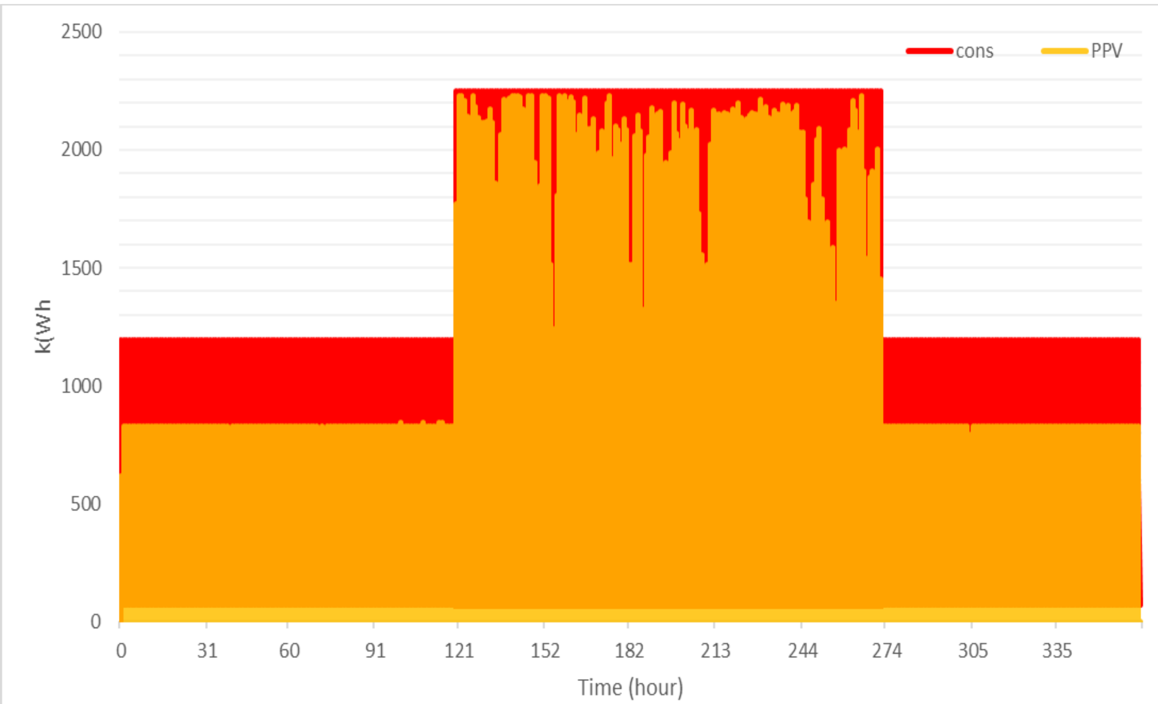


Figure 5.3: Comparison between solar photovoltaic production and demand

By comparing the solar photovoltaic production and demand of rural village (figure5.3), we notice that renewable generator is able to cover complete demand if we add another renewable generator or storage system. However, this will increase the global investment cost. We summarize in the next table simulation result of the photovoltaic system:

Table 5.1: Simulation result of the photovoltaic field

Installed capacity (MW)	2,250
Annual production (GWh)	2,56
Percentage %	49%
Used time (hour)	4608

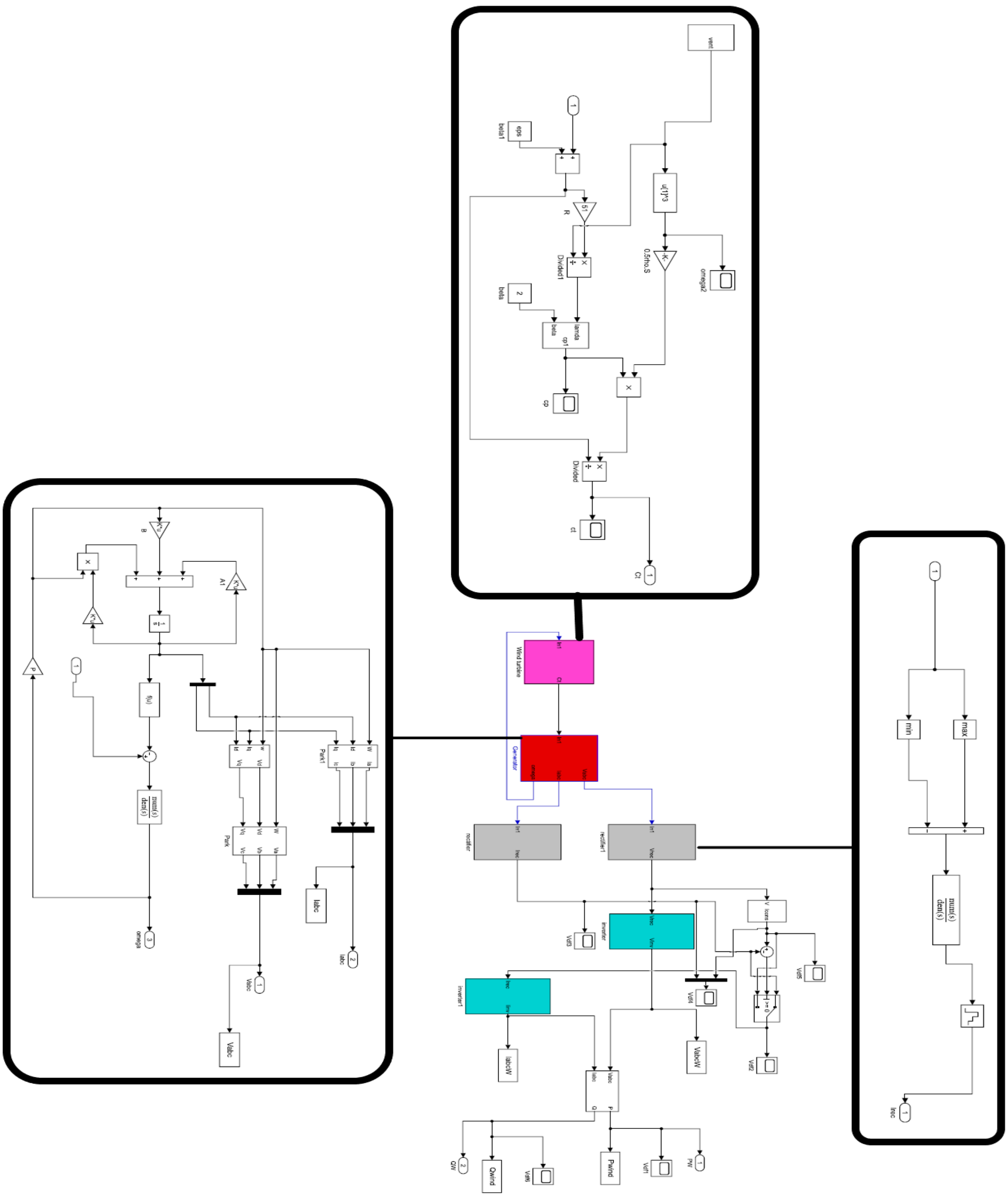


Figure 5.4: Simulation bloc of wind turbine

B- Wind turbine

Many models of wind turbine generator are proposed in MATLAB Simulink but in our system, we make our wind turbine using a specific parameter as stated in this chapter. Figure 5.4 illustrates block simulation of the wind turbine.

After simulation, the results show low efficiency production of the wind turbine throughout the year due to low wind potential in this area (figure 5.5). The wind turbine produces 0.45 GWh every year and represents more than 8% from global production. In the next table, the simulation results are summarized.

Table 5.2: Simulation result of wind turbine

Installed Capacity (kW)	600
Annual production (GWh)	0,45
Percentage %	8.61%
Used time (hour)	8760

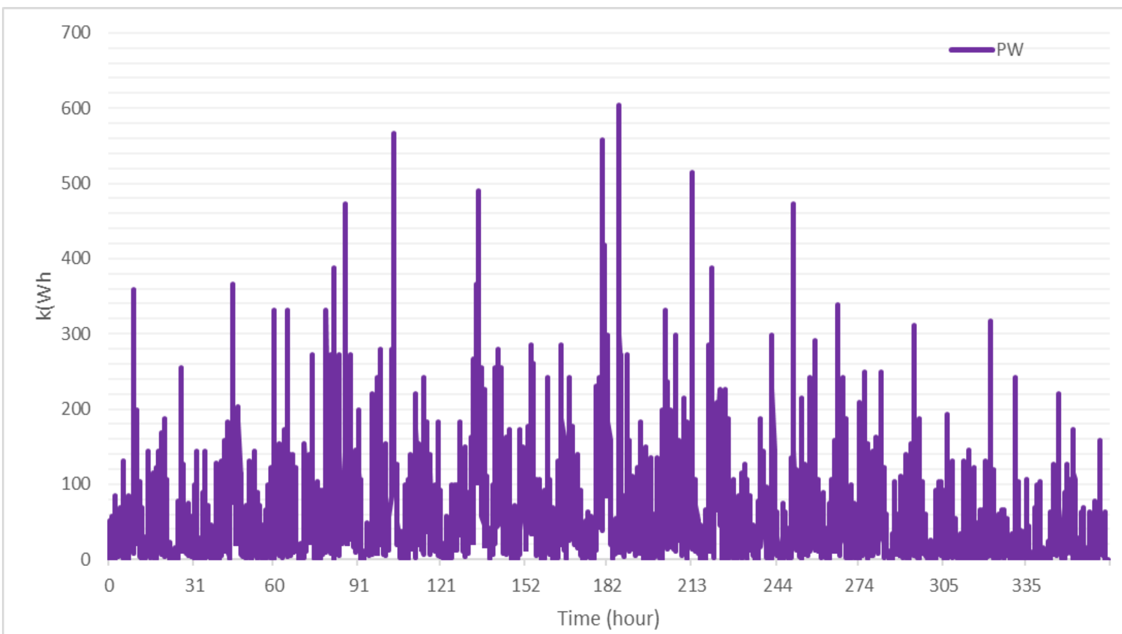


Figure 5.5: Daily wind turbine production

The comparison between renewable generators production and the use of rural village, shoes that these renewable generators can cover energy demand between sunrise and sunset (figure 5.6). During pic demand, renewable generators produce maximum power but sometime this production is not sufficient and an unmet load occurs. To solve this problem, we use a diesel generator to cover demand in the following four cases:

1- The absence of renewable generators due to maintenance or weather conditions
2- Low production of renewable generators
3- Pic demand
4- During the night

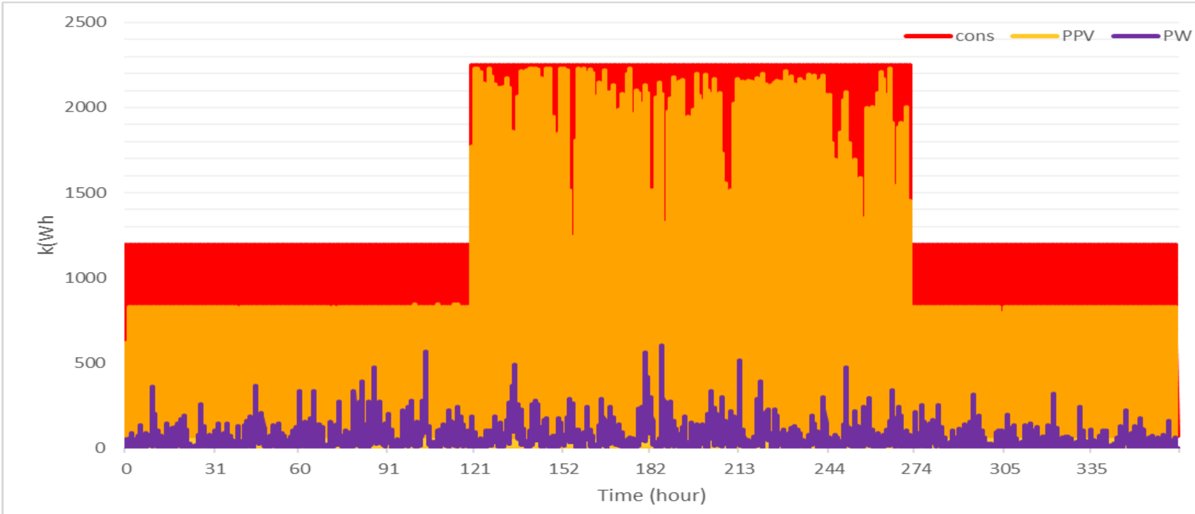


Figure 5.6: Comparison between renewable generators production and consumption

C- Diesel generator

Using mathematical models of the previous chapter, we simulate the diesel generator and we obtain the results shown in the next table:

Table 5.3: Simulation result of diesel generator

Installed Capacity (MW)	1,850
Annual production (GWh)	2,26
Percentage %	42%
Used time (hour)	5203

It can be noticed that the diesel generator is the most operating generator in the hybrid system with 5203 hours/year compared with 4608 hours/year for the solar photovoltaic generator. However it produces lower energy (2,26 GWh) compared to the solar photovoltaic generator (2,56 GWh).

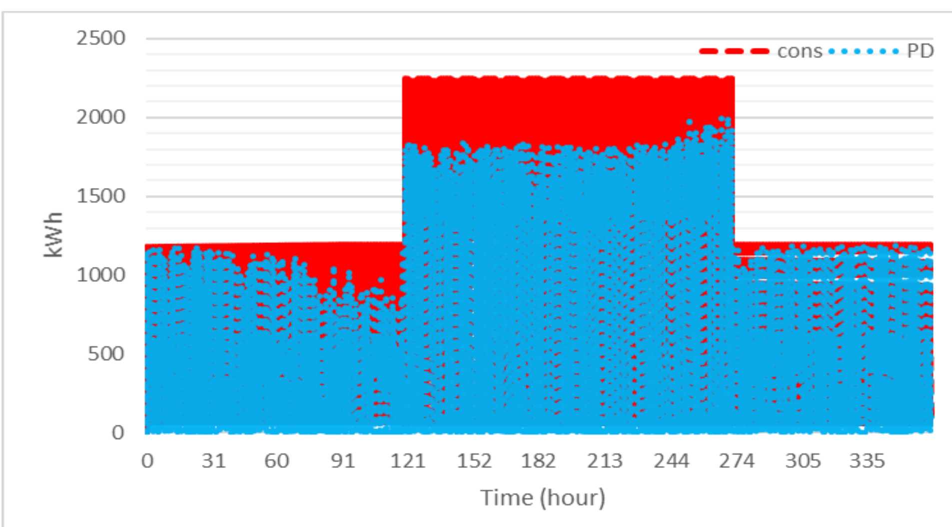


Figure 5.7: Diesel generator production and Timiaouine demand

By comparing the production of diesel generator and power demand, we notice that fossil generator complements renewable generators production during maximum demand period that occurs in the middle of the year (figure5.7).

