Democratic and Popular Republic of Algeria

Ministry of Higher Education and Scientific Research

University of August 20, 1955 - Skikda

Faculty of Technology

Department of Electrical Engineering

Electrotechnical Branch

Course Material

Centralized and decentralized production

Level : Master 1 in Electrical Networks.

Created by :

Dr. SEKHANE Hocine

-Lecturer (Grade A) at the University of August 20, 1955 – Skikda-

❁ Academic year 2024/2025❁

Table of contents

Chapter I : General techniques for electricity generation

Chapter II : Decentralized Electrical Production (DEP)

Chapter III : Connection of DP to the Electrical Grid

Chapter IV : Critical Infrastructure of the Electrical System

Chapter V : Self-production in renewable energies (Microgrids)

Foreword

The handout you have in your hands is primarily intended for Master's students in Electrical Networks, specifically those taking the module titled « Centralized and Decentralized Production ».

The objective of this material is to provide students with a comprehensive study document that enables them to fully grasp the fundamental principles of Centralized Production (CP) and Decentralized Production (DP) in the field of electricity. Furthermore, the course includes a sufficient number of explanatory examples, images, photographs, and supplementary information in the appendix to deepen the concepts being taught.

Lastly, I sincerely pray that Allah assists me in imparting the message of knowledge to our esteemed students. I also wish them success and guidance. Amen.

Dr. SEKHANE Hocine

September 2024

Course Syllabus :

Centralized and Decentralized Production

١) Course Information

Faculty : Technology.

Department : Electrical Engineering.

Target Audience : Master's 1 in Electrical Networks (electrical engineering branch).

Course Title : Centralized and Decentralized Production.

Credits : 02.

Coefficient : 01.

Class Hours : 22 hours and 30 minutes (over 15 weeks).

Instructor : Dr. Hocine SEKHANE.

Contact : Email : docsekhoc@gmail.com ; h.sakhane@univ-skikda.dz

Availability : In the teachers' room : between working hours.

٢) Course Overview

The course is divided into five chapters, with each chapter being covered through pedagogical sequences to facilitate the assimilation of the intended concepts.

The management of all course learning units (chapters) is as follows :

Chapter	Hours per Week
I- General techniques for electricity generation	3
II- Decentralized Electrical Production (DEP)	4
III- Connection of DEP to the Electrical Grid	4
IV- Critical Infrastructure of the Electrical System	4
V- Self-Production in Renewable Energies (Microgrids)	4

٣) Prerequisites

To fully benefit from this course, it is recommended to have a solid grasp of the following prerequisite knowledge :

- ❶ **Knowledge in Basic Electricity :** A solid understanding of fundamental electrical concepts such as voltage, current, power, and electrical circuits is essential to grasp centralized and decentralized production systems.

❷ **Studies in Engineering Sciences :** Prerequisite knowledge in engineering sciences, including thermodynamics, fluid mechanics, and electromagnetism, can be beneficial when delving into advanced topics related to electrical power production.

❸ **Electrical Engineering Concepts :** Familiarity with the basic principles of electrical engineering, such as electric machines, transformers, and electrical networks, can enhance understanding of production systems.

❹ **Mathematics :** Mathematical skills, including calculus and linear algebra, may be necessary to solve complex problems related to electricity production and distribution.

❺ **Energy Economics Concepts :** A basic understanding of economic principles related to energy, such as production costs, electricity tariffs, and energy policies, can be valuable for analyzing the economic aspects of centralized and decentralized production.

٤) Learning Objectives

The course "Centralized and Decentralized Production" aims to :

① **Understand Fundamental Concepts :** Students should gain a deep understanding of the fundamental principles of electrical energy production, including various production technologies, laws of energy conversion, and basic electromagnetic concepts related to electrical production.

② **Learn About Technologies :** Students should learn about the technologies and equipment used in centralized and decentralized electricity production, including power plants, renewable energy sources, energy storage systems, and more.

③ **Analyze Energy Systems :** Students should be able to analyze complex energy systems, including the planning and management of electrical networks, considering technical, economic, and environmental aspects.

④ **Raise Awareness of Environmental and Economic Challenges :** Students should understand the environmental implications of electrical energy production and be able to assess the economic costs and benefits of various production methods.

٥) Methods of Assessing Learning

The evaluation will be conducted through a written exam covering the entire course content, where the score obtained will represent 100% of the final grade.

٦) Supporting Resources

To enrich the learning experience, I provide students with various supporting resources, accessible upon request via email :

- **Reference Documents :** Students can obtain files containing recommended knowledge to deepen their skills in the field.
- **Explanatory Videos :** I also offer explanatory videos and links to online resources that will help students better understand the concepts covered in the course.
- **Tutoring Sessions :** If students require individual assistance, I offer in-person or online tutoring sessions to address their specific questions and help them overcome challenges encountered in the course.
- **Discussion Forums :** Students are encouraged to participate in our online discussion forums where they can engage with their peers and ask questions for a deeper understanding.

I am committed to providing students with a wide range of resources to help them succeed in their learning in this course. Students should not hesitate to use these resources to strengthen their knowledge and understanding of the course.

General Introduction

Since the inauguration of the world's first electric power station in 1882 at Pearl Street Station in southern Manhattan by the father of electricity, Thomas Alva Edison, electrical energy has become an indispensable daily necessity and one of the most important factors for the development of any country [1].

Since then, and with the aim of meeting the growing demand for electrical energy, electricity has been produced over the years from various primary energy sources, the production of which can be categorized into two main categories: centralized production and decentralized production.

Centralized production is a method of electrical energy production in which the sources of energy are typically centralized at specific sites, such as hydroelectric power plants (near waterfalls), thermal power plants (near water sources), and nuclear power plants. Centralized productions are generally large-scale installations connected to the transmission network, with the power produced exceeding 500 MW in most installations of this type of production.

Decentralized production is generally defined as the opposite of centralized production, with sources that have a capacity not exceeding 50 to 100 MW, such as wind energy, solar energy, biomass, etc. Decentralized production is typically intermittent, and its production units are connected to the distribution network near consumption centers rather than the transmission network. Another characteristic of decentralized production is that it is dispersed across a territory, unlike conventional (centralized) production, which focuses on a limited number of well-defined sites [2].

This course is divided into five (05) chapters, beginning with a study of general electricity production techniques in the first chapter (different sources of electrical energy, conventional power plants (thermal and nuclear), etc.).

In order to discuss decentralized electrical production (DEP), the technologies of decentralized production, including both conventional and new and renewable sources (geothermal, solar, wind, biomass, etc.), are covered in the second chapter.

The third chapter is dedicated to the study of connecting decentralized electrical production (DEP) to the electrical grid. This chapter covers topics such as the conditions for connecting DEP to the electrical system, regulatory and organizational aspects of DEP development, technical aspects of connection to high-voltage networks, interactions between DEP and the electrical grid, and relevant standards.

The fourth chapter primarily deals with critical infrastructure of the electrical system, focusing on key aspects such as management in the presence of a high penetration rate of DEP, technical costs related to intermittency, methodology for managing critical situations, etc.

The last chapter is dedicated to the study of self-production in renewable energies, or in other words, microgrids. It covers details about the operation of microgrids, their operation and control, hybrid microgrids, monitoring, and data recording.

Finally, additional information is available in the appendix to further clarify the concepts covered.

Chapter I : General techniques for electricity generation

I.1. Sources of Electrical Energy

The production of electricity is carried out from various primary energy sources, which can be distinguished into two major categories :

I.1.1. Fossil Energy Sources

Also known as non-renewable sources such as oil, coal, gas, etc., are formed in the Earth over millions of years. These sources are inexhaustible as the Earth has the ability to replenish them, but this occurs over eons, such as the millions of years required to transform organic matter into fossil fuels [3, 4]. However, relying solely on these sources can lead to geopolitical challenges in certain countries, making energy independence unattainable.

I.1.2. Renewable Energy Sources

Such as solar energy, wind energy (wind power), biomass, hydropower, geothermal, etc. These sources are inexhaustible as they are replenished by natural processes over time [3, 4], resulting in low-cost electricity, nearly constant availability, and providing energy independence.

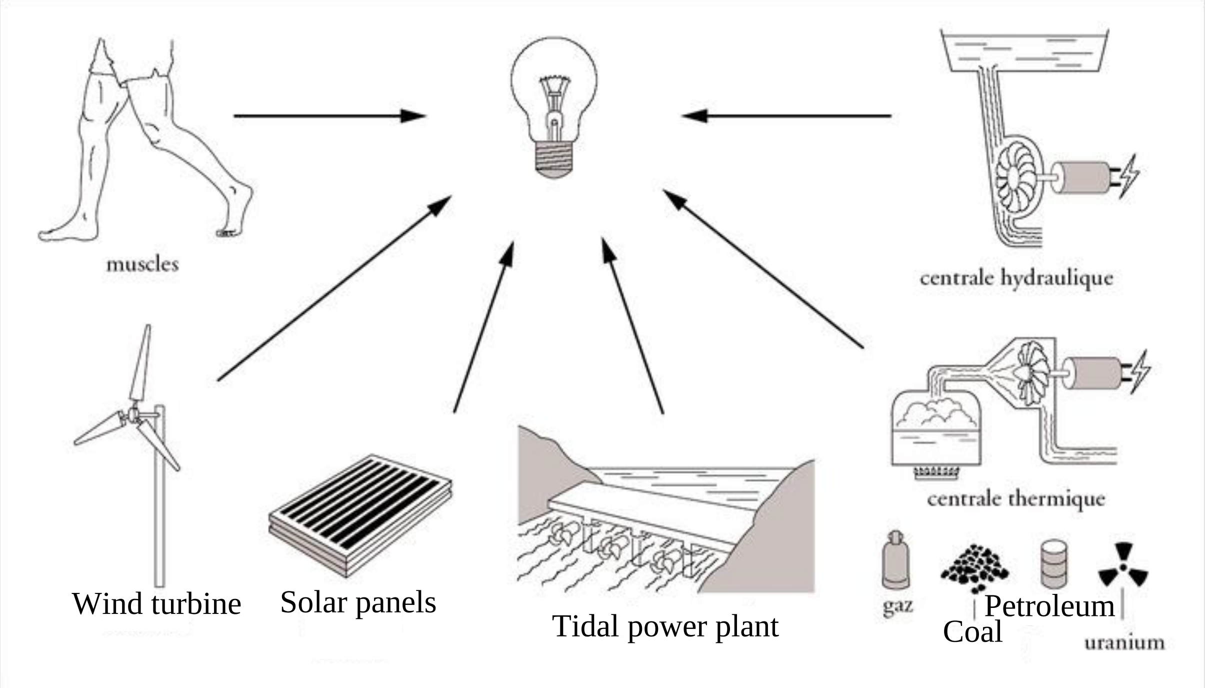


Fig. I.1. Different sources of electrical energy.

I.2. Conventional power plants (thermal and nuclear)

As an example, the graph in Fig. I.2. below, representing the annual power demand, indicates that a base power demand of 6 GW is required at all times, an intermediate power of 6 GW is needed for approximately 15% of the time, and a peak power of 3 GW is only required for a short period. Based on these fluctuations in energy demand, three classes of power plants have been envisaged as follows [5] :

a) **Base Load Power Plant :** This type of power plant generates high power continuously and operates at its full capacity at all times. The production thus matches the consumption, and as a result, the electricity cannot be stored. An example capable of fulfilling this role is « nuclear power plants ».

b) **Intermediate Load Power Plant :** During certain seasons, the demand exceeds the base load. Therefore, intermediate load power plants are needed to produce average power and can respond quickly to fluctuations in demand, such as « hydroelectric power plants ».

c) **Peak Load Power Plant :** During certain hours, there are peak consumption periods when the demand exceeds the base or intermediate load. Therefore, peak load power plants with lower capacity are needed, and they only operate at full capacity for short periods, meaning they are activated only when required.

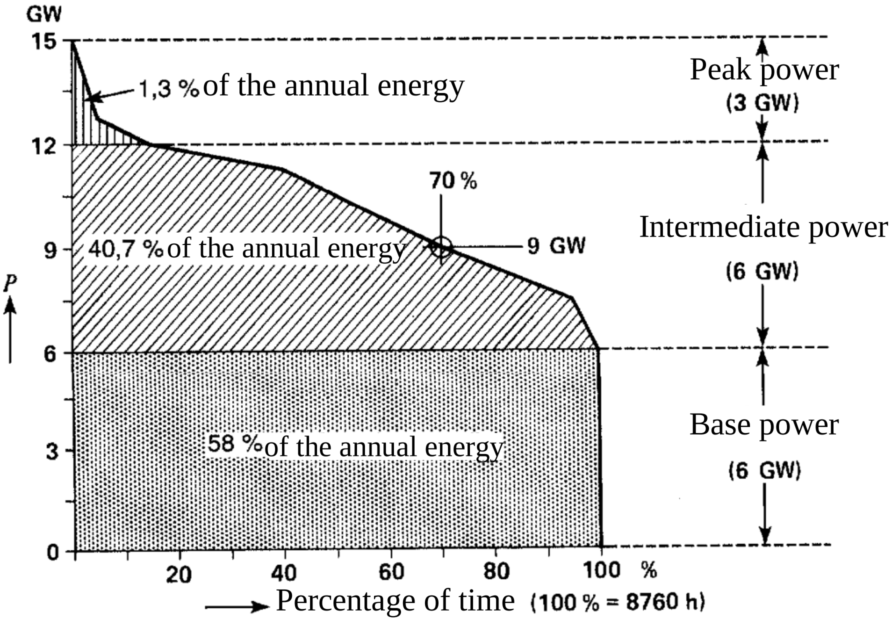


Fig. I.2. Power demand based on its annual usage time [5].

There are three (03) main types of power plants for generating electrical energy: hydraulic, thermal, and nuclear power plants. In the following, we will discuss the latter two.

I.2.1. Thermal power plants

A thermal power plant generates electricity from a heat source (such as oil, coal, natural gas, etc.). Because large quantities of water are required to cool and condense the steam coming out of the turbines, it is often located near a river or lake [5]. The turbine's action can be produced in two ways, leading to two main types of thermal power plants :

I.2.1.1. Steam Thermal Power Plants : Steam has the advantage of being extractable from water heated by the ignition of a fuel. This steam is injected into the steam turbine to set it in motion [6]. The turbine's action drives a generator, which subsequently transforms the mechanical force into electrical energy.

As illustrated in Fig. I.3. below, a steam power plant has the following equipment [6]:

1- Furnace for burning the fuel.

2- Steam generator or boiler containing water. The heat generated in the furnace is used to convert water into steam.

3- Main power unit such as an engine or turbine to harness the thermal energy of the steam and perform work.

4- Piping system to convey steam and water.

In addition to the above equipment, the power plant requires various auxiliaries and accessories depending on the availability of water, fuel, and the purpose for which the plant is intended.

The schematic diagram of a thermal power plant consists of the following four main circuits :

(1) Feedwater and steam flow circuit
(2) Coal and ash circuit
(3) Air and gas circuit
(4) Cooling water circuit.

Steam is generated in a boiler, expanded in the main engine, condensed in the condenser, and reintroduced into the boiler.

Fig. I.3. depicts a schematic layout of the equipment in a steam power plant. The coal received in the power plant's coal storage yard is transferred to the furnace by the coal handling unit. The heat produced by coal combustion is used to convert the water in the boiler drum into steam at an appropriate pressure and temperature. The generated steam passes through the superheater. The superheated steam then flows into the turbine. After performing work in the turbine, the steam pressure is reduced. The steam exiting the turbine passes through the condenser, which maintains low pressure at the turbine exhaust. The steam pressure in the condenser depends on the flow and temperature of the cooling water and the efficiency of the air removal equipment. The water circulating in the condenser can come from various sources such as rivers, lakes, or the sea. If a sufficient amount of water is not available, the warm water exiting the condenser can be cooled in cooling towers and recirculated through the condenser. Steam extracted from the turbine at appropriate extraction points is sent to low and high-pressure feedwater heaters.

The air extracted from the atmosphere first passes through the air preheater, where it is heated by the combustion gases. The hot air then flows through the furnace. The combustion gases, after passing through the boiler and superheater tubes, go through the dust collector, then through the economizer, the air preheater, and finally, they are discharged into the atmosphere through the chimney.

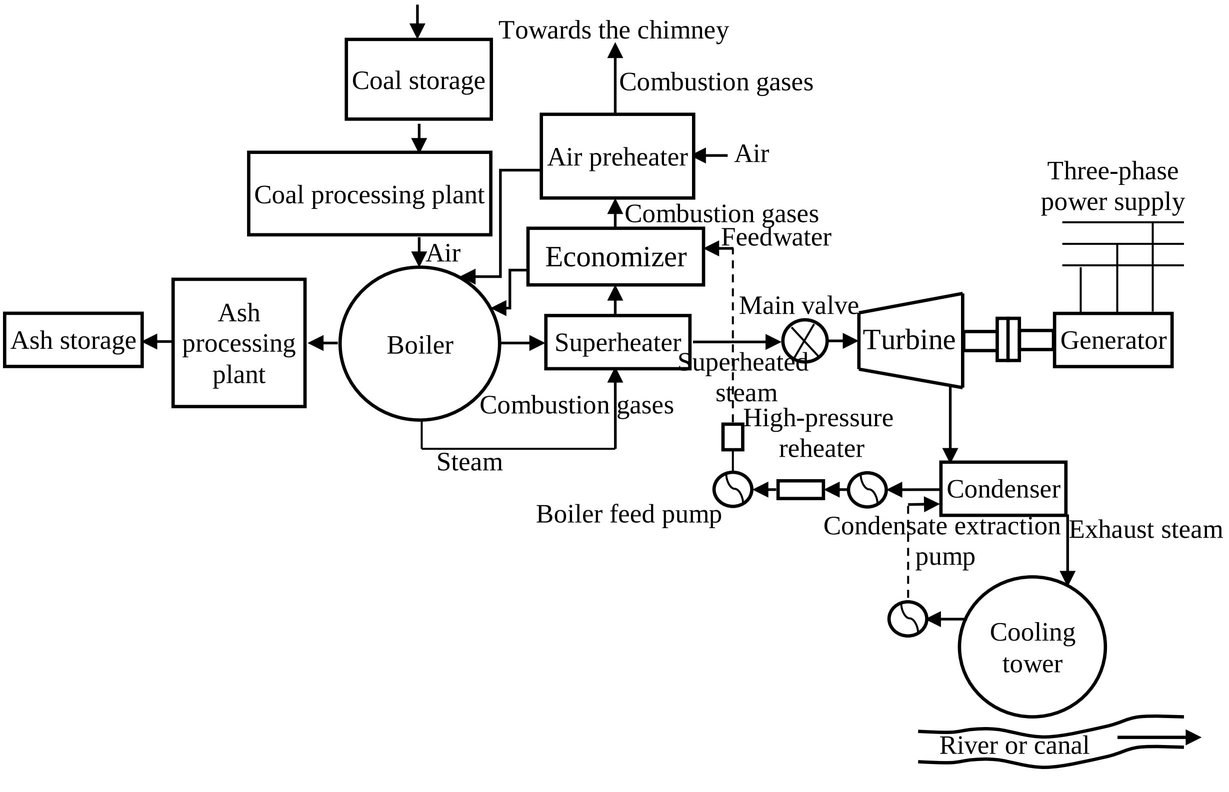


Fig. I.3. Schematic diagram of a steam thermal power plant.

The design of thermal power plants requires extensive experience. Satisfactory design includes the following steps [6] :

(1) Site selection

(2) Estimation of power plant capacity.

(3) Selection of turbines and their auxiliaries.

(4) Selection of boilers and their auxiliaries.

(5) Design of the fuel handling system.

(6) Selection of condensers.

(7) Design of the cooling system.

(8) Design of a piping system to transport steam and water.

(9) Selection of the electric generator.

(10) Design and control of instruments.

(11) Design of the power plant layout. The quality of coal used in the steam power plant plays a crucial role in power plant design. Various factors to consider when designing boilers and coal handling units include:

  (a) Ash scorching and erosion properties.

  (b) Moisture content in coal. Excessive moisture creates additional problems, especially in the case of pulverized fuel power plants.

  (c) Coal combustion characteristics.

  (d) Corrosive nature of ashes.

I.2.1.2. Combustion power plants (gas-fired) : Ignition of a fuel generates heat and expansion of gases into the surrounding air. This expansion creates a mechanical motion that drives the turbine. The turbine is connected to a generator that converts mechanical energy into electrical energy.

Combustion (gas-fired) power plants can be started and stopped quickly, making them suitable for use as peak-load plants. This type of plant efficiently manages operations at variable loads. They have a relatively low investment cost, require less space, and do not need a large amount of water, as in the case of steam power plants. They do not require a boiler and condensation facility, making them compact. They can be installed rapidly and are constructed in relatively smaller sizes, up to 70 MW. For larger sizes, steam turbine power plants are commonly used. Gas power plants are employed for electricity generation in areas where fuel is readily available or inexpensive, water is scarce, and the capacity factor is very low, typically around 15% to 18%. The heat lost during the operation of gas turbines in the combustion process can be utilized for gasification gas production and district heating. The gas cycle inherently exhibits a high thermodynamic efficiency, with a thermal efficiency of around 40%. It requires minimal maintenance [7].

Combustion power plants can be used as emergency backup plants. They require fewer auxiliaries, and their control is straightforward. They do not need high-pressure piping. Gas turbine power plants have a drawback ; they require a starting motor to bring them to the initial speed. A separate small diesel generator is used to power the starting motor [7].

As illustrated in Fig. I.4, a combustion (gas-fired) power plant in its simplest form consists of three main sections that perform the processes necessary for transforming the chemical energy of the fuel into mechanical energy: a compressor, a combustion chamber, and a turbine. Firstly, the compressor draws in air from the atmosphere and delivers it under pressure to the combustion chamber. Fuel is injected into the combustion chamber in atomized form and burned, raising the temperature. Finally, the hot gas formed in the combustion chamber expands through the turbine, producing mechanical power. The compressor is also connected to the same shaft, and the turbine provides power to drive the compressor, as well as the output shaft to drive the electric generator [7, 8]. The combustion products are expelled through a nozzle into the atmosphere [8].

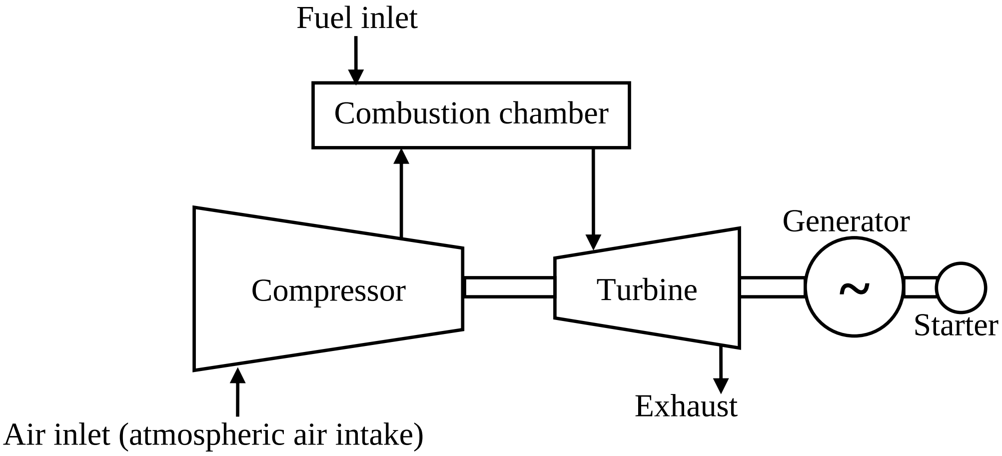


Fig. I.4. Simple configuration of a combustion (gas-fired) thermal power plant.

a) Compressor : Two types of compressors are used in gas turbine power plants : centrifugal and axial. In the early stages of gas turbine development, centrifugal compressors were used because they were easier to design and cheaper to manufacture. Axial flow compressors are more efficient and have now reached a high stage of development, being employed in most gas turbines. Each stage of an axial compressor consists of a row of rotor blades followed by a row of stator blades. The rotor blades accelerate the air, and the stators convert kinetic energy into pressure energy. An axial compressor has a large number of stages, up to 17 in some cases. For a single-shaft compressor, the practical maximum pressure ratio is 6:1.

b) Combustion Chamber : Consists of a container into which pressurized air and pressurized fuel are introduced in appropriate proportions, ultimately mixed, ignited, and introduced at the correct temperature into the turbine inlet. Approximately 30% of the main air flow passes into the burner zone as primary air. The air-fuel ratio in the zone is maintained at about 15:1. Secondary air is used to dilute the burned gases to lower their temperature to a level acceptable and suitable for the turbine blades. The fuel burner contains an atomizer that uses the fuel pressure to break it into an extremely fine spray that mixes with the primary air in the correct proportion for complete combustion. A high-energy igniter used is an electric spark plug to initially ignite the gas. Optical flame detection is provided so that in the absence of a flame, the fuel supply to the burners can be immediately and automatically cut off.

c) Turbine : It must fulfill two functions; the first is to provide energy to drive the compressor, and the second is to power the output shaft from which the alternator can be driven. In some cases, these two functions are separated; the high-pressure turbine drives the compressor, and the low-pressure turbine powers the generator—this arrangement is often referred to as the power turbine. This configuration is highly useful when fuel-fired thermal power plants are employed for electricity generation. For alternator drives, the speed of the power turbine must remain constant. The speed of the compressor turbine can vary depending on the required power.

I.2.2. Nuclear Power Plants

Public utility companies consider nuclear energy as a beneficial source of bulk electricity production, given the substantial increase in global electricity demand on one hand and the depletion of fuel reserves in many countries on the other hand. This form of energy does not produce air pollution and therefore represents an attractive alternative in the field of electricity generation, even though the reactor area poses a potential source of radioactivity and requires special protective measures [9].

Nuclear power plants generate electricity from the heat released through a nuclear reaction [5]. Compared to the energy release potential of fossil fuels, the energy released by nuclear fuel is astronomically high. While only 1 kg of U^{235} can release approximately 853106 MJ of heat through nuclear fission, a quantity of about 53106 kg of high-calorific-value coal at 17 MJ/kg must be burned to obtain an equivalent amount of energy [9].

I.2.2.1. Advantages of a Nuclear Power Plant

A nuclear power plant has several advantages compared to a conventional thermal power plant [7] :

1- It reduces the demand for fuel, the costs of which tend to increase as stocks deplete.

2- The transportation of conventional fuel to the station involves costs and potential delays if transportation means are not available on time. The weight of the nuclear fuel required for a plant of the same capacity is nearly negligible in comparison, and transportation issues are not a concern.

3- In addition to producing large quantities of energy, the nuclear power plant can generate valuable fissile materials, which are extracted when the fuel needs to be renewed.

4- The nuclear power plant requires less surface area and volume compared to a conventional power plant of equal capacity.

On the other hand, nuclear power plants can be used as base-load power stations. They are not suitable for variable load operation as reactors cannot be easily controlled to respond quickly to changes in load. They are operated at a capacity factor of at least 80%.

I.2.2.2. Methods of Generating Energy from Nuclear Fuel

There are two distinct methods of generating energy from nuclear fuel :

a) Nuclear fission: When heavy fissile elements undergo nuclear fission in a nuclear reactor, chain reactions of these elements occur, releasing a tremendous amount of energy.

b) Nuclear fusion : In nuclear fusion, simple atomic nuclei are fused to form complex nuclei (as in the case of the fusion of hydrogen isotopes to form helium), thereby releasing a large amount of energy.