V.2.2 Simulation of the global system

After obtaining above detailed results of each generator, we compare now between the total production of the hybrid system and the rural village demand. The results obtained are summarized in table 5.4:

Table 5.4: Simulation results of the hybrid system

PV array (kW)	2250
Annual PV production (GWh)	2,56
Wind turbine(kW)	600
Annual wind turbine production (GWh)	0,45
Diesel generator (kW)	1850
Annual diesel generator production (GWh)	2,26
Annual fuel use (L/year)	596700
Unmet electrical load (kW)	0
Total production (GWh)	5,28
Percentage production from source renewable	58%
production from Renewable energy (GWh)	3,02

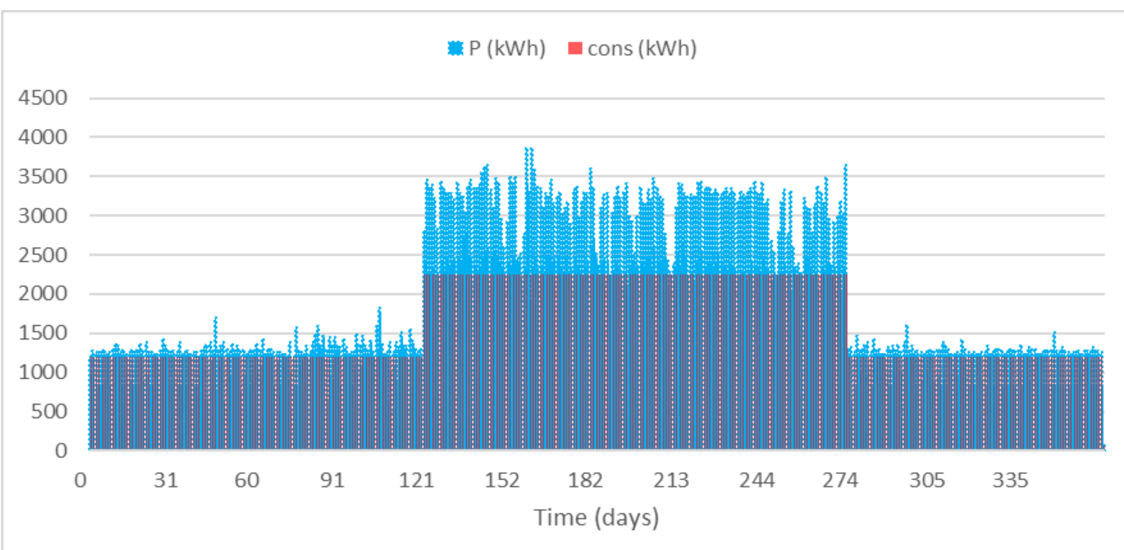


Figure 5.8: Comparison between annual total production and demand

It is noted that the hybrid system covers all power demand throughout the year (unmet load equal 0), also production always grows higher than power demand (figure 5.8), however, it is possible to the use battery in this system and hence reduce demand of fuel and dioxide carbon emission.

V.2.3 Control of the hybrid system

After simulation of the hybrid system, we need to integrate management system to control the production of each generator based on using renewable resource more than fossils on. The management system is based on three strategies (figure 5.9):

- **1st strategy**: use solar photovoltaic and wind turbine to cover demand.
- **2nd strategy**: if the renewable generators cannot cover demand, we combine diesel generator with the renewable resources to meet consumption
- **3rd strategy**: use all generators to obtain maximum production

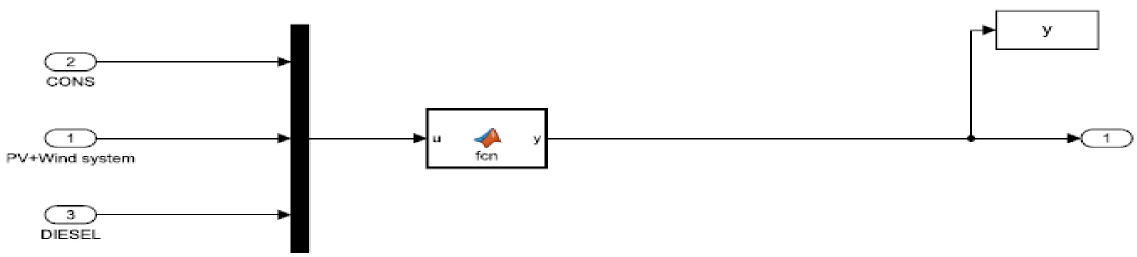


Figure 5.9: Simulation bloc of the management system

The obtained results show that renewable generators provide the highest production level in the hybrid system with 68% as shown in figure 5.10. The system manager will compare every hour between three inputs; Renewable energy production (solar photovoltaic and wind turbine), demand and production of the diesel generator. Using the previous strategy, the system manager will select which one will be turned on and supply power to the rural village. The other one will be put in standby for any critical condition like decrease of production of generator due to climatic condition or showdown of some generator for maintenance (figure5.11).

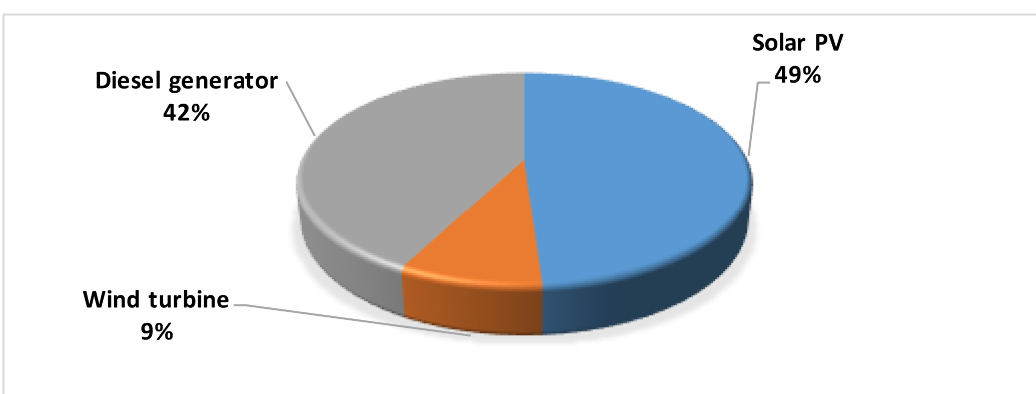


Figure 5.10: Reparation of global generator production

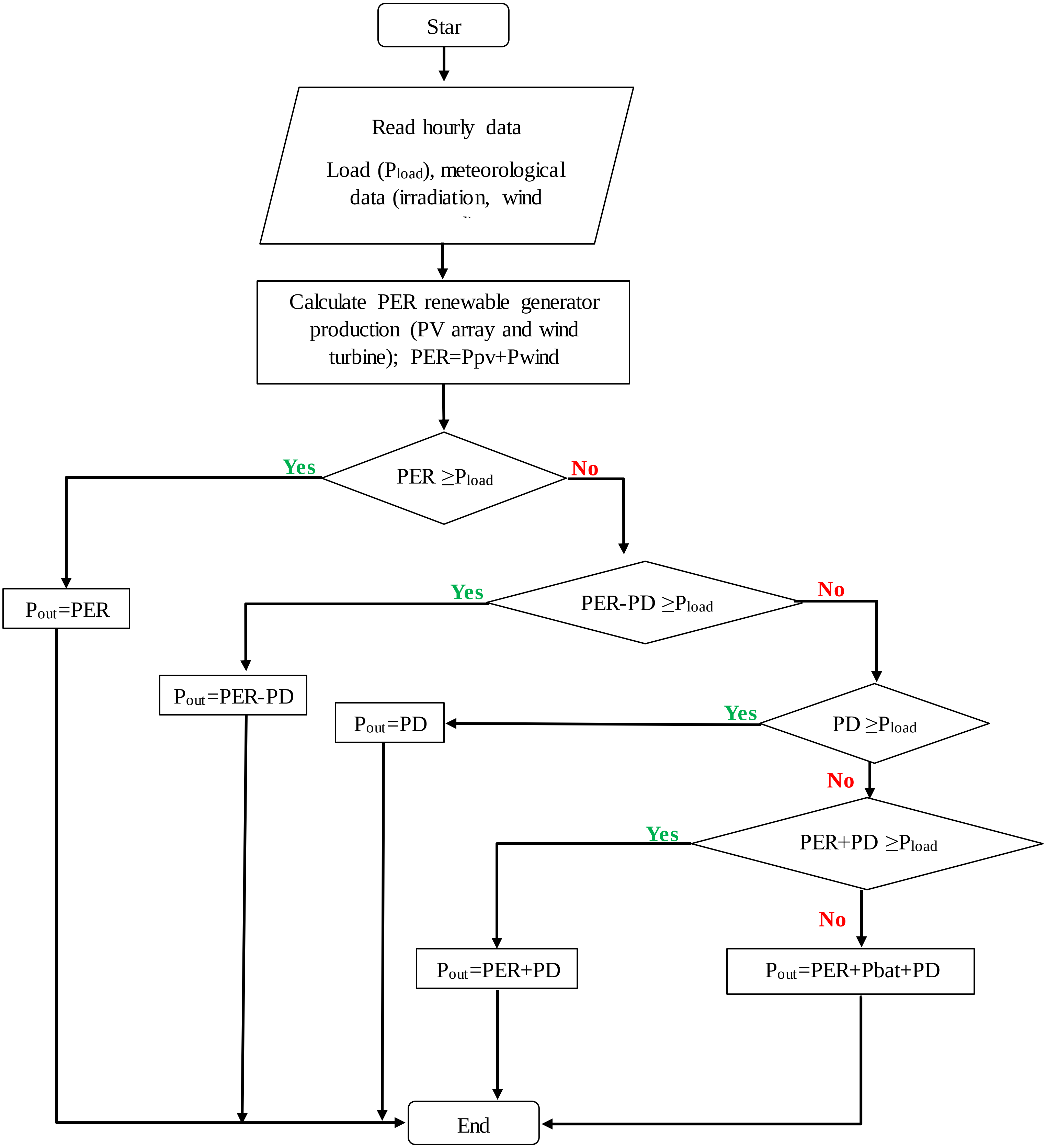


Figure 5.11: Flowchart of hybrid system control

V.3 HOMER PRO results

In this part, we describe simulation results obtained from HOMER PRO for each generator of the hybrid system.

A- Solar photovoltaic

Meteorological data show an important solar potential in "Timiaouine", being the most favorable area in the number of sunny days. The obtained results from HOMER PRO software show a high energy production (4,41 GWh/year) as shown in the next figure:

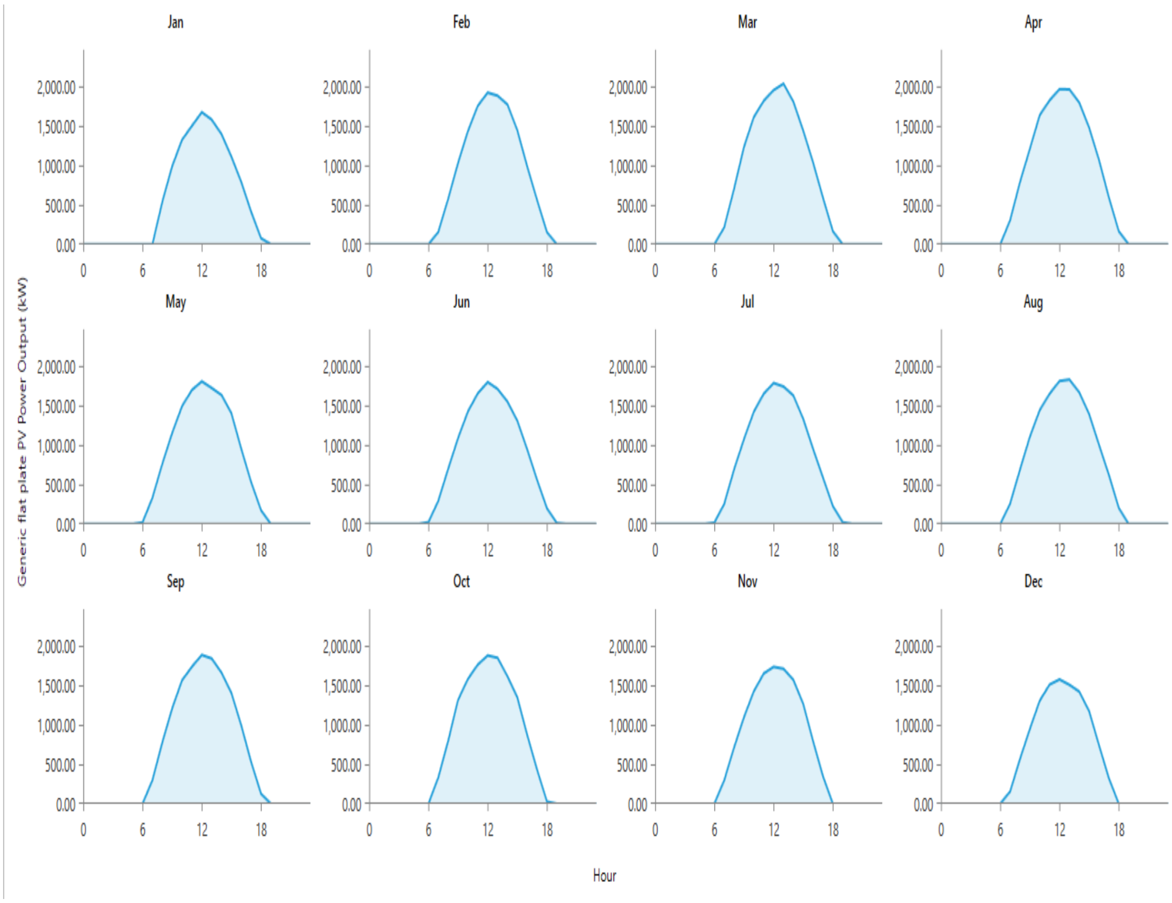


Figure 5.12: Monthly solar photovoltaic production

B- Wind turbine

Due to low wind potential, HOMER PRO system sizing gives four wind turbines and the results show that the production equals to 2,81 GWh (27% from global production). The production reaches high value during February and October and random value will be obtained through the year due to fast wind speed variation (figure 5.13). Also, we notice that the production of the wind turbine is permanent and this implies limited use of diesel generator in the night and HOMER PRO software sizes wind turbine to cover energetic demand in the night in case of low demand.