The nuclear fusion process, also known as thermonuclear reaction, is still extremely challenging to control today. Therefore, at present, the primary source of nuclear energy is only available from nuclear fission.

The most common fissile radioactive heavy metals are the natural isotope of uranium (U^{235}), the artificial isotope of uranium (U^{233}), and the artificial element plutonium (P^{239}). In a nuclear reactor, a controlled chain reaction of nuclear fission of these heavy elements takes place.

I.2.2.3. Primary Elements and Operating Principle of a Nuclear Power Plant

The main components of a nuclear power plant are the nuclear reactor and a heat exchanger, along with the steam turbine, condenser, and generator. In a conventional furnace, heat is produced by burning fuel. In a nuclear reactor, heat is generated by converting the nuclear energy released through the fission of atoms in nuclear fuel. A coolant (also known as a heat transfer fluid, such as liquid sodium, pressurized water, etc.) absorbs this heat and transfers it to the heat exchanger, leading to the generation of steam for the turbine [7, 9].

The rest of the power plant is similar to a conventional steam power plant. The steam generated in the heat exchanger is admitted into the turbine, and after work is done by the expansion of steam through the turbine to produce electricity, the steam is condensed in the condenser and returned by the condensate pump to the heat exchanger, thus forming a closed-loop system. The reactor and heat exchanger are equivalent to the furnace and boiler in a conventional steam power plant. The other auxiliary components are similar to those of a familiar steam power plant [7, 9].

On one hand, the steam generator is environmentally friendly as it does not emit carbon dioxide, sulfur, or mercury. However, on the other hand, a major concern with a nuclear power plant is that the area surrounding the nuclear reactor is potentially radioactive. Additionally, if nuclear waste is not carefully managed, it could have a devastating impact on living organisms and inanimate objects, including the environment [9].

The Fig. I.5. below shows a simple schematic layout of the main components of a nuclear power plant.

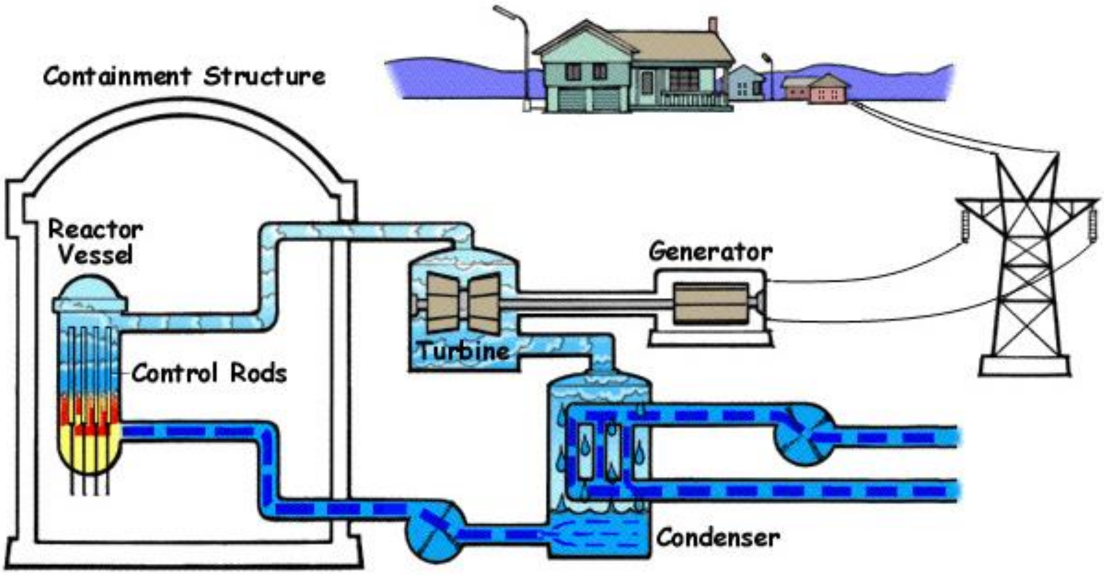


Fig. I.5. Main Components of a Nuclear Power Plant.

I.2.2.4. Types of Nuclear Reactors

There are different types of nuclear reactors used to generate electricity. Some of these reactors commonly used worldwide are as follows :

a) Pressurized Water Reactor (PWR)

A Pressurized Water Reactor (PWR), is composed of two series-connected loops, namely the coolant loop, referred to as the primary loop, and the steam/water or working fluid loop, also known as the secondary loop (see Fig. I.6).

The pressurized water in the primary loop passes over the reactor core to act as both a moderator and coolant. The coolant does not flow directly to the turbine ; instead, it absorbs heat from the reactor and transfers it to the working fluid in the secondary loop, which is an unheated steam generator that produces steam. The steam is then used to drive a turbine and generate electricity. The pressure and temperature of the coolant are typically maintained at around 15.5 MPa and 618 K, which is below the saturation temperature, thus avoiding boiling of the coolant inside the reactor.

In a Pressurized Water Reactor (PWR), enriched uranium is used as fuel. The reactor core typically contains 150 to 200 fuel assemblies. During design, all precautions are taken to prevent boiling of pressurized water inside the reactor. One significant advantage of a PWR is that in the event of fuel leakage into the core, radioactive contaminants would not pass into the turbine and condenser. Another advantage is that the pressure and temperature (approximately 10.5 MPa and 588 K, respectively) of the steam from the PWR are higher than the pressure and temperature available from a boiling water reactor. The drawback of a PWR is that the reactor is more complex and costly to construct [9].

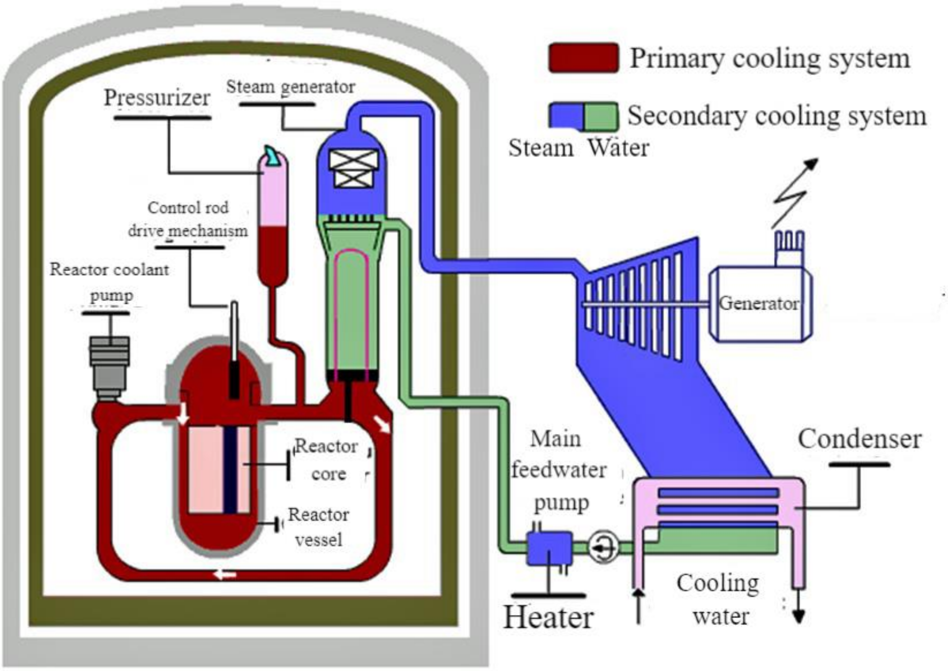


Fig. I.6. Schematic diagram of a Pressurized Water Reactor (PWR).

b) Boiling Water Reactor (BWR)

In a Boiling-Water Reactor (BWR), the same water loop serves as a moderator, coolant for the core, and steam source for the turbine (see Fig.I.7). The coolant comes into direct contact with the heat-producing nuclear fuel and boils in the same compartment as the fuel. The liquid enters the reactor core from the bottom, where it receives sensible heat up to saturation plus a certain amount of latent heat of vaporization. Upon reaching the top of the core, it is transformed into a highly wet mixture of liquid and steam. The steam is then separated from the liquid in a steam separator and flows through a turbine to generate energy. The condensate is pumped back to the bottom of the reactor.

The main concern with adopting a Boiling-Water Reactor (BWR) is that any fuel leakage occurring inside the reactor would render the water radioactive. The radioactivity then propagates to the turbine and the rest of the loop. A typical operating pressure for a BWR is around 7 MPa, approximately half the cooling pressure of a PWR. The steam temperature exiting a BWR corresponds to the saturation temperature at a pressure of 7 MPa, which is approximately 558 K [9].

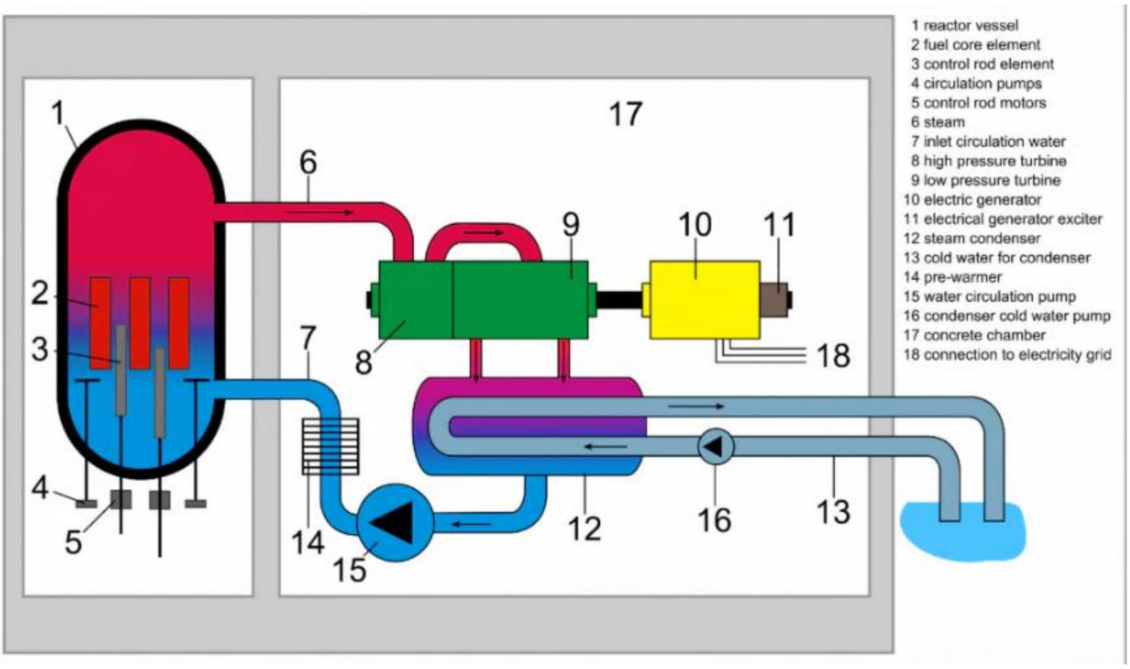


Fig. I.7. Schematic diagram of a Boiling-Water Reactor (BWR).

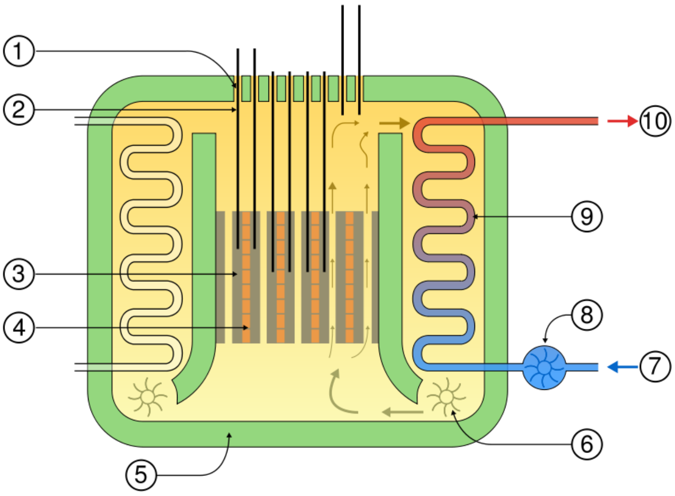
c) Gas-Cooled Reactor (GCR)

A Gas-Cooled Reactor (GCR) is cooled by a gas (helium or carbon dioxide), unlike the coolant used in a PWR and a BWR. During the reactor cooling process, the gas absorbs heat; this hot coolant can then be used either directly as a driving fluid for a combustion turbine to generate electricity or indirectly to generate steam, which in turn is used in a turbo-generator to produce electricity (see Fig.I.8). There are two types of GCR. In one type, natural and enriched uranium fuels are used with CO_2 as the coolant and graphite as the moderator. In the other type, only enriched fuels are used, with helium as the coolant and heavy water as the moderator.

The main advantages of adopting this technology are as follows :

❶ A higher steam temperature, typically around 838 K, could be used with a GCR. As a result, greater power plant efficiency could be achieved compared to water-cooled designs.

❷ The GCR is less susceptible to terrestrial hazards that could be encountered with water-cooled/moderated reactors.