.

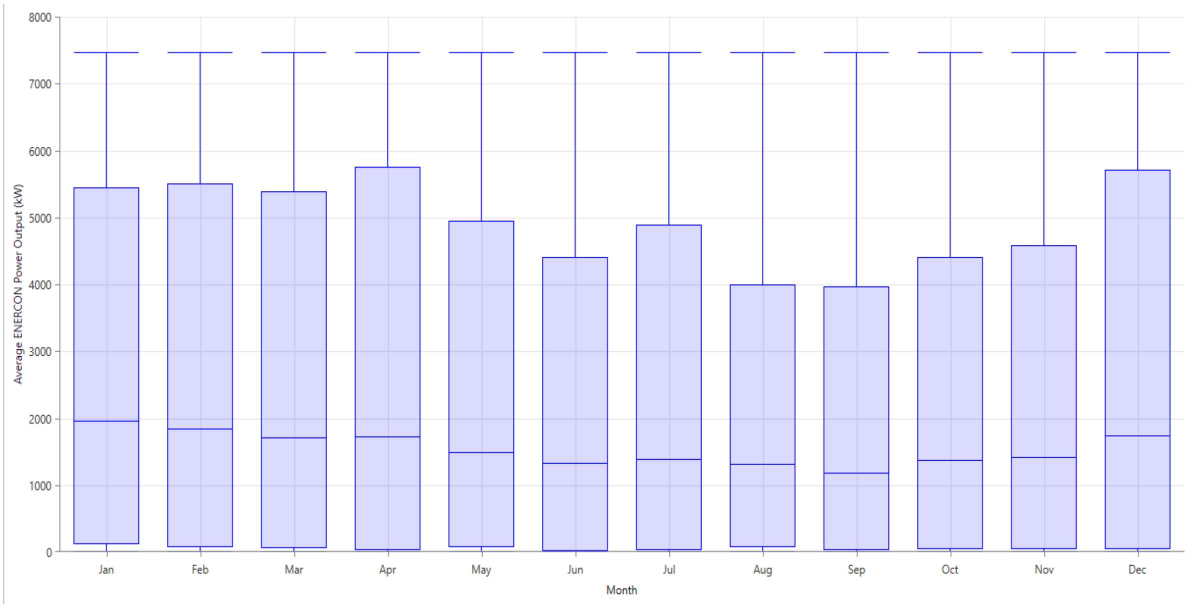


Figure 5.13: Wind turbine monthly production

C- Diesel generator

The obtained results after simulation show that production of diesel generator grows in the middle of the year during high demand. In addition, production is concentrated between sunset and sunrise. The diesel generator works all year and its production varies between minimum production (500 kW) and the maximum value (1900 kW). This decreases the lifetime of the generator and increases fuel demand that means more dioxide carbon. Figure 5.14 illustrates annual production of diesel generator

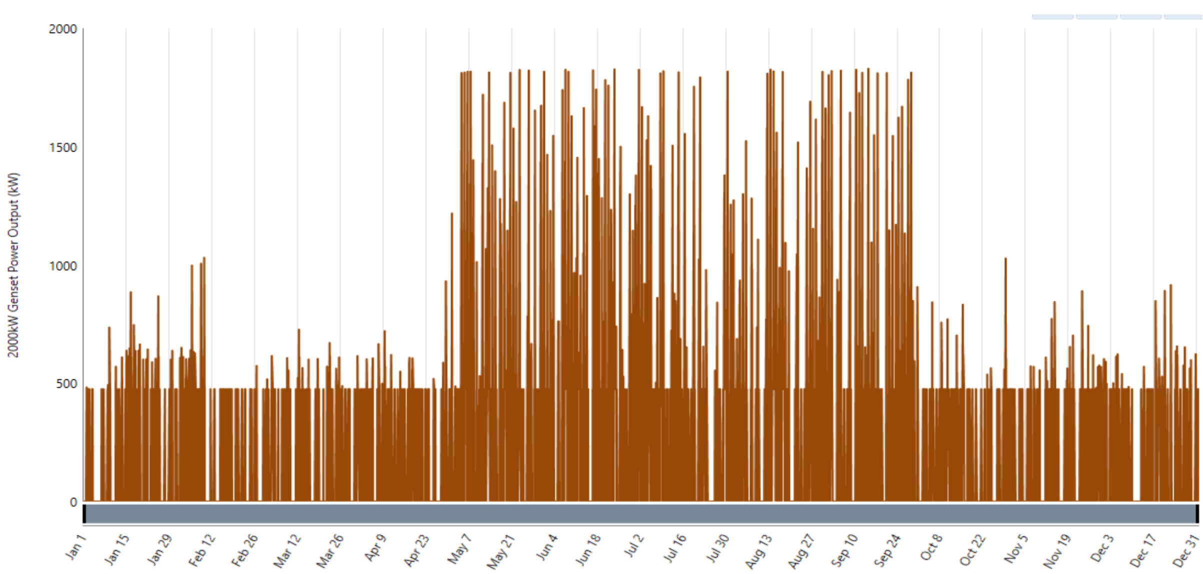


Figure 5.14: Production of diesel generator through a year

D- Global system

After the description of obtained results for each generator, we summarize in following table simulation results of the hybrid system using HOMER PRO:

Table 5.5: Simulation results of the hybrid system using HOMER PRO

PV array (kW)	2500
Annual PV production (GWh)	4,86
Wind turbine(kW)	7800
Annual wind turbine production (GWh)	13,53
Diesel generator (kW)	1900
Annual diesel generator production (GWh)	1,68
Annual fuel use (L/year)	484767
Unmet electrical load (kW)	0
Total production (GWh)	20,07
Percentage production from source renewable	91%
production from Renewable energy (GWh)	18,39

The results show that the hybrid system produces energy from renewable resources (figure 5.15) more than from fossil resources because the renewable generator was sized three times compared to Diesel generator (10.03 GW for renewable generator compared to 1900 kW for diesel generator). We also notice that the hybrid system produces two times of the rural village energy demand, and this means that there is a possibility to connect this system to grid or use a battery to minimize dioxide carbon.

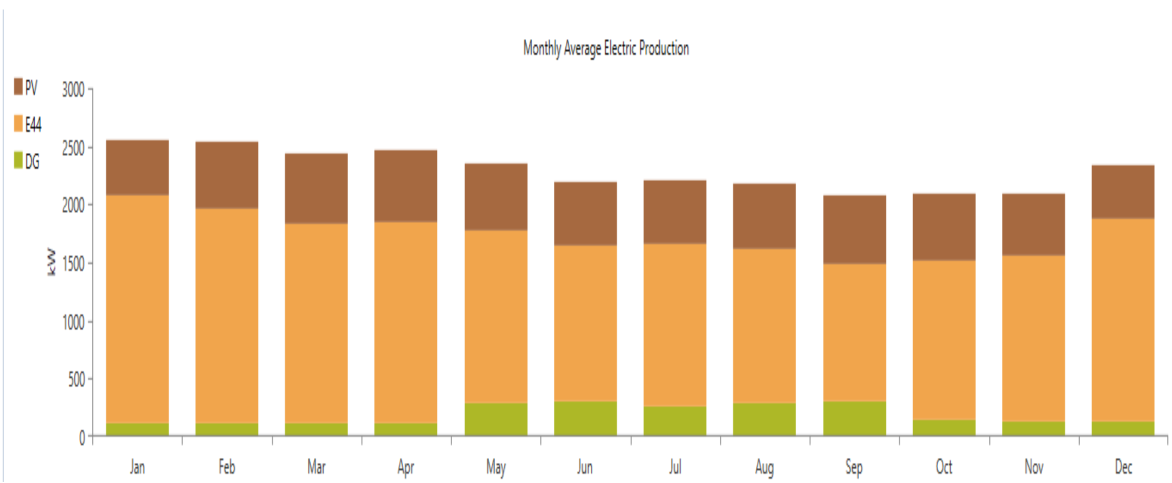


Figure 5.15: Annual production of hybrid system generator

V.4 Comparison between two methods of simulation

After simulating the hybrid system using two different software and two sizing methods, we compare between obtained results from each generator technically, economically and ecologically.

V.4.1 Technical comparison

In this part, we compare below technical parameter:

1. Capacity installed for each generator
2. Production of generators
3. Unmet load
4. Renewable energy production

We summarize the results obtained in the below table:

Table 5.6: Technical comparison between obtained results from MATLAB and HOMER PRO

Parameter	MATLAB	HOMER PRO
PV array (kW)	2250	2500
Annual PV production (GWh)	2,56	4,86
Wind turbine(kW)	600	7800
Annual wind turbine production (GWh)	0,45	13,53
Diesel generator (kW)	1850	1900
Annual diesel generator production (GWh)	2,26	1,68
Unmet electrical load (kW)	0	0
Total production (GWh)	5,28	20,07
Total consumption (GWh)	5,07	5,07
Percentage production from source renewable	57%	91%
production from Renewable energy (GWh)	3,01	18,39

The obtained results from MATLAB show that the global production of the hybrid system is lower than HOMER PRO, that means that the integrated system manager in MATLAB is working correctly and manage all the integrated resources in the system better than HOMER PRO that requires adding storage system or connecting the system to the grid.

Due to the high capacity of installed renewable generators, the hybrid system in HOMER PRO uses green energy more than the simulated system in MATLAB.

The solar photovoltaic field in HOMER PRO produces energy more than in MATLAB for two reasons; the first reason is that HOMER PRO use command and regulation to receive more energy from photovoltaic modules (like MPPT), which is not the case in MATLAB simulation. The second reason is that HOMER PRO uses efficiency of photovoltaic panels to calculate power output but in MATLAB, we use complicate equations to simulate solar photovoltaic field.

V.4.2 Economically comparison

We note in this part that the price of 1kWh is 1100€ for solar photovoltaic, 0,17M€ for one wind turbine and 500€/kWh for a diesel generator. Below is the table of economic parameters:

Table 5.7: Economical comparison between results from MATLAB and HOMER PRO

Parameter	MATLAB	HOMER PRO
PV area (kW)	2250	2500
Investment cost for PV field (M€)	2,475	2,75
Wind turbine(kW)	600	7800
Investment cost forwind turbine (M€)	0,17	2,21
Diesel generator (kW)	1850	1900
Investment cost for diesel generator (M€)	0,925	0,950
Total generators investment cost (M€)	3,57	5,91
Levilized cost (c€/kWh)	0,6	0.3

Table 5.7 shows that obtained results in MATLAB are much better than those obtained by HOMER PRO in terms of investment cost, but HOMER PRO takes the lead in levilized cost with 0.3 c€/kWh compared to MATLAB with 0.6 c€/kWh.

V.4.3 Ecological comparison

Before comparing between the two methods, we need to know how to calculate fuel use and dioxide carbon emission in MATLAB.

A- Fuel use

We need two parameters from appendix C to calculate fuel use, these parameters are:

1. Fuel Use for 100% load and equal to 497.3 L/hrs.
2. The nominal capacity of diesel generator and equal 1820 kW

Fuel uses for one-kilo watt-hour is

$$\text{Fuel use} = \frac{\text{Fuel Use for 100\%}}{\text{Nominal capacity}} = \frac{497.3}{1820} = 0.27L/kWh \tag{5.1}$$

$$\text{Total fuel use} = \text{ annual production} \times \text{Fuel use} = 611477\text{L/year} \tag{5.2}$$

B- Dioxide carbon emission

Each gallon of diesel has 10,084 g of pure carbon that means:

In MATLAB:

(161535.1*10,084)/1000= 1628.91 kg/year

In HOMER PRO:

(235783.6*10,084)/1000=2377.64 kg/year

We summarize the ecologic parameter of each method in the following table:

Table 5.8: Ecological comparison between results from MATLAB and HOMER PRO

Parameter	MATLAB	HOMER PRO
Diesel generator (kW)	1850	1900
Fuel use (L/year)	596700	484767
Dioxide carbon (kg/year)	1627	1291

Similarly to the economic comparison, obtained results from MATLAB are better compared to HOMER PRO esults because the capacity of installing diesel generator in the first method is lower and the management system integrated in MATLAB uses diesel generator just in case of power output of renewable generator cannot cover demand.

V.5 Conclusion

In this chapter, we have described the simulation bloc of each generator of the hybrid system; hybrid system was simulated using two software; MATLAB Simulink and HOMER PRO.

The results show that hybrid system, simulated in MATLAB and based on classical modified sizing method, was better technically and economically than hybrid system simulated and sized using HOMER PRO.

In addition to that, the capacity installed of renewable generators in the hybrid system sized using HOMER PRO was biggest than hybrid system sized using classical modified method, what makes the first better ecologically.

General conclusion

The availability of energy is necessary for socio-economic and industrial development of the country. Today, it is clear that the world energy consumption is largely covered by fossil resources that are not eternally sustainable due to limited reserves and environmental damage of these resources. However, it has been proved that the massive consumption of these types of energy has an adverse effect on the planet (greenhouse effect).

The economic and ecologic 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. They are available in excess of current energy consumption and do not emit greenhouse gases into the atmosphere during their operations. As a part of the exploitation of photovoltaic and wind energy for the generation of electrical energy, this research is carried out to improve their advantages (energy efficiency, control and quality of energy.)

In this thesis, a hybrid system was simulated and optimized using two different methods, this hybrid system was based on three sources, two on renewable energy (solar and wind) and one combustion resource (diesel generator) for feeding rural village in southwest Algeria named "Timiaouine", the objective of this thesis is to build a hybrid system based on green energy and covering all consumption of this rural village.

In the first chapter, we describe energy condition in the whole world and in Algeria, then some generality of a hybrid system like the definition of this system, classification of the hybrid system in many ways and finish by possible configuration on the hybrid system.

The second chapter summarizes the last and main research published on the hybrid system recently, the chapter was divided on three sections:

- Sizing methods
- Control methods
- Management methods

In the end of each section, a full comparison between methods was achieved.

The third chapter focuses on the sizing component of the hybrid system. First, description is made on rural village demand in high and low seasons (summer and winter respectively), then on size of generators of hybrid system using two different methods; the first one is classical as modified method and the second one uses commercial software, the results show that there are differences in the capacity of each method that makes the obtained technical results using commercial software better than those obtained in classical modified methods. On the other hand, economically speaking, the classical method was better. It is also beneficial in terms of the environment, considering the low capacity of the generator and low consumption of fuel.

In the fourth chapter, we describe mathematical models for each component of the hybrid system (generators and converter). These mathematical models will help us analyze and understand the hybrid system and also each production part.

This chapter was divided into four sections:

- Solar photovoltaic
- Wind turbine
- Diesel generation
- Power rectifier

The last chapter evaluates results obtained in chapter three to simulate the hybrid system using two methods. The first one is by using MATLAB Simulink and the second one is by using HOMER PRO, the results show that the system sized by a classical modified method was better technically, economically and environmentally than the system sized using HOMER PRO.

It is recommended that further work is focused on:

1 Sizing hybrid system using a different algorithm (fuzzy logic, artificial neural network, algorithm genetic…etc.) and predictive methods

2 Control stability, power balance and protection of hybrid system based on last genetic methods

3 Improve the quality of produced energy (frequency, voltage, current, reactive power)

4 Implanting hybrid system in real experience using electronic appliance (Dspace, C2000...etc.)

In the end, we conclude that hybrid system can be the solution for people who are living out access to electricity and covers their demand through days and nights, produces energy with attractive cost and low dioxide carbon emission.

References

[1] Ghosh, T. K., & Prelas, M. A. (2009). Energy Resources and Systems. Volume 1: Fundamentals and non-renewable resources. New York. Revista Springer.

[2] Kreith, F., & Goswami, D. Y. (2007). Energy conversion. CRC Press.

[3] Laughton, M. A., & Say, M. G. (Eds.). (2013). Electrical engineer's reference book. Elsevier.

[4] Marques AJ, Boccaletti C, Ribeiro EFF. Uninterruptible Power Production in standalone Power Systems for Telecommunications presented at the International Conference on Renewable Energies and Power Quality (ICREPQ'09) Valencia (Spain), 2009.

[5] Erdinc O, Uzunoglu M. Optimum design of hybrid Renewable energy systems: Overview of different approaches. Renew Sustain Power Rev 2012; 16:1412–25

[6] Energies Nouvelles, Renouvelables et Maitrise de l'Energie (French), Ministry of power. Algeria. Edition 2016 (http://www.power.gov.dz/francais/uploads/2016/Energie/energie-renouvelable.pdf)

[7] Masters, G. M. (2013). Renewable and efficient electric power systems. John Wiley & Sons.

[8] Kaltschmitt, M., Streicher, W., & Wiese, A. (Eds.). (2007). Renewable energy: technology, economics and environment. Springer Science & Business Media.

[9] Smith, Z. A., & Taylor, K. D. (2008). Renewable and alternative energy resources: a reference handbook. ABC-CLIO.

[10] Rashid, M. H. (2015). Electric Renewable Energy Systems. Academic Press.

[11] Bajpai P, Dash V. Hybrid Renewable energy systems for power generation in stand-alone applications: A review. Renew Sustain Power Rev 2012;16:2926–39.

[12] Shivarama Krishna, K., & Sathish Kumar, K. (2015). A review on hybrid Renewable energy systems. Renewable and Sustainable Power Reviews, 52, 907–916. https://doi.org/10.1016/j.rser.2015.07.187

[13] Intergovernmental Panel on Climate Change. (2017). Climate Change 2017 – The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press. doi:10.1017/CBO9781107415324

[14] IEA International Power Agency (2015) World Power Outlook Executive Summary English version (https://www.iea.org/Textbase/npsum/WEO2015SUM.pdf)

[15] IEA International Power Agency (2017) World Power Outlook Executive Summary English version (https://www.iea.org/Textbase/npsum/WEO2017SUM.pdf)

[16] Steve Cole,John Leslie, Rani Gran / Aries Keck, NASA Headquarters press release No. 12-422April 2012, https://www.nasa.gov/mission_pages/NPP/news/earth-at-night.html

[17] Enerdata, Global Power Statistical Yearbook. "Total power use. [Online]https://yearbook.enerdata.net/total-power/world-use-statistics.html." Consulted in (2018)

[18] Factbook, C. I. A. "The world factbook." See also: https://www.cia.gov/library/publications/resources/the-world-factbook/geos/ag.html

[19] Bilan énergétique national (French), Ministry of power, Algeria. Edition 2017;[Online]http://www.power.gov.dz/francais/uploads/2017/Bilans_et_statistiques_du_secteur/Bilan-Energ etique/Bilan_Energetique_National_2016_edition_2017.pdf

[20] Mekideche MA. Synthèse des bilans d'activités et Comptes sociaux consolides 2013 des sociétés et du Groupe Sonelgaz, Juin. 2014. Newsletter press n29. [Online]http://www.sonelgaz.dz/Media/upload/13%2006%2003_newsletter_bilan%202013_final_rev1_final.pdf

[21] BP Power Outlook June 2017;[Online]https://www.bp.com/content/dam/bp/pdf/power-economics/power-outlook-2017/bp-power-outlook-2017.pdf

[22] Exxon Mobil, 2017 Outlook for Power: A View to 2040. [Online]http://cdn.exxonmobil.com/~/media/global/files/outlook-for-power/2017/2017-outlook-for-power.pdf

[23] BP Statistical Review of World Power June 2017; [Online]https://www.bp.com/content/dam/bp/en/corporate/pdf/power-economics/statistical-review-2017/bp-statistical-review-of-world-power-2017-full-report.pdf

[24] Electricity Production by Country, ChartsBin.com, viewed 16th January, 2018, (http://chartsbin.com/view/41878)

[25] Stambouli, Amine Boudghene. "An overview of different power sources in Algeria." Jordan Engineers (2009).

[26] Renewable energies and power efficiency development program in Algeria, Ministry of power. Algeria. Edition 2016(http://www.power.gov.dz/francais/uploads/2016/Projets_du_Secteur/Programme_EnR_2016/Plaquette_PNEREE_2016_En.pdf)

[27] Girardet, H., & Mendonca, M. (2009). A Renewable World: Energy. Ecology, Equality.

[28] Vivas, F. J., Heras, A. De, Segura, F., & Andújar, J. M. (2018). A review of power management strategies for renewable hybrid power systems with hydrogen backup, 82(April 2016), 126–155. https://doi.org/10.1016/j.rser.2017.09.014

[29] Chauhan A, Saini RP. A review on Integrated Renewable energy System based power generation for stand-alone applications: configurations, storage options, sizing methodologies and control. Renew Sustain Power Rev 2014;38:99–120.

[30] Stoyanov, L. (2011). Etude de différentes structures de systèmes hybrides à sources d'énergie renouvelables. Thesis doctorate, Technical University of Sofia, Bulgaria

[31] Aeidapu, M., Kanwarjit, S. (2015) Hybrid wind/photovoltaic power system developments: Critical review and findings. Renewable and Sustainable Power Reviews, 52, 1135–1147

[32] Kempener, I. R., Lavagne, O., Saygin, D., Skeer, J., Vinci, S., & Gielen, D. (IRENA) OFF-GRID RENEWABLE ENERGY SYSTEMS: STATUS AND METHODOLOGICAL ISSUES, WORKING PAPER 2015

[33] M. Benatmane and R. Maltby, "Integrated Electric Power and Propulsion System on Land An Overview," 2007 IEEE Electric Ship Technologies Symposium, Arlington, VA, 2007, pp. 7-13.doi: 10.1109/ESTS.2007.372057

[34] "TYPE 45 – The Anti-Air Warfare Destroyer" (PDF). Royal Navy. Archived from the original (PDF) on 2009-04-18. Retrieved 2010-06-08

[35] "Queen Mary 2 Technical" (PDF). Cunard. Archived from the original (PDF) on 2010-01-06. Retrieved 2013-01-08. (archived from the original 6 January 2009)

[36] Ramakumar R.Integrated Renewable energy systems: power engineering review.IEEE1995;15(2):10–3.

[37] Akikur RK, SaidurR, Ping HW, UllahKR. Comparative study of stand-alone and hybrid solar power system suitable for off-grid rural electrification: are view. Renew Sustain PowerRev2013;27:738–52.

[38] Outlook, Africa Power. "A focus on power prospects in Sub-Saharan Africa." International Power Agency IEA (2014).

[39] Gary D. Burch, Hybrid Renewable energy Systems, U.S. DOE Natural Gas / Renewable energy Workshops August 21, 2001Golden, Colorado, USA

[40] Indragandhi, V., Subramaniyaswamy, V., & Logesh, R. (2017). Resources, configurations, and soft computing techniques for power management and control of PV/wind hybrid system. Renewable and Sustainable Power Reviews, 69(May 2015), 129–143. https://doi.org/10.1016/j.rser.2016.11.209

[41] YangH, Wei Z, Chengzhi L. Optimal design and techno-economic analysis of a hybrid solar–wind power generation system. Applied Power 2009;86 (2):163–9.

[42] Chen J., Che Y., Zhao L. Design and research of off-grid wind-solar hybrid power generation systems. In: Proceedings of the 2011 4th International Conference on Power Electronics Systems and Applications (PESA); 2011.

[43] Elhadidy MA, Shaahid SM. Promoting applications of hybrid power systems in hot regions. Renew Power 2004;29:517–28.

[44] Notton G, Muselli M, Louche A. Autonomous hybrid photovoltaic power plant using a back-up generator: a case study in a Mediterranean Island. Renew Power 1996;7:371–91.

[45] Li, Xiangjun, Dong Hui, and Xiaokang Lai. "Battery power storage station (BESS)-based smoothing control of photovoltaic (PV) and wind power generation fluctuations." IEEE Transactions on Sustainable Power 4.2 (2013): 464-473.

[46] Mohammed, A., Pasupuleti, J., Khatib, T., & Elmenreich, W. (2015). A review of process and operational system control of hybrid photovoltaic / diesel generator system. Renewable and Sustainable Power Reviews, 44, 436–446. https://doi.org/10.1016/j.rser.2014.12.035

[47] Ashari M, Nayar C. An optimum dispatch strategy using set points for a photovoltaic (PV)–diesel–battery hybrid power system. SolPower1999; 66: 1–9.

[48] Elmitwally A, Rashed M. Flexible operation strategy for an isolated PV–diesel micro grid without power storage. IEEE Trans Power Convers 2011; 26:235–244.

[49] David Blaise TSUANYO, Technico-economic approaches for optimization of decentralized power systems: case of PV /Diesel hybrid systems (in French), thesis doctorate, university of Perpignan, France, June 2015

[50] Carole Darcissac, technical document of hybrid central of Kaw (in French), August 2009 (http://www.ctguyane.fr/www/ressources/File/sept09/PRME-Plaquette-Decideurs_BAT.pdf)

[51] International Hydropower Association. "2015 hydropower status report'." International Hydropower Association, London, United Kingdom (https://www.hydropower.org/2015-hydropower-status-report).

[52] Chauhan, A., & Saini, R. P. (2014). A review on Integrated Renewable energy System based power generation for stand-alone applications: Configuration, storage options, sizing methodologies and control. Renewable and Sustainable Power Reviews, 38, 99–120. https://doi.org/10.1016/j.rser.2014.05.079

[53] Sao C K, Lehn PW. A transformer less power storage system based on a cascade multi-level PWM converter with star configuration. IEEE Trans Ind Appl 2008; 44(5):1621–30.

[54]A. Green, C. Diep, R. Dunn, J. Dent, High capacity factor CSP-PV hybrid systems, Power Procedia 69 (2015) 2049–2059.

[55] K.Larchet, Solar PV-CSP Hybridisation for Baseload Generation: ATechno- economic Analysis for the Chilean Market, in, KTH School of Industrial Engineering and Management, 2015.

[56] T.T. Chow, A review on photovoltaic/thermal hybrid solar technology, Appl Power 87 (2010) 365–379.
[57] M. Vetter, Hybrid CPV-CSP approach 100 % renewables for ASKAP and SKA, in Fraunhofer ISE, 2011.

[58] X. Han, C. Xu, X. Ju, X. Du, Y. Yang, Power analysis of a hybrid solar concentrating photovoltaic/concentrating solar power (CPV/CSP) system, Sci.Bull. 60 (2015) 460–469.