1. Charge tubes
2. Control rods
3. Graphite moderator
4. Fuel assemblies
5. Pressure vessel & radiation shielding
6. Gas circulator
7. Water
8. Water circulator
9. Heat exchanger
10. Steam

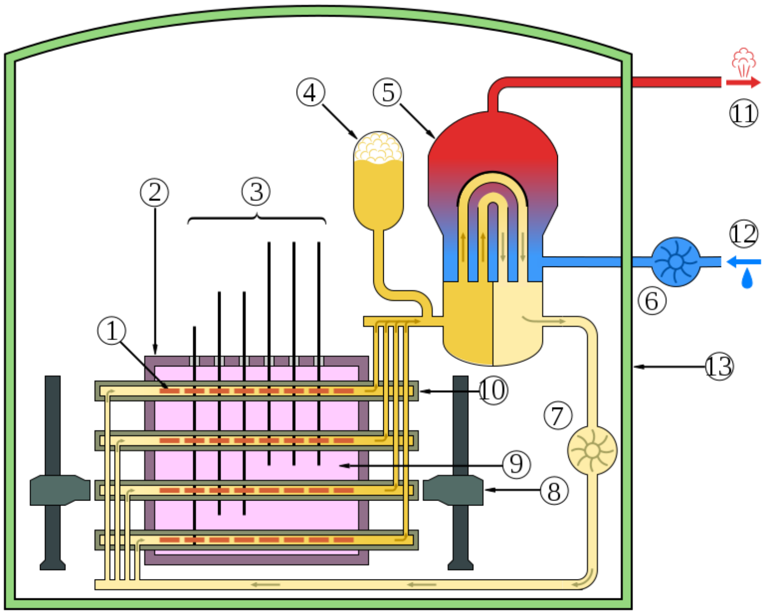
Fig. I.8. Cross-sectional view of a typical Gas-Cooled Reactor (GCR).

d) Heavy Water Reactor (HWR)

In a Heavy-Water Reactor (HWR), or more specifically, a Pressurized Heavy-Water Reactor (PHWR), the fuel used is natural uranium with heavy water under pressure (deuterium oxide: D_2O) serving as both the coolant and moderator (See Fig.I.9). Because heavy water is under pressure, it can be heated to higher temperatures without boiling, as is the case with pressurized water in a PWR.

An HWR requires large-diameter pressure vessels. The production costs of D_2O are significantly higher compared to H_2O. However, this higher cost is partially offset by the use of natural uranium, as in the case of PWRs, where additional costs are incurred to produce enriched uranium.

A proprietary version of the HWR is CANDU, which stands for « CANada Deuterium Uranium » (See Fig.I.10). The reactor was designed by « Atomic Energy of Canada Limited (AECL) (AECL EACL) » and is currently marketed by « Candu Energy Inc (candu) », based in Mississauga, Ontario. The steam pressure and temperature at the outlet of the CANDU reactor are typically 4 MPa and 524 K, respectively.



🟨 Hot Zones of the Primary Circuit (Heavy Water)
⬜ Cold Zones of the Primary Circuit (Heavy Water)
🟥 Hot Zones of the Secondary Circuit (Light Water)
🟦 Cold Zones of the Secondary Circuit (Light Water)
🟪 Cold Moderator (Heavy Water) in the Calandria

1- Fuel bundle.
2- Calandria (reactor core)
3- Control rods
4- Heavy Water Pressurizer
5- Steam generator
6- Light Water Secondary Circuit Pump
7- Heavy Water Pump (Coolant Pump)
8- Fuel Handling Machine
9- Heavy Water Moderator
10- Pressure Tube
11- Steam heading to the steam turbine
12- Pressurized Light Cold Water returning from the turbine
13- Reinforced Concrete Containment Building

Fig. I.9. Cross-sectional view of a typical Heavy-Water Reactor (HWR).

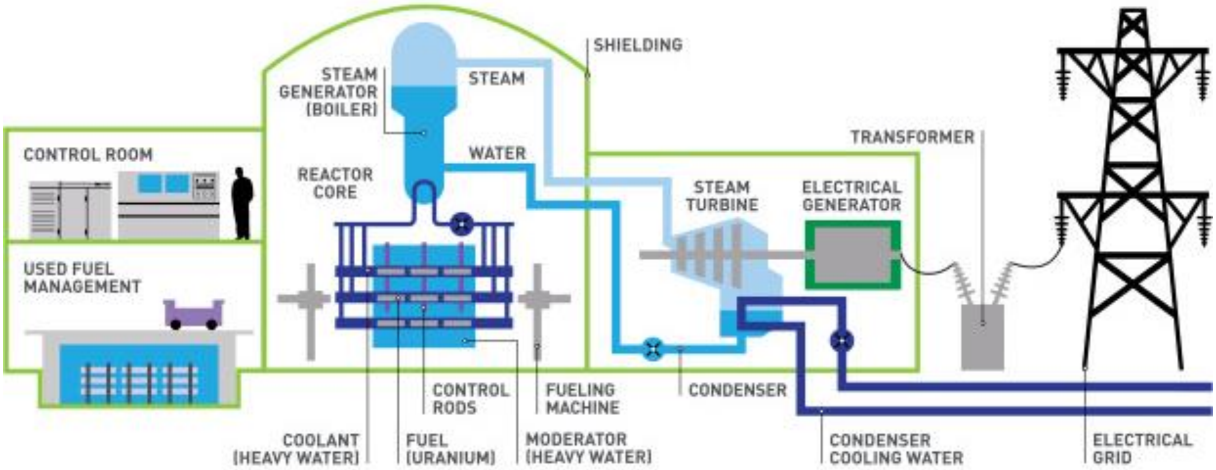


Fig. I.10. General layout of a CANDU reactor power plant.

e) Fast Breeder Reactor (FBR)

The fuel used in a Fast-Breeder Reactor (FBR) is typically Pu^{239}, but U^{235} is also used in some reactors. Fast breeder reactors are so named because of their design to produce fuel by generating more fissile material than they consume [9]. In an FBR, the moderator is eliminated, allowing neutrons to bombard a fuel such as uranium dioxide ($^{238}UO_2$) at high speed. This results in heat release and a transformation of uranium. In turn, the transformed uranium can act as fuel. This type of reactor is of interest because traditional reactors only extract 2% of the available energy in uranium dioxide [5].

The reactors are cooled by liquid sodium, which also serves as the coolant fluid. Instead of sodium, lithium can also be used as a coolant, but sodium, being more abundant, is commonly employed [9].

A major drawback of an FBR is that it requires a higher degree of fuel enrichment compared to water-moderated reactors.

The advantages of using sodium compared to pressurized water are :

❶ At atmospheric pressure, sodium can be liquefied at a moderate temperature of 371 K, and it boils at 1156 K. Therefore, the operating temperature range of sodium is broad at atmospheric pressure and does not require additional pressurization.

❷ The thermal conductivity of sodium is very high compared to that of water. Therefore, it is an efficient heat transfer medium.

The disadvantages of using sodium are :

❶ It is opaque, which hinders visual monitoring.

❷ Sodium is an extremely reactive chemical ; when it comes into contact with air or water, it begins to burn. Upon contact with water, sodium can even cause an explosion, posing a safety risk.

❸ During operation, radioactive sodium-24 can be formed through neutron activation. Therefore, there is also a slight risk of radiation.

In order to eliminate radioactive risks, a separate design was developed, where an intermediate loop is introduced between the primary loop and the secondary loop. This new reactor is called a Liquid-Metal Fast-Breeder Reactor (LMFBR). In this reactor, liquid sodium is used as the coolant in the primary loop of the reactor. The heat contained in the primary coolant is exchanged with the intermediate coolant, which is also a liquid metal, either sodium or a combination of sodium and potassium (NaK), in a primary heat exchanger. The hot intermediate coolant is then introduced into a secondary heat exchanger, i.e., the steam generator, as a heat source to boil water and generate steam. A cross-sectional view of a typical LMFBR is illustrated in Fig.I.11. In a typical design, the steam conditions at the outlet of the superheater are approximately 10 MPa and 759 K.

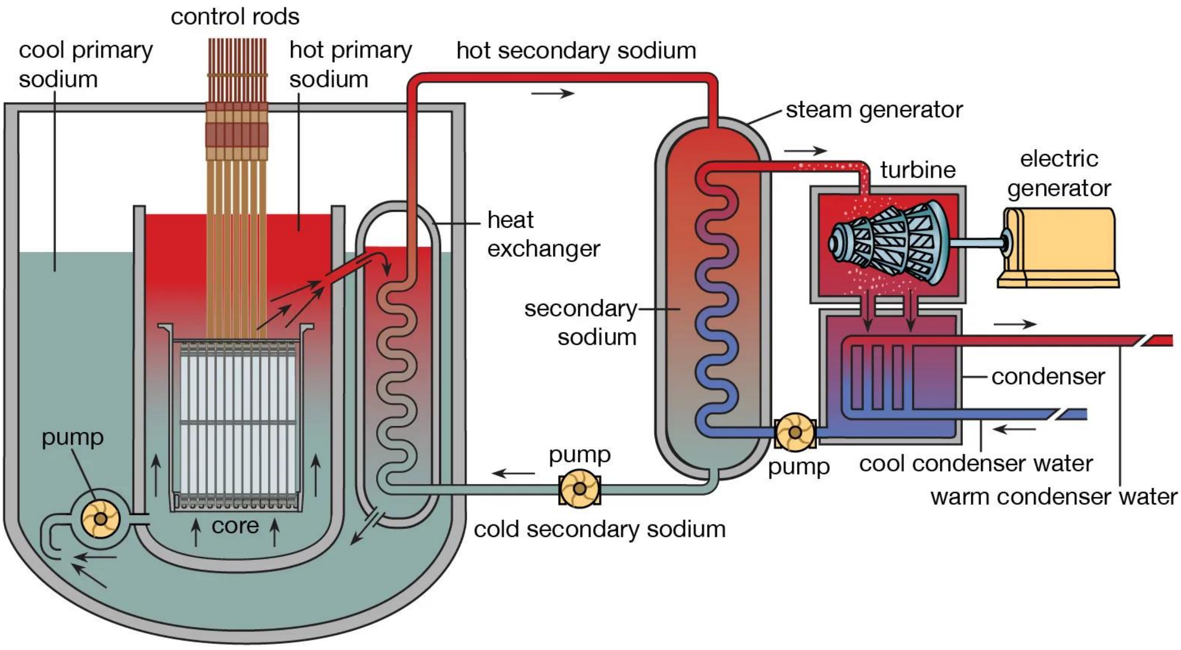


Fig. I.11. Cross-sectional view of a typical fast breeder reactor.

I.3. Systems service

System services are essential for ensuring the secure and reliable operation of the electrical network. Their management is carried out by network operators, relying on contributions from connected producers. Key system services include : voltage control, frequency regulation, black start, and network restoration.

The variability and uncontrollable nature of wind and photovoltaic energy sources, as well as the nature of the technologies used, significantly limit their capacity to provide these system services. Currently, installations utilizing wind and solar as primary sources are exempt from participating in system services. This exemption leads to increased demands on other production groups. The system's ability to maintain a sufficient level of system services, despite the integration of renewable energies, will be one of the main constraints on the integration of these sources if they cannot provide these services [30].

N.B. Black start : starting a unit without auxiliary power supply from the grid.

I.3.1. Voltage control and reactive power compensation

Energy production units, including those using renewable sources, must operate in accordance with guidelines defined by the network operator. They are required to ensure effective voltage control and/or reactive power at the delivery point. Three primary control modes can be used [30] :

- Type 1 : constant reactive power control at the delivery point.
- Type 2 : voltage control at the delivery point, linearly adjustable based on reactive power.
- Type 3 : voltage control at the installation terminals, following commands linked to secondary voltage control orders.

In France, legislative provisions (Decree of April 23, 2008) impose the following constraints regarding voltage control and reactive power compensation :

- Wind and photovoltaic installations connected at low voltage must not consume reactive power.
- Plants connected to the distribution network (with a capacity of less than 17 MW) must be capable, under normal operating conditions, of either producing reactive power representing at least 40% of their maximum active power or absorbing reactive power representing at least 35% of their maximum active power.
- Plants connected to the public transmission network must, within the normal voltage range, be capable of :
    - Providing reactive power up to 0.32 Pmax and absorbing reactive power up to 0.35 Pmax at Pmax ;
    - Providing reactive power up to 0.30 Pmax and absorbing reactive power up to 0.28 Pmax at any operating power P.

For synchronous generators, reactive power needs are met by compensation batteries, connected either directly at the installation level or at the HV/MV transformer substation.

I.3.2. Frequency regulation

Installations using intermittent energies, such as wind and photovoltaic, are exempt from the obligation of frequency regulation [30].

I.4. Management and performance

A long-term plan for electrical energy management assists facility and organizational managers in defining electrical energy-saving measures, incorporating them into their planning, and integrating energy efficiency into the organization's daily activities. The bundling of energy efficiency projects aimed at maximizing their cost-effectiveness is one of the elements of an effective electrical energy management plan.

Intelligent management of electrical consumption is a major concern not only for managers and providers but also for energy consumers. To address this, two management systems are discussed :

a) Energy Management System (EMS) : is a structured and systematic process of continuous improvement in energy. Inspired by the voluntary standard for Energy Management - ISO 50001 (adopted in 2011), monitoring energy consumption becomes an integral part of management methods by making energy visible, with the aim :

- to identify and quantify the unnecessarily used energy consumption ;
- to discover untapped potential for energy savings ;
- to improve energy efficiency ;

b) Energy Management Information System (EMIS) : provides relevant data that contributes to making energy efficiency visible at various levels of an organization, enabling departments and employees to plan, make decisions, and implement effective measures for electrical energy management. Additionally, it enhances productivity through continuous monitoring of energy performance and energy savings. The performance data provided by an EMIS allows organizations to take actions to create financial value through energy management and control [10].

An effective EMIS requires communication, integration, and a commitment to continuous improvement with the goal of optimizing performance.

Chapter II : Decentralized Electrical Production (DEP)

II.1. Definition of decentralized electrical production (DEP)

Decentralized electrical production (DEP), also known as distributed or dispersed production, is the generation of electrical energy using small-scale facilities with a capacity not exceeding 50 to 100 MW. These facilities are connected to the distribution electrical grid at low or medium voltage levels. Decentralized production includes combined heat and power units, renewable energy systems, or traditional production units, installed by independent producers [11].