[59] Ju, X., Xu, C., Hu, Y., Han, X., Wei, G., & Du, X. (2017). Solar Power Materials & Solar Cells A review on the development of photovoltaic / concentrated solar power (PV- CSP) hybrid systems. Solar Power Materials and Solar Cells, 161(December 2016), 305–327. https://doi.org/10.1016/j.solmat.2016.12.004

[60] Powell, K. M., Rashid, K., Ellingwood, K., Tuttle, J., & Iverson, B. D. (2017). Hybrid concentrated solar thermal power systems: A review. Renewable and Sustainable Power Reviews, 80, 215-237.

[61] Abengoa plans 210 MW CSP-PV hybrid projects in northern Chile, in, 2013.

[62] ABENGOA, Abengoa obtains environmental approval for Atacama 2, its second solar complex of 210 MW in Chile, in, 2015.

[63] Avezova, N. R., et al. "Solar thermal power plants in the world: The experience of development and operation." Applied Solar Power 53.1 (2017): 72-77.

[64] Loisel, R., Mercier, A., Gatzen, C., & Elms, N. (2011). Market evaluation of hybrid wind-storage power systems in case of balancing responsibilities. Renewable and Sustainable Power Reviews, 15(9), 5003–5012. https://doi.org/10.1016/j.rser. 2011.07.054

[65] Drouilhet, S. (n.d.). Wind-Diesel Hybrid System Options for Alaska Wind-Diesel Hybrid Power Systems.

[66] Sawle, Y., Gupta, S. C., & Bohre, A. K. (2017). Review of hybrid Renewable energy systems with comparative analysis of off -grid hybrid system Loss of Power Supply Probability Loss of Load Probability, (June). https://doi.org/10.1016/j.rser.2017.06.033

[67] Muhammad Shahazad Aziz, Sohaib Ahmed, Umair Saleem, Gussan Maaz Mufti, Wind-hybrid Power Generation Systems Using Renewable energy Sources-A Review, INTERNATIONAL JOURNAL of RENEWABLE ENERGY RESEARCH, Vol.7, No.1, 2017.

[68] M. Hassan, R. Shakoor, A. Raheem, Pecuniary Optimization of Biomass/Wind Hybrid Renewable System, Proceedings of the 1st International e- Conference on Energies (Switzerland), 2014, 1-10.

[69] C. Retzke, P. Mulard, M. Wenske, Wind hydrogen feasibility study: terms of investment analysis. In the TOTAL and ENERTRAG cooperation to develop and integrated wind hydrogen approach. NHA Conference and Hydrogen Expo Columbia, S

[70] Monaaf D.A. Al-falahi , S.D.G. Jayasinghe, H. Enshaei (2017). A review on recent size optimization methodologies for standalone solar and wind hybrid Renewable energy system. Power Conversion and Management, 143, 252–274. https://doi.org/10.1016/j.enconman.2017.04.019

[71] Fathima, A. H., & Palanisamy, K. (2015). Optimization in microgrids with hybrid power systems – A review. Renewable and Sustainable Power Reviews, 45, 431–446. https://doi.org/10.1016/j.rser.2015.01.059

[72] Arul, P. G., Rama chandaramurthy, V. K., & Rajkumar, R. K. (2015). Control strategies for a hybrid Renewable energy system: A review. Renewable and Sustainable Power Reviews, 42, 597–608. https://doi.org/10.1016/j.rser.2014.10.062

[73] Okinda, V. O., & Odero, N. A. (2015). A REVIEW OF TECHNIQUES IN OPTIMAL SIZING OF HYBRID RENEWABLE ENERGY SYSTEMS, 153–163.

[74] Upadhyay, S., & Sharma, M. P. (2014). A review on configurations, control and sizing methodologies of hybrid power systems. Renewable and Sustainable Power Reviews, 38, 47–63. https://doi.org/10.1016/j.rser.2014.05.057

[75] Krishna, K. S., & Kumar, K. S. (2015). A review on hybrid Renewable energy systems. Renewable and Sustainable Power Reviews, 52, 907–916. https://doi.org/10.1016/j.rser.2015.07.187

[76] Chauhan, A., & Saini, R. P. (2014). A review on Integrated Renewable energy System based power generation for stand-alone applications: Configuration, storage options, sizing methodologies and control. Renewable and Sustainable Power Reviews, 38, 99–120. https://doi.org/10.1016/j.rser.2014.05.079

[77] Siddaiah, R., & Saini, R. P. (2016). A review on planning, configuration, modeling and optimization techniques of hybrid Renewable energy systems for off grid applications. Renewable and Sustainable Power Reviews, 58, 376–396. https://doi.org/10.1016/j.rser.2015.12.281

[78] Suganthi, L., Iniyan, S., & Samuel, A. A. (2015). Applications of fuzzy logic in Renewable energy systems – A review. Renewable and Sustainable Power Reviews, 48, 585–607. https://doi.org/10.1016/j.rser.2015.04.037

[79] Bajpai, P., & Dash, V. (2012). Hybrid Renewable energy systems for power generation in stand-alone applications: A review. Renewable and Sustainable Power Reviews, 16(5), 2926–2939. https://doi.org/10.1016/j.rser.2012.02.009

[80] Dawoud, S. M., Lin, X., & Okba, M. I. (2017). Hybrid renewable microgrid optimization techniques: A review. Renewable and Sustainable Power Reviews, (August), 0–1. https://doi.org/10.1016/j.rser.2017.08.007

[81] Mahesh, A., & Sandhu, K. S. (2015). Hybrid wind/photovoltaic power system developments: Critical review and findings, 52, 1135–1147. https://doi.org/10.1016/j.rser.2015.08.008

[82] Fadaee, M., & Radzi, M. A. M. (2012). Multi-objective optimization of a stand-alone hybrid Renewable energy system by using evolutionary algorithms: A review. Renewable and Sustainable Power Reviews, 16(5), 3364–3369. https://doi.org/10.1016/j.rser.2012.02.071

[83] Bahramara, S., Moghaddam, M. P., & Haghifam, M. R. (2016). Optimal planning of hybrid Renewable energy systems using HOMER: A review. Renewable and Sustainable Power Reviews, 62, 609–620. https://doi.org/10.1016/j.rser.2016.05.039

[84] Sinha, S., & Chandel, S. S. (2015). Review of recent trends in optimization techniques for solar photovoltaic–wind based hybrid power systems. Renewable and Sustainable Power Reviews, 50, 755–769. https://doi.org/10.1016/j.rser.2015.05.040

[85] Mohammed, A., Pasupuleti, J., Khatib, T., & Elmenreich, W. (2015). A review of process and operational system control of hybrid photovoltaic / diesel generator systems. Renewable and Sustainable Power Reviews, 44, 436–446. https://doi.org/10.1016/j.rser.2014.12.035

[86] Ata, R. (2015). Artificial neural networks applications in wind power systems: a review, Renewable and Sustainable Power Reviews 49 (2015) 534–562 Contents. https://doi.org/10.1016/j.rser.2015.04.166

[87] Karabacak, K., & Cetin, N. (2014). Arti fi cial neural networks for controlling wind – PV power systems: A review, Renewable and Sustainable Power Reviews 29 (2014) 804–827 Contents. https://doi.org/10.1016/j.rser.2013.08.070

[88] Unamuno, E., & Barrena, J. A. (2015). Hybrid ac / dc microgrids — Part II: Review and classification of control strategies. Renewable and Sustainable Power Reviews, 52, 1123–1134. https://doi.org/10.1016/j.rser.2015.07.186

[89] Khare, V., Nema, S., & Baredar, P. (2016). Solar – wind hybrid Renewable energy system: A review. Renewable and Sustainable Power Reviews, 58, 23–33. https://doi.org/10.1016 /j.rser.2015.12.223

[90] Vivas, F. J., Heras, A. De, Segura, F., & Andújar, J. M. (2018). A review of power management strategies for renewable hybrid power systems with hydrogen backup. Renewable and Sustainable Power Reviews, 82(September 2017), 126–155. https://doi.org/10.1016/j.rser.2017.09.014

[91] Olatomiwa, L., Mekhilef, S., Ismail, M. S., & Moghavvemi, M. (2016). Power management strategies in hybrid Renewable energy systems: A review. Renewable and Sustainable Power Reviews, 62, 821–835. https://doi.org/10.1016/j.rser.2016.05.040

[92] Liu, Y., Yu, S., Zhu, Y., Wang, D., & Liu, J. (2018). Modeling, planning, application and management of power systems for isolated areas: A review. Renewable and Sustainable Power Reviews, 82(September 2017), 460–470. https://doi.org/10.1016/j.rser.2017.09.063

[93] Erniza, N., Rozali, M., Ra, S., Alwi, W., & Abdul, Z. (2016). Process Integration for Hybrid Power System supply planning and demand management – A review, 66, 834–842. https://doi.org/10.1016/j.rser.2016.08.045

[94] Akikur, R. K., Saidur, R., Ping, H. W., & Ullah, K. R. (2013). Comparative study of stand-alone and hybrid solar power systems suitable for off-grid rural electrification: A review. Renewable and Sustainable Power Reviews, 27, 738–752. https://doi.org/10.1016/j.rser.2013.06.043

[95] Goel, S., & Sharma, R. (2017). Performance evaluation of standalone, grid connected and hybrid Renewable energy systems for rural application: A comparative review. Renewable and Sustainable Power Reviews, 78(October 2016), 1378–1389. https://doi.org/10.1016/j.rser.2017.05.200

[96] Junaid, M., Kumar, A., & Mathew, L. (2017). Techno economic feasibility analysis of different combinations of PV-Wind- Diesel-Battery hybrid system for telecommunication applications in different cities of Punjab, India. Renewable and Sustainable Power Reviews, 76(January), 577–607. https://doi.org/10.1016/j.rser.2017.03.076

[97] Sinha, S., & Chandel, S. S. (2014). Review of software tools for hybrid Renewable energy systems. Renewable and Sustainable Power Reviews, 32, 192–205. https://doi.org/10.1016/j.rser.2014.01.035

[98] Saïd Bentouba, Mahmoud Bourouis, Feasibility study of a windphotovoltaic hybrid power generation system for a remote area in the extreme south of Algeria, Applied Thermal Engineering (2015), http://dx.doi.org/doi: 10.1016/j.applthermaleng.2015.12.014.

[99] Fadaeenejad M, Radzi MAM, AbKadir MZA, Hizam H. Assessment of hybrid Renewable energy sources for rural electrification in Malaysia. Renew Sustain Power Rev 2014;30:299–305.

[100] Mills A, Al-Hallaj S. Simulation of hydrogen-based hybrid systems usingHybrid2. Int J Hydrogen Power 2004;29:991–9.

[101] Liqun L, Chunxia L. Feasibility analyses of hybrid wind–PV-battery power system in Dongwangsha, Shanghai. Przegląd Elektrotechniczny2013;1a:239–42.

[102] Kalogirou SA. Use of TRNSYS for modelling and simulation of a hybrid thermal solar system for Cyprus. Renew Power 2001;23:247–60.

[103] Markvart T. Sizing of hybrid PV–wind power systems. Sol Power 1996;59(4):277–81.

[104] Mahesh, A., & Sandhu, K. S. (2015). Hybrid wind/photovoltaic power system developments: Critical review and findings. Renewable and Sustainable Power Reviews, 52, 1135–1147. https://doi.org/10.1016/j.rser.2015.08.008

[105] Amos Madhlopa Debbie Sparks, Keen Samantha, Moorlach Mascha, KrogPieter, Dlamini Thuli. Optimization of a PV/wind hybrid system under limited water resources. Renewable Sustainable Power Rev 2015;47(0):324–31.

[106] Camargo Nogueira Carlos Eduardo, Vidotto Magno Luiz, Niedzialkoski Rosana Krauss, de Souza Samuel Nelson Melegari, Incio Chaves Luiz, Edwiges Thiago, dos Santos Darlisson Bentes,

van Werncke. Sizing and simulation of a photovoltaic-wind power system using batteries, applied for a small rural property located in the South of Brazil. Renewable Sustainable Power Rev2014;29(0):151–7.

[107] Sharafi M, ELMekkawy TY. Multi-objective optimal design of hybrid Renewable energy systems using PSO-simulation based approach. Renew Power 2014;68:67–79.

[108] Lujano-Rojas JM, Dufo-López R, Bernal-Agustín JL. Probabilistic modeling and analysis of stand-alone hybrid power systems. Power 2013;63:19–27.

[109] Ogunjuyigbe ASO, Ayodele TR, Akinola OA. Optimal allocation and sizing of PV/Wind/Split-diesel/Battery hybrid power system for minimizing life cycle cost, carbon emission and dump power of remote residential building. Appl Power 2016;171:153–71.

[110] Chen H-C. Optimum capacity determination of stand-alone hybrid generation system considering cost and reliability. Appl Power 2013;103:155–64.

[111] Kamjoo A, Maheri A, Dizqah AM, Putrus GA. Multi-objective design under uncertainties of hybrid Renewable energy system using NSGA-II and chance constrained programming. Int J Electr Power Syst 2016;74:187–94.

[112] Fathy A. A reliable methodology based on mine blast optimization algorithm for optimal sizing of hybrid PV-wind-FC system for remote area in Egypt. Renewable energy 2016;95:367–80.

[113] Askarzadeh A, dos Santos Coelho L. A novel framework for optimization of a grid independent hybrid Renewable energy system: A case study of Iran. Sol Power 2015;112:383–96.

[114] Shi B, Wu W, Yan L. Size optimization of stand-alone PV/wind/diesel hybrid power generation systems. J Taiwan Instit Chem Eng 2016.

[115] Suhane P, Rangnekar S, Khare A, Mittal A. Sizing and performance analysis of standalone wind-photovoltaic based hybrid power system using ant colony optimization. IET Renew Power Gener 2016;10:964–72.

[116] Shi Z, Wang R, Zhang T. Multi-objective optimal design of hybrid Renewable energy systems using preference-inspired coevolutionary approach. Sol Power 2015;118:96–106.

[117] Bansal AK, Kumar R, Gupta RA. Economic analysis and power management of a small autonomous hybrid power system (SAHPS) using biogeography-based optimization (BBO) algorithm. IEEE Trans Smart Grid 2013;4(1):638–48.

[118] Sanajaoba S, Fernandez E. Maiden application of Cuckoo Search algorithm for optimal sizing of a remote hybrid Renewable energy System. Renewable energy 2016;96:1–10.

[119] Maleki A, Askarzadeh A. Optimal sizing of a PV/wind/diesel system with battery storage for electrification to an off-grid remote region: A case study of Rafsanjan, Iran. Sustain Power Technol Assess 2014;7:147–53.

[120] Askarzadeh A. A discrete chaotic harmony search-based simulated annealing algorithm for optimum design of PV/wind hybrid system. Sol Power2013;97:93–101.

[121] Akbar Maleki, Alireza Askarzadeh. Artificial bee swarm optimization for optimum sizing of a stand-alone PV/WT/FC hybrid system considering fLPSPg concept. Sol Power2014;107(0):227–35.

[122] Jingyi Zhao, Yuan Xiaofang. Multi-objective optimization of stand-alone hybrid PV wind diesel battery system using improved fruit fly optimization algorithm. Soft Computer 2015:1–13.

[123] Kuo-Hao Chang, Lin Grace. Optimal design of hybrid Renewable energy systems using simulation optimization. Simul Modell Pract Theory 2015;52(0):40–51.

[124] Panigrahi BK, Pandi VR, Sharma R, Das S, Das S. Multi objective bacteria foraging algorithm for electrical load dispatch problem. Power ConversManag2011;52(2):1334–42.

[125] Quan DM, Ogliari E, Grimaccia F, Leva S, Mussetta M. Hybrid model for hourly forecast of photovoltaic and wind power. Fuzzy Systems (FUZZ), 2013 IEEE International Conference on: IEEE; 2013. p. 1-6. ⟨http://dx.doi.org/10.1109/FUZZ-IEEE.2013.6622453⟩.

[126] Erdinc O, Elma O, Uzunoglu M, Selamogullari US. Real-time performance analysis of an optimally sized hybrid Renewable energy conversion unit. Power Build 2014;75:419–29.

[127] Khatod DK, Pant V, Sharma J. Analytical approach for well-being assessment of small autonomous power systems with solar and wind power sources. IEEE Trans Power Convers 2010;25(2):535–45.

[128] Siddaiah R, Saini RP. A review on planning, configurations, modeling and optimization techniques of hybrid Renewable energy systems for off grid applications. Renew Sustain Power Rev 2016;58:376–96.

[129] Ramakumar R, Abouzahr M, Ashenay K. A knowledge-based approach to the design of integrated Renewable energy systems. IEEE Trans Power Convers 1992;7(4):648–59.

[130] Deshmukh SS, Deshmukh MK. A new approach to micro-level power plan- ning—a case of Northern parts of Rajasthan, India. Renew Sustain Power Rev 2009;13:634–42.

[131] Xavier P, Daniel F, Geoff L. Multi-objective optimization of integrated power systems for remote communities considering economics and CO2 emissions. J Thermal Sci 2005;44(12): 1180–9.

[132] Ferrer-Martí L, Domenech B, et al. A MILP model to design hybrid wind– photovoltaic isolated rural electrification projects in developing countries. Eur J Oper Res 2013;226(2):293–300.

[133] Das TK, Chakraborty D, Swapan S. Power use and prospects for Renewable energy technologies in an Indian village. Power 1990;15(5):445–449.

[134] El-Zeftawy AA, Abou El-Ela AA. Optimal planning of wind-diesel generation units in an isolated area. Electr Power Syst Res 1991;22(1):27–33.

[135] Deb Kalyanmoy. Multi-objective optimization using evolutionary algorithms. vol.2012.Chichester: John Wiley & Sons; 2001.

[136] Goldberg David Edward. Genetic algorithms in search, optimization, and machine learning. Reading Menlo Park: Addison-Wesley; 1989.

[137] Mitchell, M. (1998). An introduction to genetic algorithms. MIT press.

[138] Bilal BO, Nourou D, Kébé CMF, Sambou V, Ndiaye PA, Ndongo M. Multi-objective optimization of hybrid PV/wind/diesel/battery systems for decentralized application by minimizing the levelized cost of power and the CO2 emissions. Int J Phys Sci 2015;10(5):192–203.

[139] Jangi, R. Neuro-Fuzzy modeling: Architecture, Analysis and Application. PhD thesis, University of California, Berkeley.

[140] Leekwijck, W. V. and Kerre, E. E. Defuzzification: criteria and classification. Fuzzy Sets and Systems, 108(2):159 – 178. Page 14

[141] Madau D., D. F. Influence value defuzzification method. Fuzzy Systems, Proceedings of the Fifth IEEE International Conference, 3:1819 – 1824.

[142] Laughton, M. A., & Say, M. G. (Eds.). (2013). Electrical engineer's reference book. Elsevier.

[143] Mukhtaruddin RNSR, Rahman HA, Hassan MY, Jamian JJ. Optimal hybrid Renewable energy design in autonomous system using Iterative-Pareto-Fuzzy technique. Int J Electr Power Syst 2015;64:242–9.

[144] Mamlook R, Akash BA, Mohsen MS. A neuro-fuzzy program approach for evaluating electric power generation systems. Power 2001;26:619–32.

[145] Tasri A, Susilawati A. Selection among Renewable energy alternatives based on a fuzzy analytic hierarchy process in Indonesia. Sustain Power Technol Assess 2014;7:34–44.

[146] Chen HH, Kang HY, Lee AHI. Strategic selection of suitable projects for hybrid solar-wind power generation systems. Renew Sustain Power Rev2010;14:413–21.

[147] Niknam T, Fard AK, Seifi A. Distribution feeder reconfiguration considering fuel cell/wind/photovoltaic power plants. Renew Power 2012;37:213–25.

[148] Kalantar M, Mousavi GSM. Dynamic behavior of a stand-alone hybrid power generation system of wind turbine, microturbine, solar array and battery storage. Appl Power2010;87:3051–64.

[149] Perera ATD, Attalage RA, Perera KKCK, Dassanayake VPC. A hybrid tool to combine multi-objective optimization and multi-criterion decision making in designing standalone hybrid power systems. Appl Power 2013;107:412–25.

[150] Moghaddam AA, Seifi A, Niknam T, Pahlavani MRA. Multi-objective operation management of a renewable MG (micro-grid) with back-up microturbine/fuel cell/battery hybrid power source. Power 2011;36:6490–507.

[151] Niknam T, Kavousifard A, Tabatabaei S, Aghae J. Optimal operation management of fuel cell/wind/photovoltaic power sources connected to distribution networks. J Power Sources2011;196: 8881–96.

[152] Bigdeli N. Optimal management of hybrid PV/fuel cell/battery power system: a comparison of optimal hybrid approaches. Renew Sustain Power Rev2015;42:377–93.

[153] Sinha S, Chandel SS. Prospects of solar photovoltaic–micro-wind based hybrid power systems in western Himalayan state of Himachal Pradesh in India. Power Convers Manage 2015;105:1340–51.

[154] Esmin AA, Lambert-Torres G, Zambroni, de Souza AC. A hybrid particle swarm optimization applied to loss power minimization. IEEE Trans Power Syst2005;20(2):859–66.

[155] Shang C, Srinivasan D, Reindl T. An improved particle swarm optimization algorithm applied to battery sizing for stand-alone hybrid power systems. Int J Electr Power Syst 2016;74:104–17.

[156] Sharafi M, El Mekkawy TY, Bibeau EL. Optimal design of hybrid Renewable energy systems in buildings with low to high Renewable energy ratio. Renew Power 2015;83 :1026–42.

[157] Katsigiannis YA, Georgilakis PS, Karapidakis ES. Hybrid simulated annealing—Tabu search method for optimal sizing of autonomous power systems with renewables. IEEE Trans Sustainable Power 2012;3(3):330–8.

[158] Bashir M, Sadeh J. Optimal sizing of hybrid wind/photovoltaic/battery considering the uncertainty of wind and photovoltaic power using Monte Carlo simulation. In: Proceedings of IEEE international conference, 2012.

[159] Khatib Tamer, Mohameda Azah, Sopian K. Optimization of a PV/wind micro-grid for rural housing electrification using a hybrid iterative/genetic algorithm: case study of Kuala Terengganu, Malaysia. Power Build 2012;47:321–33.

[160] Lujano-Rojas JM, Dufo-Lopez Rodolfo, José L, Agustin Bernal. Probabilistic modeling and analysis of stand-alone hybrid power systems. Power2013;63:19–27.

[161] Zhou T, Sun W. Optimization of battery–super capacitor hybrid power storage station in wind/solar generation system. IEEE Trans Sustainable Power 2014;5(2):408–15.

[162] Mukhtaruddin RNSR Rahman HA, Hassan MY, Jamian JJ. Optimal hybrid renewable power design in autonomous system using Iterative-Pareto-Fuzzy technique. Electr Power Syst 2015;64:242–9.

[163] Alsayed M, Cacciato M, Scarcella G, Scelba G. Design of hybrid power generation systems based on multi criteria decision analysis. Sol Power2014;105:548–60.

[164] Justo JJ, Mwasilu F, Lee J, Jung JW. AC-microgrids versus DC-microgrids with distributed power resources: a review. Renew Sustain Power Rev2013;24:387–405.

[165] Bidram A, Davoudi A. Hierarchical structure of microgrids control system. IEEE Trans Smart Grid 2012;3(4):1963–76.

[166] Olivares DE, Mehrizi-Sani A, Etemadi AH, Canizares CA, Iravani R, Kazerani M, et al. Trends in microgrid control. IEEE Trans Smart Grid 2014;5(4):1905–19.

[167] Zamora R, Srivastava AK. Controls for microgrids with storage: review, challenges, and research needs. Renew Sustain Power Rev 2010;14 (7):2009–18.

[168] Wai, L., Wong, Y. W., Rajkumar, R. K., Rajkumar, R. K., & Isa, D. (2016). Hybrid power storage systems and control strategies for stand-alone Renewable energy systems, 66, 174–189. https://doi.org/10.1016/j.rser.2016.07.059

[169] Ren YF, Bao GQ. Control strategy of maximum wind power capture of direct- drive wind turbine generator based on neural-network. In: Proceedings of the Asia-Pacific power and power engineering conference (APPEEC); 2010. p. 1–4.

[170] Ganjefar S, Ghassemi AA, Ahmadi MM. Improving efficiency of two-type maximum power point tracking methods of tip-speed ratio and optimum torque in wind turbine system using a quantum neural network. Power2014;67:444–53.

[171] AHMA Rahim, Raza SA. A differential evolution based adaptive neural network pitch controller for a doubly fed wind turbine generator system. Res J Appl Sci Eng Technol 2013;6(22):4271–80.

[172] Farzad Sedaghati, Ali Nahavandi, Mohammad Ali Badamchizadeh, Sehraneh Ghaemi, Mehdi Abedinpour Fallah. PV maximum power point tracking by using artificial neural network. Mathematical Problems in Engineering 2012;2012:10 Article ID 506709, http://dx.doi.org/10. 1155/2012/506709.

[173] Almonacid F, Rus C, Pérez PJ, Hontoria L. Estimation of the power of a PV generator using artificial neural network. Renewable energy 2009;34(December (12)):2743–50.

[174] Roumila Z, et al., Power management based fuzzy logic controller of hybrid system wind/photovoltaic/diesel with storage battery, International Journal of Hydrogen Power (2017), http://dx.doi.org/10.1016/j.ijhydene.2017.06.006

[175] Vandoorn TL, Vasquez JC, De Kooning J, Guerrero JM, Vandevelde L. Microgrids: hierarchical control and an overview of the control and reserve management strategies. IEEE Ind Electron Mag 2013;7(4):42–55.

[176] Liu X, Wang P, Loh PC. A hybrid AC/DC micro grid and its coordination control. IEEE Trans Smart Grid 2011;2(2):278–86.

[177] Milczarek A, Malinowski M, Guerrero JM. Reactive power management in islanded micro grid –proportional power sharing in hierarchical droop control. IEEE Trans Smart Grid 2015;6(4):1631–8.

[178] Shafiee Q, Dragicevic T, Vasquez JC, and Guerrero JM. Hierarchical control for multiple DC-microgrids clusters. In: Proceedings of the IEEE 11th international multi-conference on systems, signals & devices (SSD14); 2014. p. 1–6.

[179] Shafiee Q, Guerrero JM, Vasquez JC. Distributed secondary control for islanded micro grids –approach. IEEE Trans Power Electron 2014;29(2):1018–31.

[180] Torreglosa JP, García P, Fernández LM, Jurado F. Hierarchical power management system for stand-alone hybrid system based on generation costs and cascade control. Power Convers Manag 2014;77(1):514–26.

[181] Pan T-L, Wan H-S, Ji Z-C. Stand-alone wind power system with battery/super capacitor hybrid power storage. Int J Sustain Eng 2014;7:103–10. http://dx.doi.org/10.1080/19397038.2013.779327.

[182] Kollimalla SK, Mishra MK, Narasamma NL. Design and analysis of novel control strategy for battery and supercapacitor storage system. IEEE Trans Sustain Power 2014;5:1137–44. http://dx.doi.org/10.1109/TSTE.2014.2336896.

[183] Hredzak B, Agelidis VG, Jang M. A model predictive control system for a hybrid battery-ultracapacitor power source. IEEE Trans Power Electron 2014;29:1469–79. http://dx.doi.org/10.1109/TPEL.2013.2262003.

[184] García P, Torreglosa JP, Fernández LM, Jurado F. Optimal power management system for stand-alone wind turbine/photovoltaic/hydrogen/battery hybrid system with supervisory control based on fuzzy logic. Int J Hydrogen energy 2013;38:14146–58. http://dx.doi.org/10.1016/j.ijhydene.2013.08.106.

[185] Safari S, Ardehali MM, Sirizi MJ. Particle swarm optimization based fuzzy logic controller for autonomous green power system with hydrogen storage. Power Convers. Manag 2013;65:41–9. http://dx.doi.org/10.1016/j.enconman.2012.08.012.