II.2. Technologies of decentralized electrical production

There are two main technologies for decentralized electrical energy production sources :

II.2.1. Technologies based on conventional (non-renewable) sources

Are programmable and controllable systems based on constantly available and storable energy sources, allowing the output power to be controlled and programmed at any time based on system loads and requirements [12]. The main technologies utilizing these primary energy sources are :

II.2.1.1. Diesel generators

Diesel generator sets use a diesel engine that converts fossil fuel energy through internal combustion into mechanical energy. The latter is further transformed into electrical energy through a synchronous generator [11, 12] (see Fig.II.1.).

Fig.II.1. Diesel generator unit.

a) Advantages:

❶ Diesel generators are perfectly suitable for isolated loads.

❷ Diesel generators exhibit high dynamics and are well-suited for applications where sudden power demands are anticipated.

b) Disadvantages:

❶ They produce high levels of CO_2 emissions.

❷ Their electrical efficiency is moderate, reaching approximately 35 to 40%.

❸ They cannot operate below a minimum load of 40%.

II.2.1.2. Microturbines

Mini and micro gas turbines are very small combustion turbines. They utilize heat from the combustion of gas, rather than steam, to drive a generator and generate electricity. Their power ranges from 30 kW to a few hundred kW.

a) Advantages:

❶ They have lower emissions [13].

❷ Greater reliability [13].

❸ Less noise [13].

❹ Microturbines can perform cogeneration (heat recovery), significantly increasing their overall efficiency from 20 to 30% without cogeneration to up to 80% with cogeneration, depending on their load.

b) Disadvantages:

❶ Microturbines lack the ability to respond rapidly to energy demand.

❷ Require storage systems when rapid transients are necessary.

❸ They currently face challenges in ensuring a transition without voltage ripples or interruptions between grid-connected and islanded modes, and vice versa. For instance, the CAPSTONE 30 kW turbine requires between 2 and 4 minutes to transition from grid-connected to islanded mode. A complete transition from islanded to grid-connected mode takes 30 minutes [13].

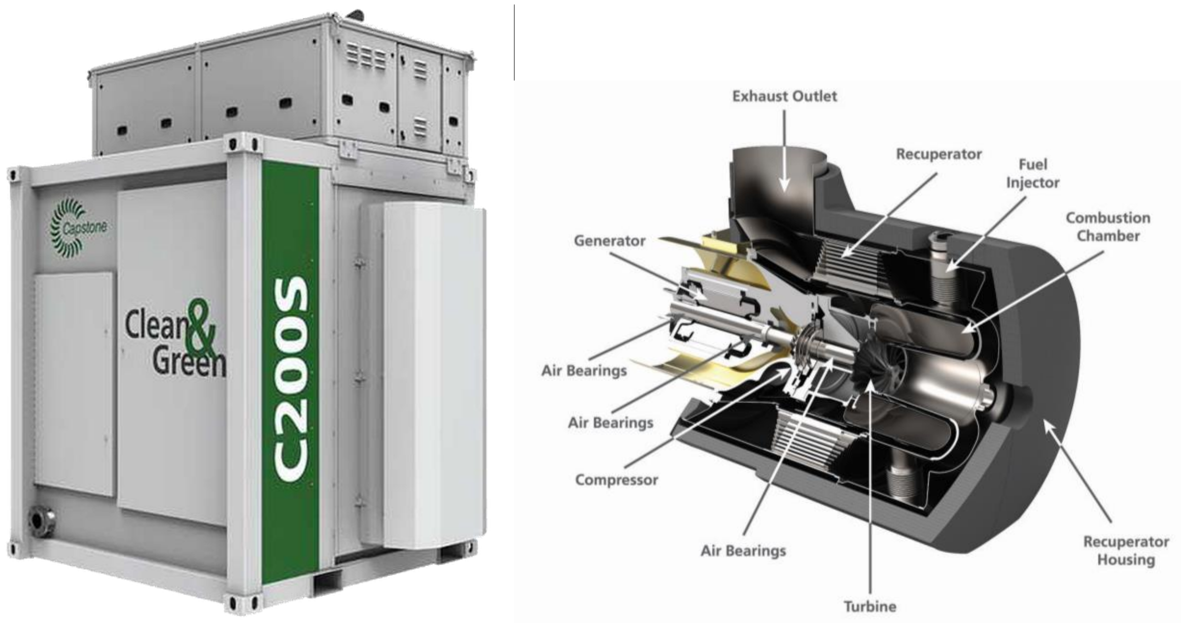


Fig.II.2. Capstone microturbine unit.

II.2.1.3. Cogeneration

Cogeneration is the combined production of heat and electricity, representing a highly efficient technique to enhance energy efficiency. The overall energy efficiency of such an installation can reach 80 to 90%, and the local use of the produced heat helps avoid additional energy consumption for heating buildings or industrial processes [11]. This technology is currently under development. The system can effectively contribute to grid services, such as peak-hour compensation, voltage adjustment, and sometimes frequency regulation [12].

On the other hand, it is noteworthy that the previous definition of programmable systems based on conventional sources may be ambiguous because the primary energy source is always available, but electrical production is based on heating (thermal) demand rather than electrical demand [12].

II.2.1.4. Storage devices

There are several storage technologies that indirectly store electrical energy in another form (chemical, kinetic, etc.) and are highly useful in distribution systems whose task is to balance disparities between production and consumption. The most developed technologies include:

a) Electrochemical batteries

Electrochemical batteries consist of two electrodes separated by an electrolyte, and oxidation or reduction reactions occur at interfaces that release or absorb electrons. The ions thus generated circulate within the electrolyte. The amount of stored energy is inherently limited by the size of the batteries. Chemical reactions are temperature-sensitive, which is why some types of accumulators are ineffective at low temperatures (<0°C), and others require high temperatures (300°C) [12].

The main families of accumulators currently available for massive energy storage are lead-acid and sodium aluminate (NaS) batteries [14]. Other technologies are in development, such as lithium-ion batteries. Lead-acid batteries are the most cost-effective solution, but they have a limited lifespan, low energy densities, and low efficiencies [15]. Some improvements, like tubular electrodes, significantly increase cycle and lifespan. Sodium batteries with aluminate electrolytes, however, exhibit higher energy densities and efficiencies, but their costs are also higher [12].

Fig.II.3. The world's largest electric storage battery is being installed in Guyana (solar electricity is stored in the form of compressed gas in bottles stacked inside 12-meter-long containers).

b) Flywheel energy storage

A flywheel is a rotating system that allows the storage and release of electrical energy in the form of kinetic energy. A mass (disk, ring, cylinder, etc.) attached to an axis is set in rotation by applying torque. The amount of stored energy is proportional to the moment of inertia of the wheel and the square of the rotation speed :

$$E_c = \frac{1}{2} J \Omega^2 \tag{II.1}$$

Where :

J : is the moment of inertia of the storage wheel.

Ω : is the rotation speed of the storage wheel.

Therefore, to increase the stored energy, the wheels rotate at very high rotation speeds on the order of 90,000 rpm.

Fig.II.4. First flywheel energy storage facility in Europe (Ireland).

The charging and discharging occur through electromechanical conversion in the motor/generator of the drive system. Energy is stored in the flywheel when the machine operates in drive mode by accelerating the wheel. It is discharged when the machine operates in generator mode by slowing down the wheel [12].

The flywheel responds very rapidly to demand, making it suitable for various applications such as power quality, transient stability in networks, voltage sag smoothing, and fluctuating load smoothing, where significant injection of dynamic power is required [12].

c) Super capacitors

Super capacitors, also known as "ultra-capacitors," store electrical energy in the form of electrostatic energy. The stored energy depends on the capacitance of the capacitor and the square of the voltage across the capacitor:

$$E = \frac{1}{2} C \mathrm{V}^2 \tag{II.2}$$

Where :

C : is the capacitance of the storage capacitor.

V : is the voltage across the capacitor.

Super capacitors have a double layer that enhances energy storage capacity due to a significant increase in surface area facilitated by the use of a porous electrolyte (they still have relatively low permittivity and voltage withstand capabilities) [16]. Various combinations of electrode materials and electrolytes have been employed in ultracapacitors, with different combinations yielding variable capacity, energy density, lifespan, and cost characteristics. An ultracapacitor can provide extended power availability during voltage sags and momentary interruptions. Super capacitors can be fully charged and discharged, easily installed, are compact in size, and can operate effectively in various environments (hot, cold, and humid) [15].

Fig.II.5. Maxwell 165F 48V 14.2kg supercapacitor.

Ultra-capacitors and hyper-capacitors initially found application in low-energy applications, with much of the development for higher-energy applications being directed towards electric vehicles. Super capacitors can be added to the DC bus of motors to improve transit times during voltage sags [17, 18]. They can also be added to a Dynamic Voltage Restorer (DVR) or interfaced with the DC bus of a Distribution Static Compensator (DSTATCOM) [19], [20].

II.2.2. Technologies based on new and renewable sources

An energy is considered "renewable" if its source replenishes rapidly enough to be deemed inexhaustible on a human time scale. The main advantage of this energy is its cleanliness, while its primary drawback is its intermittent nature, as the output power depends on the availability of the primary source at any given moment. Among the technologies based on these renewable energy sources :

II.2.2.1. Small hydropower plant

Also known as a "micro-hydropower plant," it utilizes hydraulic energy to generate electricity on a small scale. Similar to traditional centralized hydropower plants, it distinguishes itself by its small size. The operating principle is the same : it converts the potential energy from the fall of a water mass from rivers, lakes, streams, waterfalls, etc., into mechanical energy using a small hydraulic turbine (see Fig.II.6. below). This turbine then drives a generator where the mechanical energy is transformed into electrical energy. The power produced depends on the water fall and flow rate, with power levels ranging from a few kW to several MW [11]. This small power plant can be used to supply isolated sites (a few homes, a craftsman's workshop, a barn, etc.) or sold to a public distribution network.

Fig.II.6. Francis-type turbine with its generator for a small hydropower plant.

a) Advantages :

❶ Gratuity of primary energy and electric production.

❷ Completely clean energy.

❸ Attractive efficiency.

❹ Great production flexibility: easy to adapt to the needs of the grid by deciding to open or close the dam to a greater or lesser extent.

❺ Absolute safety : There is no risk of explosion within these plants as they do not use any fossil or nuclear fuel.

❻ The cost of security is significantly lower than that of other power plants.

b) Disadvantages :

- ❶ High initial investment cost : Building a large, safe, and sustainable dam (source) requires significant civil engineering costs.
- ❷ Drought risk : Potential drought can have significantly negative impacts on overall production. Nonetheless, the drought risk is difficult to predict, and it can lead to a complete halt in energy production, causing significant disruptions to the energy grid.

II.2.2.2. Photovoltaic panels

Electric energy can be produced by transforming the energy from solar radiation, also known as photovoltaic solar energy, through photovoltaic panels (PV modules). These panels consist of multiple interconnected photovoltaic cells, made of semiconductor materials and operating on the principle of the P-N junction. Currently, the majority of these cells are produced using monocrystalline silicon [11]. However, polycrystalline silicon is increasingly being used as it is less expensive to produce [12].

A photovoltaic power plant comprises multiple PV modules installed over a sufficient area, forming what is called a « photovoltaic field ». Thus, the construction of these plants becomes a crucial element in future electric power systems, microgrids, and smart grids. Large or medium-scale solar power generators operate as decentralized production units, primarily installed in rural areas where sufficient space is available, and they can be connected to radial distribution networks [21]. The obtained energy can then be stored in batteries to be available continuously. A regulator protects the battery from overcharging and discharging [12].

Fig.II.7. Silicon block.

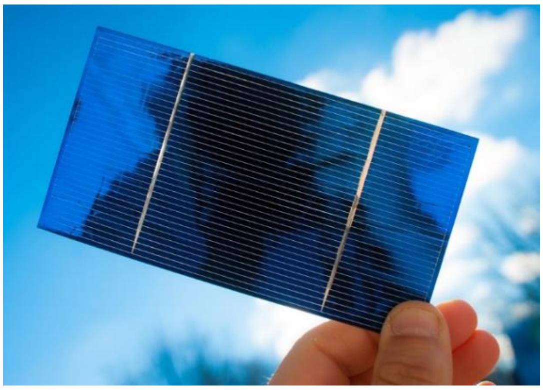


Fig.II.8. Photovoltaic cell.

Fig.II.9. PV panel (composed of 48 photovoltaic cells).

Fig.II.10. Photovoltaic field (solar farm).

a) Operating principle of photovoltaic cells

A semiconductor crystal (P) is covered with a very thin zone (N) with a diameter of a few thousandths of a millimeter (See Fig.II.11). Between the two zones, there is a junction (J). The zone (N) is covered with a metal grid serving as the cathode (k), while a metal plate (a) covers the other face of the semiconductor and acts as an anode. The total thickness of the crystal is approximately 1mm. A beam of light (ph) striking the device can penetrate the crystal through the grid and generate a voltage between the cathode and the anode.

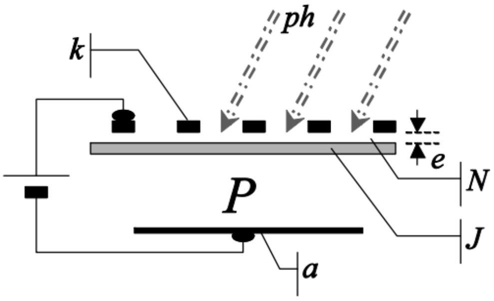


Fig.II.11. Operating principle of a photovoltaic cell.

b) Efficiency and adaptation

An individual cell produces very low electrical power, typically ranging from 1 to 3W, with a voltage below 1V. To generate more power, cells are combined to form a module (panel).

Connecting multiple cells in series increases the voltage for the same current, while connecting them in parallel increases the current while preserving the voltage. Most commercially available modules consist of 36 crystalline silicon cells connected in series for 12V applications. The output current, and thus the power, will be proportional to the panel's surface area (or panels connected in parallel). Interconnecting modules, either in series or in parallel, to achieve even greater power defines the concept of a photovoltaic array. 1 MW requires approximately 10,000 m^2 of photovoltaic panels. Panels must be oriented towards the sun, with an optimal tilt angle depending on the installation latitude [12].

The efficiency of a cell made from monocrystalline silicon is greater than 15%, and the efficiency of polycrystalline silicon is approximately 10 to 15%, while amorphous silicon ranges between 5 and 10% (manufacturing costs are also decreasing). A photovoltaic panel must operate for three (for polycrystalline) or four (for amorphous) years before it begins to provide energy beyond that used in its own manufacturing. The power consumed during the manufacturing and installation process of photovoltaic panels using monocrystalline or polycrystalline cells connected to the grid is around 600 kWh/m^2. Silicon rectification and crystallization are the process stages that require the most energy. The crystal must then be cut into slices and assembled into modules. In the case of an amorphous photovoltaic module, the energy used in their creation is approximately 420 kWh/m^2 [12].

A photovoltaic generator, being a source of direct current (DC), needs to be adapted for connection to an alternating current (AC) grid or for supplying an AC load. This can be achieved in two stages with a DC/DC converter and a DC/AC inverter, or in a single stage with a DC/AC inverter [12, 22].

II.2.2.3. Solar thermal power plants

The solar thermal power plant is undoubtedly considered the most promising and viable option among renewable energy technologies for electricity production in the present and future [23]. Approximately one percent of the surface area of the Sahara Desert would be sufficient to meet the entire global demand for electricity from solar thermal power plants. For this reason, many people hope that solar thermal energy will be implemented in countries within the solar belt. Unlike photovoltaic power plants, solar thermal power plants do not rely on the photovoltaic effect but generate electricity from heat produced by sunlight [24].

a) Operating principle

The operation of solar thermal power plants can be summarized in the following techniques :

❶ Mirrors capture solar radiation at a focal point to generate very high temperatures (from 400 to 1,000°C).

❷ The heat obtained transforms water into steam in a boiler.

❸ The pressurized steam rotates a turbine that drives a generator.

❹ The generator produces alternating current.

b) Types of solar thermal power plants

Depending on the method of focusing solar rays used, solar thermal installations can be distinguished into those that use reflection and those that use refraction [25] :

b1) Reflection-based installations

Reflection-based installations use mirrors that absorb nothing, allowing the reflected light to cover the entire spectrum of wavelengths, concentrating solar energy. This results in either a single derivation (direct concentrators) or multiple derivations (indirect concentrators) of the radiation :

b1-1) Direct concentrators

Direct concentrators include cylindrical-parabolic mirrors and flat parabolic reflectors. Firstly, the generated heat energy is primarily used to heat fluids circulating in the conduit located in the focal line of the reflector (Fig.II.12). Flat parabolic reflectors can be full-surface parabolic concentrators when the entire surface forms an approximately parabolic shape or multifacet concentrators composed of various facets arranged in a parabolic structure that reflects solar radiation by concentrating it at its focal point. The concentration factor depends on the size, aperture, and quality of the surface. Solar radiation striking the focal point and its energy efficiency are very high due to the high concentration.

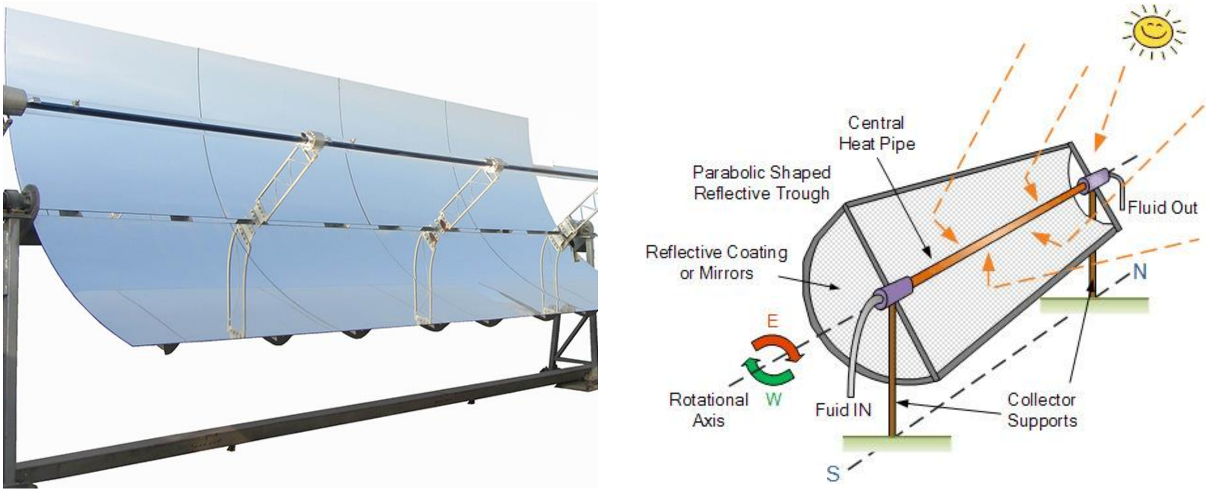


Fig.II.12. Cylindrical-parabolic concentrators.

b1-2) Indirect concentrators

Indirect concentrators primarily include solar furnaces. These are systems that harness the thermal energy generated by the sun for use in applications requiring moderate to high temperatures. They are indirect concentrators that produce multiple derivations of radiation through specially designed optical systems to deflect incident light. To deflect radiation, they use flat-surfaced heliostat mirrors that redirect direct solar radiation. They consist of flat reflective facets and have a two-axis sun-tracking system. Since a single heliostat is generally completely flat, it does not focus. Therefore, a field of heliostats pointed at a parabolic concentrator is used for this purpose (Fig.II.14). Concentrated power can be regulated by an attenuator that adjusts the amount of incident solar light entering.

When the field of heliostats is pointed towards a tower (Fig.II.15), it is a direct concentrator because this system produces only a single derivation of solar radiation.

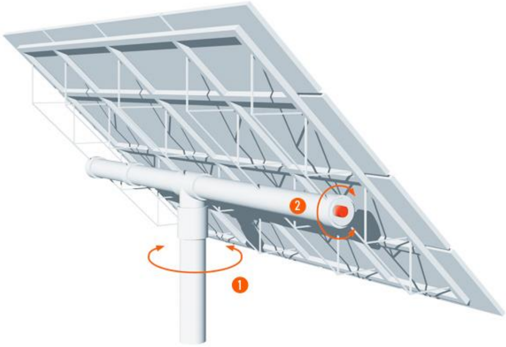


Fig.II.13. Heliostat with representation of elevation and azimuth control system.

Fig.II.14. Parabolic reflector (heliostat pointed at a parabolic concentrator).

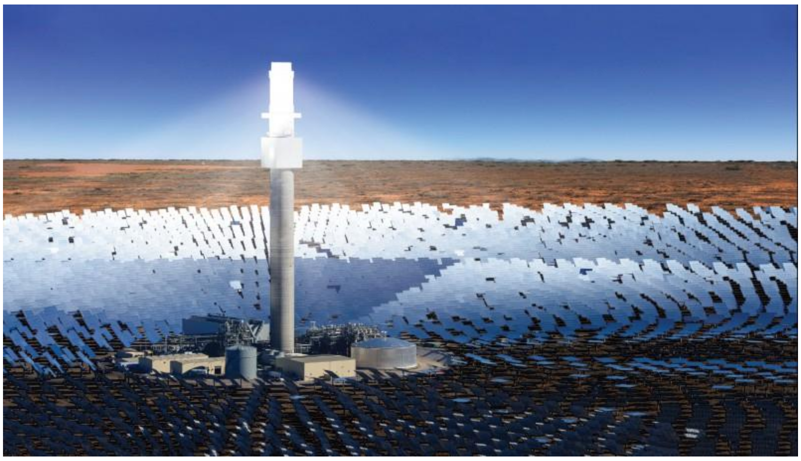


Fig.II.15. Field of heliostats pointed towards a central tower.

b2) Refraction-based installations

In these installations, light passes through a concentrating device such as converging lenses, which redirect it towards its axis and concentrate the radiation at its focal point but absorb some of the wavelength of solar light. However, to be useful for concentrating solar radiation at the required levels, conventional lenses would need to be too large and consequently too expensive. Fresnel lenses circumvent this problem, as they fulfill the same function, with the advantage of being much lighter and cheaper. Fig.II.16 shows how facets of a Fresnel lens can be created from a conventional lens.

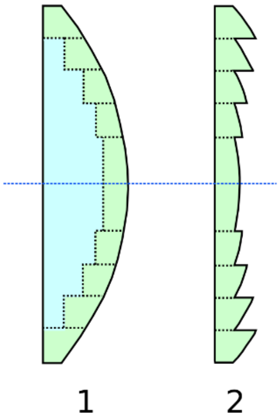


Fig.II.16. Diagram of the Fresnel lens.

Fig.II.17. Fresnel lens.

II.2.2.4. Wind turbines

Wind systems transform the kinetic energy of the wind into mechanical energy, causing the blades of a wind turbine to rotate. This rotation is then transmitted to the turbine's shaft, connected to a generator where the mechanical energy produced is converted into electrical energy [11, 12]. The amount of electricity produced by a wind turbine is determined by the wind speed. The efficiency of a wind turbine depends on its size, where available power increases with an increase in tower height and blade length. Wind turbines can be individually connected to the grid or grouped together to form wind farms. The power range of wind installations varies from a few kilowatts (small wind turbines) to several megawatts (large wind turbines) [12].

a) Advantages :

Compared to traditional energy sources, wind energy has several advantages [26] :

❶ Wind energy is a clean and environmentally friendly energy source.

❷ An endless and free source of energy.

❸ Available and abundant in most regions of the globe.

❹ The cost per kWh of wind energy is much lower than that of solar energy.

b) Composition of a wind turbine

b1) Blades (wings)

Most modern large wind turbines are horizontal-axis turbines with typically three blades (See Fig. opposite) rotating around a horizontal-axis rotor. The blades of the propeller can be made of laminated wood, fiberglass-reinforced plastic, or metal, etc. The diameter they sweep varies from 40 m to 120 m.

Annex A includes illustrations of various typical types of vertical-axis wind turbines.

b2) Nacelle

Positioned at the top of a wind turbine tower, housing most of the turbine's components inside.

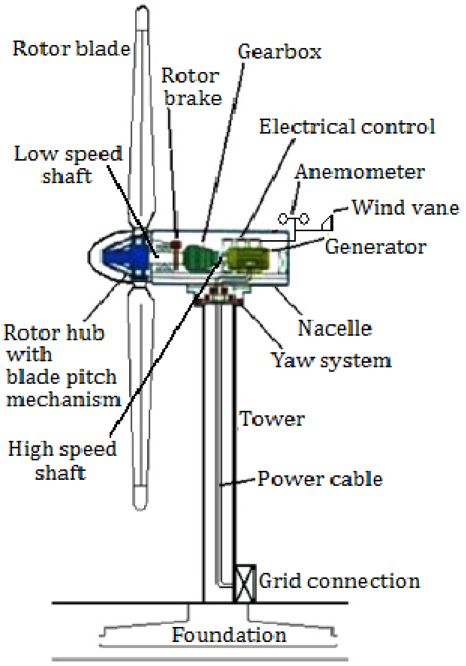


Fig.II.18. Composition of a wind turbine

b3) Tower (mast)

The wind turbine blades and the nacelle are located at the top of a tower, ranging from 50 to 110 meters. The tower can be made of assemblies of metal lattice, concrete, or metal, equipped with maintenance ladder inside.

b4) Speed multiplier

The speed multiplier is located between the wind turbine blades and the electrical generator to rotate the generator rotor, which needs to be driven at around 1500 to 3000 rpm, as the wind turbine blades rotate at speeds of only about 100 to 650 rpm [11]. The slow rotation speed of the rotor hub is increased to the desired high rotation speed of the generator rotor [26].

b5) Regulation system

With the pitch control system, each blade is individually tilted to optimize the blade's angle of attack for higher energy capture under normal operation and to protect turbine components (blade, tower, etc.) from damage in emergency situations [26].

b6) Orientation system

With feedback information such as the wind direction and instantaneous speed measured from the weather vane, the yaw control system provides the yaw control command to ensure the turbine constantly faces into the wind [26].

c) Types of wind power systems

According to the generator, there are currently three main types of wind power systems [26] :

c1) Fixed-speed wind power system with squirrel-cage asynchronous machine

This system consists of a squirrel-cage induction generator directly connected to the grid. A speed multiplier adjusts the turbine rotation speed to the required electrical frequency. Therefore, the turbine rotation speed is practically fixed for any wind speed. A squirrel-cage asynchronous generator always consumes reactive power. This reactive power is undesirable and is usually partially or entirely compensated by capacitor banks or other compensators. The main advantage of fixed-speed systems is their simplicity and low cost.

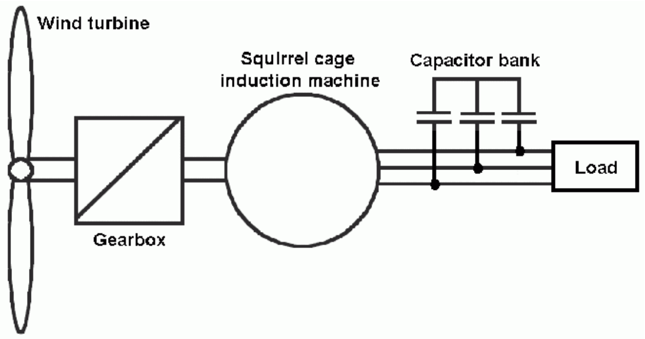


Fig.II.19. Fixed-speed wind turbine.

c2) Variable-speed wind power system with doubly fed induction machine

In this type of machine, both the stator and the rotor are connected to the grid, which is why it's called a doubly fed induction (asynchronous) machine. In this case, the back-to-back inverter feeds the rotor windings. Thus, the mechanical and electrical speeds of the rotor are decoupled, and the electrical frequency of the stator and rotor can be connected independently of the mechanical speed of the rotor.