[186] García P, García CA, Fernández LM, Llorens F, Jurado F. ANFIS-Based control of a grid-connected hybrid system integrating renewable energies, hydrogen and batteries. IEEE Trans Ind Inform 2014;10:1107–17. http://dx.doi.org/10.1109/TII.2013.2290069.

[187] Cano MH, Kelouwani S, Agbossou K, Dubé Y. Power management system for off- grid hydrogen production based on uncertainty. Int J Hydrogen Power 2015;40(23):7260-72

[188] More JJ, Puleston PF, Kunusch C, Fantova MA. Development and implementation of a supervisor strategy and sliding mode control setup for fuel-c based hybrid generation Systems. IEEE Trans Power Convers 2015;30(1):218-25

[189] Dash V, Bajpai P. Power management control strategy for a stand-alone solar photovoltaic-fuel cell–battery hybrid system. Sustain Power Technol Assess 2015;9:68–80.

[190] Thounthong P, Sikkabut S, Mungporn P, Sethakul P, Pierfederici S, Davat B. Differential flatness based-control of fuel cell/photovoltaic/wind turbine/super- capacitor hybrid power plant, In: Proceedings of the 4th international conference clean electrical power, Renewable energy Resources Impact, ICCE; 2013, p.298-305

[191] Zhang F, Thanapalan K, Procter A, Carr S, Maddy J, Premier G. Power management control for off-grid solar hydrogen production and utilization system. Int J Hydrog Power 2013;38(11):4334-41

[192] Trifkovic M, Sheikhzadeh M, Nigim K, Daoutidis P. Modeling and control of a renewable hybrid power stem with hydrogen storage. IEEE Trans Control Syst Technol 2013;22(1). [1–1].

[193] García P, Torreglosa JP, Fernández LM, Jurado F. Improving long-term operation of power sources in off-grid hybrid systems b d on Renewable energy, hydrogen and battery. J Power Sources 2014;265:149-59

[194] Trifkovic M, Marvin WA, Sheikhzadehy M, Daoutidis P. Dynamic real-time optimization and control of a hybrid power system. In European Control Conference (ECC), Zurich; 2013, p. 2669–74.

[195] Yumurtaci R. Role of power management in hybrid Renewable energy systems: case study based analysis considering seasonal conditions. Turk J Electr Eng Comput Sci 2013;21(4):1077-91

[196] Behzadi MS, Niasati M. Comparative performance analysis of a hybrid PV/FC/ battery stand-alone system using different power management strategies and sizing approaches. Int J Hydrogen Power 2015;40(1):538–48.

[197] Wang X, Tong C, Palazoglu A, El-farra NH. Power Management for the chlor-alkali process with hybrid Renewable energy generation using receding horizon optimization. In proceedings of the 53rd IEEE conference on decision and control; 2014, p. 4838–43

[198] Abedi S, Alimardani A, Gharehpetian GB, Riahy GH, Hosseinian SH. A comprehensive method for optimal power management and design of hybrid RES-based autonomous power systems. Renew Sustain Power Rev 2012;16(3):1577-87

[199] Bordons C, García-Torres F, Valverde L. Gestión Óptima De La Energía En Microrredes Con Generación Renovable. Rev Iberoam Automática Inf Ind R I 2015;12(2):117-32

[200] Cau G, Cocco D, Petrollese M, Knudsen Kær S, Milan C. Power management strategy based on short-term generation scheduling for a renewable mi rid using a hydrogen storage system. Power Convers Manag 2014;87:820-31

[201] Castañeda M, Cano A, Jurado F, Sánchez H, Fernández LM. Sizing optimization, dynamic modeling and power management strategies of a stand-alone PV/hydrogen/battery-based hybrid system. Int J Hydrogen Power 2013;38(10):3830–45.

[202] Athari MH, Ardehali MM. Operational performance of power storage as function of electricity prices for on-grid hybrid Renewable energy system by optimized fuzzy logic controller. Renew Power 2016;85:890-902

[203] Rouholamini M, Mohammadian M. Heuristic-based power management of a grid- connected hybrid power system combined with hydrogen storage. Renew Power 2016;96:354-65

[204] Türkay BE, Telli AY. Economic analysis of standalone and grid connected hybrid power systems. Renew Power 2011;36(7):1931–43.

[205] Fernandez-Ramírez LM, Garcıa-Tribiño P, Gil-mena AJ, Llorens-iborra F, Jurado F, García-Vazquez CA. Optimized operation combining costs, efficiency and lifetime of a hybrid Renewable energy system with power storage by battery and hydrogen in grid-connected applications. Int J Hydrogen Power 2016;41:23132–44.

[206] Valverde L, Pino F, Rosa F. Definition, analysis and experimental investigation of operation modes in hydrogen-renewable-based power incorporating hybrid power storage. Power Convers Manag 2016;113:290-311

[207] Torreglosa JP, García-triviño P, Fernández-ramirez LM, Jurado F. Control based on techno-economic optimization of renewable hybrid power system for stand-alone Syst App 2016;51:59–75. ISSN 0957-4174 http://dx.doi.org/10./j.eswa.2015.12.038.

[208] Bhakta S, Mukherjee V, Shaw B. Techno-economic analysis of standalone photovoltaic/ wind hybrid system for application in isolated hamlets of North-East India. J Renew Sustain Power 2015;7(2):023126

[209] "Population: Wilaya d'Adrar" (PDF) (in French). Office National des Statistiques Algérie. Retriever 1 July 2013.

[210] Structure relative de la population résidente des ménages ordinaires et collectifs âgée de 6 ans et plus selon le niveau d'instruction et la commune de résidence." (PDF) (in French). Office National des Statistiques Algérie. Retrieved 1 July 2013.

[211] Web site (https://en.wikipedia.org/wiki/Timiaouine)

[212] Web site (http://www.uni.dz/economy/article.php?id=976)

[213] Sonelgaz, G. (2014). Newsletter press n ° 29, 1–31.(http://www.sonelgaz.dz/Media/upload/13%2006%2003_newsletter_bilan%202013_final_rev1_final.pdf)

[214] El Monsif, bulletin N18, Operator Company of electrical system (OS.spa), November 2016, (PDF) (in French) (http://www.ose.dz/publications/ElMonsif18.pdf)

[215] F.J.Born, "Aiding Renewable Energy Integration through Complimentary Demand-Supply Matching,", PHD thesis, University of Strathclyde, 2001.

[216] P. Kern and I. Harris, "On the Optimum Tilt of Solar Collector", Solar Power, Vol. 17, N°2, pp. 92–112, 1975.

[217] M.M. Kassaby, “Monthly and Daily Optimum Tilt Angle for South Facing Solar Collectors, Theoretical Model, Experimental and Empirical Correlations”, Solar and Wind Technology, Vol.5, pp.589 – 596, 1988.

[218] G. Lewis, “Optimum sizing on a Collector for a Domestic Water Heating System”, Solar and Wind Technology, Vol. 4, N°3, pp. 411 - 414, 1987.

[219] H. Heywood, “Operating Experience with Solar Water Heating”, Journal of the Industrial Heat Ventilation Engineering, Vol. 39, pp. 63 – 69, 1971.

[220] Salim Makhloufi, Contribution à l’optimisation des installations photovoltaïques par des commandes intelligentes, doctorat thésis, université Hadj Lakhdar-Batna, 2013

[221] Marc Rapin, Jean-Marc Noël, ÉNERGIE ÉOLIENNE (French Edition), 2nd Edition (2010), ISSN 9782100597123

[222] Shea, K., & Howard, B. C. (2012). Build Your Own Small Wind Power System. McGraw-Hill.

[223] Victor O. Okinda, Nichodemus A. Odero, A REVIEW OF TECHNIQUES IN OPTIMAL SIZING OF HYBRID RENEWABLE ENERGY SYSTEMS, IJRET: International Journal of Research in Engineering and Technology Vol 04 Issue 11

[224] Guihéneuf Gérard (2009), Comprendre et dimensionner les installations domestiques à énergies renouvelables - Edition Elektor

[225] Kaltschmitt, M., Streicher, W., & Wiese, A. (Eds.). (2007). Renewable energy: technology, economics and environment. Springer Science & Business Media.

[226] Kanase Patil AB, Saini RP, Sharma MP. Sizing of integrated Renewable energy system based on load profiles and reliability index for the state of Uttarak- hand in India. Renew Power 2011; 36:2809–21.

[227] Khatib T, Elmenreich W. Novel simplified hourly power flow models for photovoltaic power systems. Power Convers Manage 2014; 79:441–8.

[228] Khatib T, Mohamed A, Sopian K, Mahmoud M. Optimal sizing of building integrated hybrid PV/diesel generator system for zero load rejection for Malaysia. Power Build 2011; 43:3430–5.

[229] B. S. Borowy, z. M. Salameh, "Optimum Photovoltaic Array Size for a Hybrid Wind/PV System". IEEE Transactions on Power Conversion, Vol. 9, N°3, September 1994. pp. 482-488.

[230] Intergovernmental Panel on Climate Change. (2017). Climate Change 2017 – The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press. doi:10.1017/CBO9781107415324

[231] Senjyu, T., Hayashi, D., & Yona, A. (2007). Optimal configuration of power generating systems in isolated island with Renewable energy, 32, 1917–1933.https://doi.org/10.1016/j.renene.2006.09.003

[232] Chedid R, Akiki H, Rahman S. A, decision support technique for the design of hybrid solar–wind power systems. IEEE Trans Power Convers 1998;13(1):76–83.

[233] Xia, Y., Ahmed, K. H., Member, S., & Williams, B. W. (2013). Wind Turbine Power Coefficient Analysis of a New Maximum Power Point Tracking Technique, 60(3), 1122–1132.

[234] Fernando, D. B., Hernán, D. B., & Ricardo, J. M. (2006). Wind turbine control systems: principles, modelling and gain scheduling design (advances in industrial control).

[235] J.G. Slootweg' H. Polinder Member IEEE, W.L. Kling, Member, IEEE, « Dynamic Modelling of a Wind Turbine with Doubly Fed Induction Generator », Electrical Power Systems, 2Electncat Power Processing

[236] Bindhu Babu, Divya S, Comparative study of different types of generators used in wind turbine and reactive power compensation, IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE) e-ISSN: 2278-1676, p-ISSN: 2320-3331, PP 95-99

[237] Polinder, H., van der Pijl, F. F. A., de Vilder, G. J., & Tavner, P. J. (2006). Comparison of direct-drive and geared generator concepts for wind turbines. IEEE Transactions on Power Conversion, 21(3), 725-733.

[238] Li, H., & Chen, Z. (2008). Overview of different wind generator systems and their comparisons. IET Renewable energy Generation, 2(2), 123-138.

[239] Wenping Cao, Ying Xie and Zheng Tan, Wind Turbine Generator Technologies, DOI (http://dx.doi.org/10.5772/51780), Chapter 7 Page 198,199

[240] Abdessemed, R. (2011). Modélisation et simulation des machines électriques. Ellipses.

[241] J.M. Hamilton, M. Negnevitsky, X. Wang, A. Tavakoli, M. Mueller-Stoffels, Utilization and Optimization of Diesel Generation for Maximum Renewable energy Integration, Chapter in Springer, DOI 10.1007/978-3-319-50197-0_2

[242] KANZUMBA KUSAKANA, OPTIMAL OPERATION CONTROL OF HYBRID RENEWABLE ENERGY SYSTEMS, Thesis doctoral, Central University of Technology-South Africa, October 2014.

[243] Daniel C. Garvey. A digital control algorithm for diesel engine governing. SAE Technical paper series, 850174, Feb. 25 -Mar. 1, 1985.

[244] S.D. Haddad and N. Watson. Principles and performance in diesel engineering. John Wiley & Sons, 1984.

[245] G. Erceg and **S.** Tešnjak, MODELLING AND SIMULATION OF DIESEL ELECTRICAL AGGREGATEVOLTAGE CONTROLLER WITH CURRENT SINK, Proceedings of the IEEE International Conference on Industrial Technology, 1996

[246] Sørensen, B. (2004). Renewable energy conversion, transmission, and storage. Elsevier.

[247] Rashid, M. H. (Ed.). (2017). Power electronics handbook. Butterworth-Heinemann.

[248] Sahoo, S. K., Sukchai, S., & Yanine, F. F. (2018). Review and comparative study of single-stage inverters for a PV system. Renewable and Sustainable Energy Reviews, 91(March 2017), 962–986. https://doi.org/10.1016/j.rser.2018.04.063

[249] Jana, J., Saha, H., & Bhattacharya, K. Das. (2017). A review of inverter topologies for single-phase grid-connected photovoltaic systems. Renewable and Sustainable Energy Reviews, 72(April 2015), 1256–1270. https://doi.org/10.1016/j.rser.2016.10.049

[250] M.G. Simões, B. Palle, S. Chakraborty, and C. Uriarte, Electrical Model Development and Validation for Distributed Resources, Subcontract Report NREL/SR-581-41109, Colorado School of Mines Golden, Colorado, April 2007

[251] S. Hansen, M.Malinowski, F. Blaabjerg, M.P. Kazmier kowski, Sensor less control strategies for PW M rectifier, in: Proceedings of the APEC'00, 2000, pp. 832–838.

[252] T. Noguchi, H. Tomiki, S. Kondo, I. Takahashi, Direct power control of PWM converter without power-source voltage sensors, IEEE Trans. Ind. Appl. 34 (3) (1998) 473–479.

[253] I. Takahashi, Y. Ohmori, High performance direct torque control of an induction motor, IEEE Trans. Ind. Appl. 25 (2) (1989)257–264.

[254] P.J.M. Smidt, J.L. Duarte, A unity power factor converter without current measurements, in: Proceedings of the EPE'95, vol.3, 1995, pp. 275–280.

[255] De Freitas, T. R. S., Menegáz, P. J. M., & Simonetti, D. S. L. (2016). Rectifier topologies for permanent magnet synchronous generator on wind energy conversion systems: A review. Renewable and Sustainable Energy Reviews, 54, 1334–1344. https://doi.org/10.1016/j.rser.2015.10.112

[256] Davari, P., Zare, F., & Abdelhakim, A. (2018). Active Rectifiers and Their Control. In Control of Power Electronic Converters and Systems (pp. 3–52). Elsevier Inc. https://doi.org/10.1016/ B978-0-12-816136-4.00013-0

[257] Pejovic, P. (2007). Three-phase diode rectifiers with low harmonics: current injection methods. Springer Science & Business Media.

List of Publications and communications

International journal:

Ammari, C., Hamouda,M., and Makhloufi,S. (2017) Sizing and Optimization for Hybrid Central in South Algeria Based on Three Different Generators. International Journal of Renewable Energy Development, 6(3), 263-272.http://doi.org/10.14710/ijred.6.3.263-272

Chouaib.A, Messaoud.H and Salim.M, Sizing, modelling and simulation for Hybrid Central PV/wind turbine/diesel generator for feeding rural village in South Algeria, EAI Endorsed Transactions On Energy Web, Volume 4 Issue 15, doi: 10.4108/eai.13-12-2017.153470

C.AMMARI, M. HAMOUDA and S. MAKHLOUFI, Sizing, Simulation and Optimization for Electrical Hybrid Central PV/Wind/Diesel in Southwest Algeria, J. Automation & Systems Engineering 11-2 (2017): 120-128

Conference Proceeding:

C. Ammari, M. Hamouda and S. Makhloufi, "Sizing, modeling and simulation for hybrid central based on three generator in southwest Algeria," 2017 6th International Conference on Systems and Control (ICSC), Batna, 2017, pp. 366-371.doi: 10.1109/ICoSC.2017.7958701 (IEEE)

Ammari C., Hamouda M., Makhloufi S. (2019) Comparison Between Three Hybrid System PV/Wind Turbine/Diesel Generator/Battery Using HOMER PRO Software. In: Chadli M., Bououden S., Ziani S., Zelinka I. (eds) Advanced Control Engineering Methods in Electrical Engineering Systems. ICEECA 2017. Lecture Notes in Electrical Engineering, vol 522. Springer, Cham

National Communications

Ammari Chouaib, Benoudjit Chalabia, Hamouda Messaoud, Makhloufi Salim, Dimensionnement d'un système de pompage éolien dans un site isolé, La Conférence Nationale Energie Hydrocarbure et Environnement, 3-4 Décembre 2014 Adrar-Algérie

International Communications:

C.AMMARI, M. HAMOUDA and S. MAKHLOUFI, Sizing and Optimization for Hybrid Central in South Algeria Based on Three Different Generators, International Conference on Recent Advances in Electrical Systems (ICRAES'16), 20-22 DEC. 2016, Hammamet, Tunisia

Ammari Chouaib, Hamouda Messaoud, Makhloufi Salim, Sizing, modeling and simulation for hybrid central based on three generator in southwest Algeria, 6th International Conference on System and Control (ICSC'17), MAY 7-9,Batna, Algeria

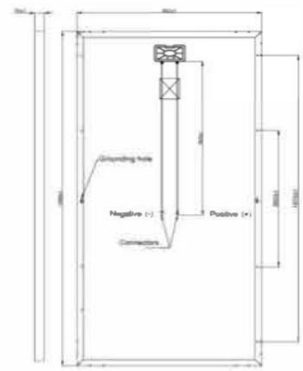
Chouaib Ammari, Hamouda Messaoud, Salim Makhloufi, Comparison Between Three Hybrid System PV/Wind turbine/Diesel Generator/Battery Using HOMER PRO Software, 3rd International Conference on Electrical Engineering and Control Applications (ICEECA2017), November 21-23, 2017, Constantine, Algeria

Appendix A

Module Photovoltaïque **Polycristallin**

72 Cellules

Caractéristiques physiques (mm) :



Caractéristiques électriques :

	Unité	Module		
Puissance nominale	W	275	280	285
Voltage Circuit ouvert (Vco)	V	44	44.6	44.6
Courant de court Circuit Isc	A	8.3	8.4	8.55
Tension mpp Vmpp	V	35.5	36	36
Courant mpp Impp	I	7.75	7.78	7.92
Système voltage max VDC	V		1000	
Charge maximale De fusibles (A)	A	15		
Facteur de température (cellule):				
Température nominale de fonctionnement	NOCT	45±2°C		
Coefficient de température de puissance	%/°C	-0,37		
Coefficient de température de courant	%/°C	+0,04		
Coefficient de température de voltage	%/°C	-0,33		

Caractéristiques mécaniques :

Type de cellule	Cellule polycristalline avec anti-reflection
Nombre de cellules par module	72cellules (6x12)
Dimensions de la cellule	156x156 mm
Dimensions du module	1956x992x50 mm
Poids du module	21kg
Cadre	Alliage en aluminium anodisé
Type de verre	Verre trempé, 3.2 mm d'épaisseur
Boite de jonction et connecteur	3 Diodes By-passe et câbles compatibles avec un connecteur MC4
Température d'utilisation	- 40°C à 85°C

STC: 1000 w/m2,AM1.5 et 25°C température de la cellule; NOCT: nominal operating cell temperature

Appendix B

ENERCON E-40/6.44 600 44.0

Company	ENERCON
Type/Version	E-40/6.44
Rated power	600,0 kW
Secondary generator	0,0 kW
Rotor diameter	44,0 m
Tower	Tubular
Grid connection	50/60 Hz
Origin country	DE
Blade type	ENERCON
Generator type	Variable
Rpm, rated power	34,5 rpm
Rpm, initial	18,0 rpm
Hub height(s)	78,0; 46,0; 50,0; 57,0; 65,0 m
Maximum blade width	1,97 m
Blade width for 90% radius	0,49 m
Valid	No
Creator	
Created	2001-06-13 16:29
Edited	2001-06-13 16:29

Power curve: Level 0 - guaranteed - - 04-2003

Source Manufacturer

Source date	Creator	Created	Edited	Default	Stop windSpeed [m/s]	Air density [kg/m3]	Tip angle [°]	Power control	CT curve type
2003-04-01 00:00		2001-06-13 16:39	2005-06-28 11:25	Yes	25,0	1,225	0,0	Pitch	User defined

Calculated by Enercon;
preliminary ct-curve taken from measurment Windtest 06/01

Power curve

Wind speed	[m/s]	1,00	2,00	3,00	4,00	5,00	6,00	7,00	8,00	9,00	10,00	11,00	12,00	13,00	14,00	15,00
Power	[kW]	0,00	0,00	1,70	14,70	41,40	79,60	135,80	207,50	295,40	405,20	508,10	571,40	600,00	600,00	600,00
Ce		0,000	0,000	0,068	0,247	0,356	0,396	0,425	0,435	0,435	0,435	0,410	0,355	0,293	0,235	0,191

Wind speed	[m/s]	16,00	17,00	18,00	19,00	20,00	21,00	22,00	23,00	24,00	25,00
Power	[kW]	600,00	600,00	600,00	600,00	600,00	600,00	600,00	600,00	600,00	600,00
Ce		0,157	0,131	0,110	0,094	0,081	0,070	0,061	0,053	0,047	0,041

Ct curve

Wind speed	[m/s]	1,00	2,00	3,00	3,50	4,00	4,50	5,00	5,50	6,00	6,50	7,00	7,50	8,00	8,50	9,00	9,50
Ct		0,00	0,00	0,86	0,86	0,84	0,82	0,80	0,78	0,76	0,76	0,75	0,74	0,74	0,73	0,73	0,73

Wind speed	[m/s]	10,00	10,50	11,00	11,50	12,00	12,50	13,00	13,50	14,00	14,50	15,00	15,50	16,00	16,50	17,00
Ct		0,71	0,70	0,70	0,66	0,53	0,45	0,39	0,34	0,30	0,27	0,24	0,22	0,20	0,18	0,17

Ct curve

Wind speed	[m/s]	17,00	17,50	18,00	18,50	19,00	19,50	20,00	20,50	21,00	21,50	22,00	22,50	23,00	23,50	24,00	24,50	25,00	25,50	26,00
Ct		0,17	0,15	0,14	0,13	0,12	0,12	0,11	0,10	0,10	0,09	0,09	0,08	0,08	0,08	0,07	0,07	0,07	0,00	0,00

HP curve comparison

Vmean	[m/s]	5	6	7	8	9	10
HP value	[MWh]	706	1 163	1 637	2 099	2 489	2 835
Level 0 - guaranteed - - 04-2003	[MWh]	752	1 214	1 694	2 145	2 541	2 870
Check value	**[%]**	**-6**	**-4**	**-3**	**-2**	**-2**	**-1**

Appendix C

Avesco AG
Energy Systems
Hasenmattstrasse 2
CH – 4901 Langenthal / BE
www.avesco.ch
info@avesco.ch

Tel: +41 (0)848 363 749
Fax: +41 (0)62 915 81 36

Ref: CAT 3516BHD-2500_EN
Date: 11 November 2013

Technical data Diesel Generator Set — CAT 3516BHD-2500

Output Ratings with Radiator	**DIN/ISO 3046**	
Combustion Strategy	Low Emissions, 60 °C ACT	
Generating set Model	**Prime**	**Standby**
400V, 50Hz, power factor 0.8	2'275 kVA 1'820 kW	2'500 kVA 2'000 kW
Feature Code	516DE92	
Performance No.	DM8382	DM8379

Diesel Engine	
Brand	Caterpillar
Type	3516B-HD TA
No. of Cylinders / Alignment	16 / V
Cycle	4-Stroke
Cooling Method	Water-cooled
Fuel	Diesel
Speed	1'500 rpm
Bore	170.00 mm
Stroke	215.00 mm
Displacement	78.08 L
Compression Ratio	15.5:1
Aspiration	Turbo after cooler
Fuel System	Electronic unit injection
Base Tank Capacity	n. a.
Jacket Water heaters	220 V / 9 kW
Starting Motor	2 x 24 V / 7 kW
Battery Type	153-5700
Quantity	4
Capacity per Battery / total	145 Ah - 12 V / 290 Ah - 24 V

Generator	
Brand	Caterpillar
Type / Frame	1844
Excitation	Permanent Magnet or AREP
Pitch	0.6667
Number of Poles	4
Number of Bearings	2
Number of Leads	6
Insulation	Class H
IP Rating	IP23
Nominal Speed	1'500 rpm
Over Speed capability	150 %
Wave form Deviation (Line to Line)	3 %
Voltage Regulator	3 Phase sensing with selectible volts/Hz
Voltage regulation	Less than ± ½% (steady state) Less than ± 1% (no load to full load)
Telephone Influence Factor (TIF)	Less than 50
Total Harmonic Distortion (THD)	Less than 5%
CBK 3pol manual, fixed mount rear	4'000 A / 50 kA
Typical Cabeling; TN-C (Prime)	10 x 4 x 240 mm² + 5 x 1 x 240 mm²
Typical Cabeling; TN-C (Standby)	10 x 4 x 240 mm² + 5 x 1 x 240 mm²

Package Dimensions		
Engine:	Length x Width x Height	3'342 x 1'468 x 1'985 mm
	Weight	8'047 kg
Generator:	Length x Width x Height	2'460 x 1'378 x 1'657 mm
	Weight	4'938 kg
Radiator:	Length x Width x Height	1'554 x 2'286 x 2'332 mm
	Dry Weight	884 kg
Complete:	Length x Width x Height	6'321 x 2'286 x 2'332mm
	Weight	14'369 kg

Illustration

Technical Data	**Prime**	**Standby**
Fuel Consumption		
100% load with Fan	497.3 L/hr	547.5 L/hr
75% load with Fan	374.4 L/hr	412.3 L/hr
50% load with Fan	255.5 L/hr	278.8 L/hr
Oil consumption 75% load	0.275 L/hr	0.302 L/hr
Cooling System		
Engine coolant Capacity with Radiator / expansion Tank	365.5 L	
Engine coolant Capacity	233.0 L	
Inlet Air		
Combustion Air inlet flow rate	167.6 m³/min	174.3 m³/min
Exhaust System		
Exhaust stack gas Temperature	506.3 °C	535.3 °C
Exhaust gas flow rate	453.7 m³/min	490.2 m³/min
Exhaust System backpressure max.	6.7 kPa	
Heat Rejection		
Heat Rejection to coolant (total)	711 kW	759 kW
Heat Rejection to exhaust (total)	1'923 kW	2'117 kW
Heat Rejection to after cooler	347 kW	406 kW
Heat Rejection to Atmosphere from Engine	164 kW	175 kW
Heat Rejection to Atmosphere from Generator	78.8 kW	83.3 kW
Lube System		
Sump refill with Filter	401.3 L	
Exhaust Emission (Nominal Data); Potential Site Variation possible		
NOx mg/nm³	1'969.6	2'095.4
CO mg/nm³	400.7	560.9
HC mg/nm³	50.3	40.9
Part Matter mg/nm³	47.9	49.9
Generator		
Motor starting capability @30% Voltage Dip	6'537 skVA	
Rated Current	3'283.7 A	3'608.4 A
Short-Circuit Current	3 x I_{NOM}	

Radiator	
Radiator Type	44.0 CTD
Design Temperature	35 °C
Radiator coolant Capacity	149.0 L
Air Flow @ 120 Pa	1'543 m³/min
Air Flow @ 180 Pa	1'459 m³/min

Sound pressure Level LPA @ 75% Last @ 7m

dB \ Hz	63	125	250	500	1000	2000	4000	8000	Overall dBA
Mechanical [Stby]	100	110	100	92	88	87	85	89	98
Exhaust [Stby]	97	108	102	93	92	94	94	89	100
Mechanical [Prim]	100	110	100	92	88	87	85	89	98
Exhaust [Prim]	96	107	101	92	92	93	93	89	100