In moderate wind, the rotor rotates at a speed lower than synchronous speed (sub-synchronous speed). However, as the wind speed increases, the rotor accelerates to rotate at a speed that can exceed synchronous speed (super-synchronous speed). The mechanical power developed by the turbine is converted into electrical power by the generator. When the generator rotates at super-synchronous speed, both the stator and the rotor provide power to the grid. The power supplied to the grid is thus the sum of these two powers.

When the rotor rotates at sub-synchronous speed, the stator still supplies power to the grid. However, the rotor absorbs power from the grid. In this case, the net power supplied to the grid is the difference between these two powers.

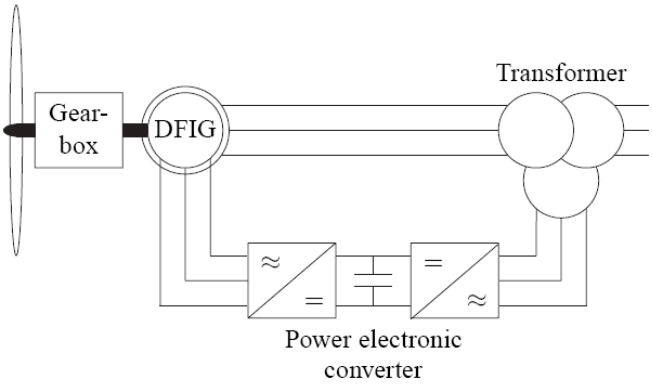


Fig.II.20. Wind turbine coupled with a Doubly-Fed Induction Generator (DFIG).

c3) Variable speed wind turbine with permanent magnet synchronous machine

In this system, the wind turbine is directly coupled to the Permanent Magnet Synchronous Generator (PMSG) with no gearbox. The generator is completely disconnected from the grid via the power converter. Both converters are required to handle all the power produced by the turbine. Consequently, these converters are larger than those used with a double-fed asynchronous (induction) generator. The direct drive eliminates the need for a gearbox. However, since the rotation speed is very low, around 50 rpm, the alternator must be much larger than if it were designed to operate, for example, at 1200 rpm.

Despite the larger size of the machine, the advantages of this configuration make it the preferred wind technology for generating higher powers (2 MW to 5 MW).

Overall, variable speed systems have high efficiency as they manage to maximize the capture of available wind energy while reducing mechanical stress on the components.

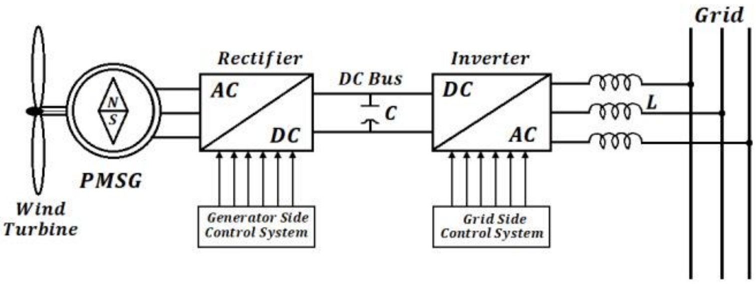


Fig.II.21. Wind turbine coupled with a Permanent Magnet Synchronous Generator (PMSG).

d) Wind properties

Wind results from the movement of air caused by atmospheric pressure gradients. The wind flows from high-pressure areas to low-pressure areas. The greater the atmospheric pressure gradient, the higher the wind speed, and consequently, the greater the wind power that can be harnessed through wind energy conversion systems [26].

The wind possesses kinetic energy due to the mass (m) and velocity (v) of the moving air. If we consider one cubic meter of air moving at a velocity of 10 m/s, and since one cubic meter of air has a mass of approximately 1.2 kg, the stored kinetic energy is thus :

$$E_c = \frac{1}{2}mv^2 = \frac{1}{2} * 1.2 * 10^2 = 60\, J \qquad \text{(II.3)}$$

This energy is captured by the blades of the wind turbine and is converted into mechanical energy, manifested through the rotation of the blades. The produced mechanical energy is further transformed into electrical energy by the generator coupled to the turbine shaft.

Now, let's consider a vertical surface of 1 m² exposed to a wind blowing at 10 m/s. This surface is crossed by a volume of air of 10 m³ every second. Therefore, the available power per square meter of surface, perpendicular to the wind, is :

$$P = 60\, J/m^3 * 10 m^3/s = 600\, J/s = 600\, W \qquad \text{(II.4)}$$

If we generalize this reasoning, we arrive at the following formula that gives the approximate power of the wind as a function of its speed:

$$P = 0.6\, v^3 \qquad \text{(II.5)}$$

e) Solved explanatory exercise

The Fig.II.22. below shows a 400 kW, 3-blade wind turbine designed to deliver its rated power at a wind speed of 18 m/s. The turbine has a diameter of 24 m, and its rated speed is 42 rpm. Calculate :

1) The swept area by the blades.
2) The wind power available to drive the turbine.
3) The speed of the blade tips.

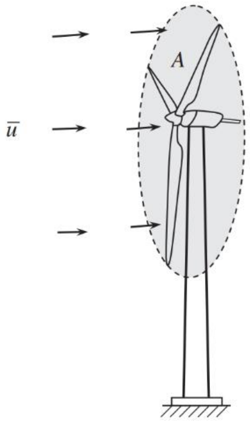


Fig.II.22. Swept area by the blades of the wind turbine.

Solution :

1) $S = \pi r^2 = \pi \left(\frac{24}{2}\right)^2 = 452.39\, m^2$

2) The available wind power per square meter : $P = 0.6 * v^3 = 0.6 * 18^3 = 3499.2\ W/m^2$

The available power to rotate the turbine : $P = 3499.2 * 452.39 = 1583\ kW$

3) The circumference of the circle described by the tip of the blades :

$$C = 2\pi r = 2\pi\left(\frac{24}{2}\right) = 75.4\ m$$

So, for one revolution, we have 75.4 m, and for 42 revolutions, we will have :

$$75.4*42 = 3166.8\ m/60\ \text{sec}$$

Therefore, the speed of the blade tips : $v_p = \left(\frac{3166.8}{60}\right) = 52.78\ m/s$

II.2.2.5. Biomass

Biomass is a renewable energy source that enables sustainable utilization of biofuel resources, typically in solid or liquid form [2] (wood, biogas, straw, organic waste, or industrial and household waste).

The greatest advantage of biomass as an energy resource is its relatively straightforward conversion into fuels [27].

a) Properties of biomass

The composition and physical properties of plants have a significant impact on the energy content of biomass [27]. Biomass is typically characterized by :

- ❶ Its **organic composition**, including the mass content of cellulose, hemicellulose, and lignin ;
- ❷ Its **elemental analysis**, typically indicating carbon, hydrogen, oxygen, nitrogen, and ash (other elements are often reported if present in significant quantities or important for the intended application, such as sulfur for combustion) ;
- ❸ Its **proximate analysis**, which measures the moisture content, volatile matter, fixed carbon, and ash ;
- ❹ Its **overall properties** such as :
  - ① **the heating value (HHV) (Higher Heating Value)**, which is defined as the amount of energy released during the complete combustion of biomass ;
  - ② **bulk density.**

The table (II.1) below represents the physical and thermochemical data representative of biomass from cereals, herbaceous, and woody sources.

Tableau.II.1. Physical and thermochemical properties of the selected biomass [28].

	Raw material	Corn husk	Herbaceous crop	Woody crop
Organic composition (% by weight)	Cellulose	53	45	50
	Hemicellulose	15	30	23
	Lignin	16	15	22
	Others	16	10	5
Elemental analysis (% by dry weight)	C	44	47	48
	H	5.6	5.8	5.9
	O	43	42	44
	N	0.6	0.7	0.5
	Ash	6.8	4.5	1.6
Proximate analysis (% dry weight)	Volatile matter	75	81	82
	Fixed carbon	19	15	16
	Ash	6	4	1.3
HHV (MJ/kg)		17.7	18.7	19.4
Bulk density (kg/m^3)		160-300	160-300	280-480
Efficiency (Mg/ha)		8400	14,000	14,000

b) Biomass resources

Scientists typically categorize bio-renewable resources as either waste or dedicated energy crops.

b1) Waste

Waste is a material traditionally discarded because of apparent lack of value or as a nuisance or even a pollutant to the local environment [27]. Categories of waste qualified as bio-renewable resources include :

- ✓ **Municipal Solid Waste (MSW) :** refers to everything thrown in the garbage and clearly includes materials not considered bio-renewable resources, such as glass, metal, and plastics. MSW includes food processing wastes, which are effluents from a wide range of industries.
- ✓ **Agricultural and Forest Residues :** Agricultural residues are simply the part of a crop rejected by farmers after harvest, such as corn stalks (husks and stems), rice husks, wheat straw, and bagasse (fibrous material remaining after sugarcane crushing).
- ✓ **Manure :** The recent concentration of animals in large-scale farming facilities has led to calls for treating animal waste in a manner similar to human waste.

b2) Energy crops

Energy crops are defined as plants cultivated specifically for the production of bio-based products, i.e., for purposes other than human or animal consumption. An energy crop is planted and harvested periodically. Harvesting may occur on an annual basis, as with sugar beets or switchgrass, or on a 5 to 7-year cycle, as with certain fast-growing tree species like hybrid poplar or willow. The planting and harvesting cycle over a relatively short period of time ensures that the resource is used sustainably ; that is, the resource will be available for future generations.

Energy crops contain significant amounts of one or more of the four important energy-rich components : oils, sugars, starches, and lignocellulose (fiber). However, the most significant constituent is invariably lignocellulose, which is the structural (fibrous) material of the plant : stems, leaves, and roots. If we harvest oils, sugars, and starches and leave lignocellulose as agricultural residue rather than using it as fuel, we would waste the majority of the biomass harvest [27].

II.2.2.6. Geothermal energy

Geothermal energy comes from underground sources of heated water or other heat reservoirs within the Earth's crust. Geothermal energy behaves as a renewable energy source because the Earth replenishes water in its water cycle [3].

There are three different types of heated groundwater contributing to geothermal energy, each occurring in the Earth trapped between rock formations, in fractures in the rock, or in porous rock :

- ❶ Wet steam consisting of hot water droplets and steam ;
- ❷ Dry steam containing only water vapor and no droplets ;
- ❸ Hot water.

Therefore, three different types of power plants also exist to convert the thermal energy from geothermal sources into electricity :

- ① **Dry steam power plants :** this is the simplest and oldest model. They pump steam directly from the underground source to the power plant's turbines ;
- ② **Condensing power plants :** this is the most common type of operating plant today. They extract hot water, convert it into steam, use it to drive turbines while letting the cooled water flow back underground ;
- ③ **Combined cycle power plants :** this is the most recent type of development. They transfer heat from water or steam to another liquid, which drives the turbines.

The Earth's main geothermal sources are located along a line bordering the entire Pacific Ocean through the Northern and Southern Hemispheres. This line, known as the « Ring of Fire », represents the major boundaries of tectonic plates where seismic and volcanic activity is highest. Fig.II.23. below shows the map of the Pacific Ring of Fire : -in red- corresponds to regions with a high density of volcanoes ; the blue lines are the main oceanic trenches, note that the blue lines are not part of the Ring of Fire.

Now, 46 countries along the Pacific Ocean use the Ring of Fire for a portion of their energy needs. In the United States, the majority of geothermal energy use occurs in California, where 2500 MW from geothermal sources provide electricity to 6 million people [3].

a) Advantages :

❶ A constant and free source of energy ;
❷ High energy conversion efficiency ;
❸ Minimal construction ;
❹ Low pollution.

b) Disadvantages :

❷ Limited number of sites ;
❷ Sometimes yields low energy per well ;
❸ Difficult to store or modulate ;
❹ Emissions, odors, and noise.

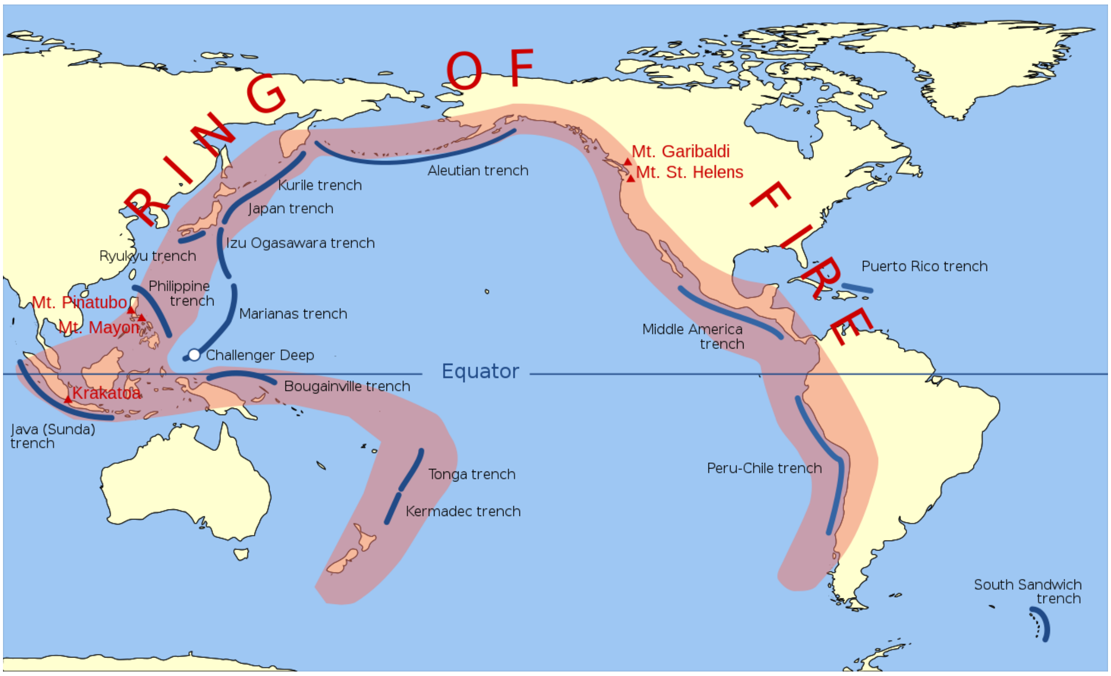


Fig.II.23. Map of the Pacific Ring of Fire.

Chapter III : Connection of DP to the Electrical Grid

III.1. DEP connection conditions in the electrical system

Studies prove that the widespread integration of decentralized production (DP) into electrical grids has impacts and consequences that cannot be ignored [11, 29]. Depending on the country, the impacts of decentralized production means on electrical networks require the establishment of specific technical connection conditions, which are defined in legislative texts (as in France and Spain) and, at a minimum, in the technical references (such as grid codes or distribution codes) of the respective network operators [30]. In this section, we will use France as an example.

III.1.1. Voltage at the point of connection

In France, the voltage at the point of connection plays a crucial role in determining the maximum power of the decentralized production (DP) installation, in accordance with Article 4 of the decree dated April 25, 2008. Table III.1 presents the voltage levels at the point of connection based on the power of the installation [30].

Table III.1. Voltage levels at points of connection based on installed power [30].

Network	Voltage Limit	Actual Levels	Power Limit
LV	$U \leq 1$ kV (single-phase connection)	230 V	$P \leq 18$ kVA
	$U \leq 1$ kV (three-phase connection)	400 V	$P \leq 250$ kVA
MV	$1 \text{ kV} < U \leq 50$ kV	15kV, 20kV, 33kV	$P \leq 17$ MW
HVB	$50 \text{ kV} < U \leq 130$ kV	63 kV, 90 kV	$P \leq 50$ MW
	$130 \text{ kV} < U \leq 350$ kV	150 kV, 225 kV	$P \leq 250$ MW
	$350 \text{ kV} < U \leq 500$ kV	400 kV	$P > 250$ MW

III.1.2. Normal and exceptional operating conditions

Any energy production installation must be capable of producing its maximum power within normal operating ranges. Additionally, it must be able to operate for a limited time when the voltage or frequency, for reasons independent of the installation, reaches exceptional values [30].

In France, the voltage and frequency levels within the normal operating range are as follows :

- Voltage : [95%-105%] in MV, [90%-110%] in LV (230 V)

- Frequency : [48Hz-52Hz]

In metropolitan distribution and transmission networks, wind energy production installations must remain operational when the frequency reaches exceptional values (Decree of April 23, 2008).

For island networks (EDF SEI, 2008), the exceptional ranges are defined as follows :

- Under-frequency of [46 Hz – 48 Hz] for 3 minutes
- Under-frequency of [44 Hz – 46 Hz] for 30 seconds
- Over-frequency of [52 Hz – 54 Hz] for 5 seconds
- Voltage of [90% - 95%] and [105% – 110%] for 1 hour (only for HVB)

III.1.3. Voltage sag tolerance

In the event of a voltage sag, wind turbines and photovoltaic panels typically disconnect from the grid more quickly than other means of production, which can exacerbate an already unstable situation by causing production losses. To minimize these risks, specific voltage sag tolerance constraints are imposed in the technical connection conditions. In France, these constraints include [30] :

- **Metropolitan transmission network (HVB1 and HVB2) :** Wind turbines are required not to disconnect for voltage sags below a certain reference threshold, as defined in Fig. III.1.

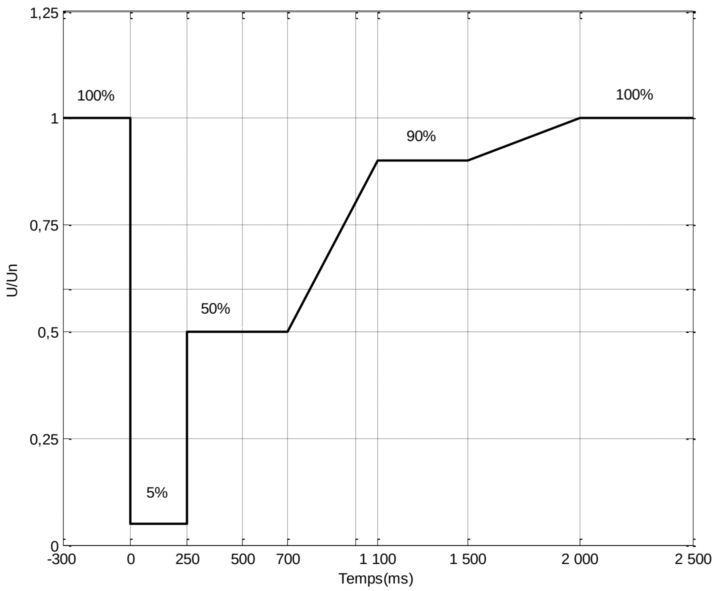


Fig. III.1. Voltage Profile for HVB1 and HVB2 (Specific Application to Wind Turbines) [30].

- **Island HVB networks (EDF SEI, 2008) :** Production installations must maintain their operation during voltage sags defined by the following specifications :
  - Voltage sag of 100% for 250 ms,
  - Plateau at 0.5 U_{dim} for the next 450 ms,
  - Linear return to 0.9 U_{dim} over the next 400 ms,
  - Plateau at 0.9 U_{dim} for the next 400 ms,
  - Linear return to U_{dim} over the next 500 ms.

The design voltage, Udim, is defined by the network operator in consultation with the producer and is typically set to 66 kV (for a 63 kV network) or 93 kV (for a 90 kV network).

- **Distribution network (metropolitan and island) :** According to the Decree of April 23, 2008, any production installation with a maximum power exceeding 5 MW, including wind and photovoltaic farms, must remain operational during a MV voltage sag at the point of connection, as illustrated in Fig. III.2.

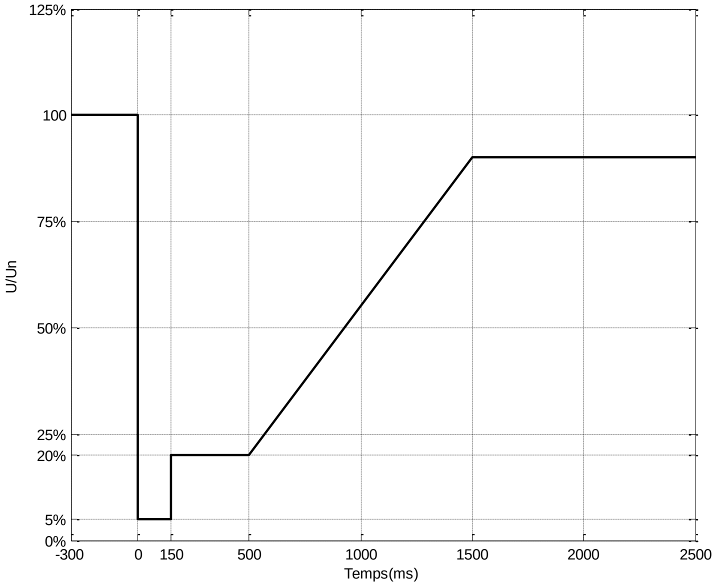


Fig. III.2. Voltage profile for the distribution network [30].

III.2. Regulatory and organizational aspects of DP development

The development of decentralized production, often associated with renewable energies such as wind and solar, presents unique challenges and opportunities from both regulatory and organizational perspectives.

III.2.1. Regulatory aspects

A) Legislative framework : Governments must establish laws and regulations to govern decentralized generation. This includes safety standards, grid connection requirements, and tariff policies for purchasing electricity generated from decentralized sources.

B) Subsidies and incentives : To encourage the adoption of decentralized generation technologies, many countries implement subsidies, tax credits, and other financial incentives. These measures can help offset high initial costs and make these projects more economically viable.

C) Grid integration : Regulators must also establish rules for integrating decentralized generation into the existing electrical grid. This includes guidelines on how these installations can sell their excess electricity to the grid and how they should be managed to ensure grid stability and reliability.

III.2.2. Organizational aspects

A) Business models : The development of decentralized generation requires new business models. This may include energy cooperatives, public-private partnerships, or local companies that manage and operate the generation facilities.

B) Resource management : Decentralized generation necessitates effective management of local resources, such as rooftop solar panels on residential buildings or small wind turbines in rural areas. This involves careful planning to maximize efficiency and profitability.

C) Training and skills development : The transition to decentralized generation also demands the development of new skills among industry workers. This includes training in the installation and maintenance of renewable energy systems, as well as the management and optimization of distributed energy production.

III.2.3. Issues and Perspectives

The development of decentralized generation offers significant advantages, such as reducing transmission losses, increasing the resilience of the electrical grid, and promoting the use of renewable energies. However, it also presents challenges, particularly in terms of regulation, financing, and management. A balanced and well-planned approach is essential to maximize the benefits while minimizing the risks associated with this energy transition.

III.3. Technical aspects of connection to high-voltage networks (HVNs)

Firstly, it is important to note that the HVA network (High Voltage A) implies an effective alternating voltage ranging between 1 kV and 50 kV. Internationally, this voltage range is often referred to as Medium Voltage (MV).

The widespread integration of distributed generation (DG) into high-voltage networks has several impacts that cannot be overlooked, including :

III.3.1. Impacts on the power flow direction

In normal circumstances, power flow is directed from the transmission network to the distribution network (cf. Fig.III.3.(a)). However, connecting distributed generation (DG) to the HVA network, with voltage levels different from the transmission network, can result in power injection in the opposite direction (i.e., from distribution to transmission) (cf. Fig.III.3.(b)). Consequently, protective equipment must be bidirectional. As the DG connection rate increases, the alteration of power flow direction may potentially lead to local congestions [11].

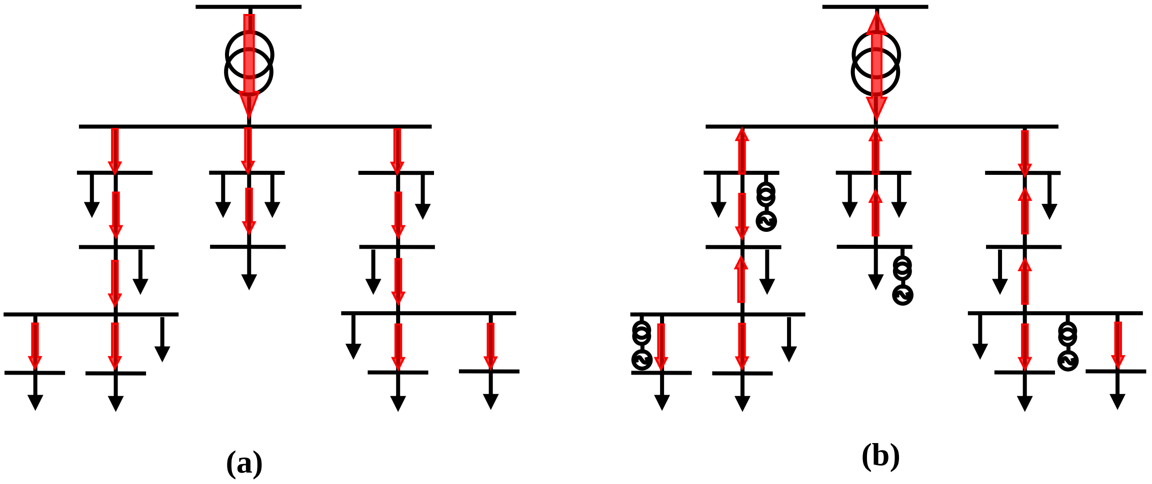


Fig.III.1. Power flow in a distribution network : **(a)** Without DG connection ; **(b)** With DG connection.

III.3.2. Impacts on system stability

In light of the fact that distributed generation units may exhibit synchronous or asynchronous characteristics, the integration of synchronous generators into the distribution network (e.g., HVA) results in a shift in the critical fault-clearing time. This critical time represents the maximum duration of a disturbance that the electrical system can endure without experiencing a loss of stability. Consequently, this alteration directly impacts the dynamic stability limit of the electrical system under consideration [11].

III.3.3. Impacts on the protection scheme

It is essential that the presence of a DG installation at a faulty feeder should not disrupt the operation of the distributor's protection plan in terms of sensitivity and selectivity. To achieve this, the decoupling protection plays the role of isolating the DG installation to prevent maintaining the fault under voltage. It eliminates the parallel connection between generators and the distribution network during a fault or another anomaly [11].

III.3.4. Impacts on service quality

In order to magnetize their magnetic circuit, asynchronous-type DG generators require reactive power consumption. Upon grid connection, these generators exhibit a substantial current draw, contributing to a voltage dip. Additionally, the inclusion of power electronics interfaces can elevate harmonic levels, significantly impairing the quality of the provided service [11].

III.3.5. Impacts on service continuity

The intermittent nature of DG generators can lead to power outages due to insufficient capacity when the system demands their output [11].

III.3.6. Impacts on the observability and controllability of the system

Due to the intermittent nature of DG generators, it becomes challenging for the operator to estimate the supplied power from these producers, consequently impacting the overall system power supply [11].

III.4. Interactions between DG and the electrical network and the applicable standards

The integration of distributed power generation (PD) into the distribution network necessitates meticulous adherence to specific technical constraints, prompting requisite modifications within the network infrastructure to ensure optimal functionality. In the context of PD connectivity, the implementation of precautionary measures through adherence to connectivity protocols becomes imperative to uphold the seamless operation of the network. These protocols encompass technical directives pertaining to design and operational facets, encompassing aspects such as protection mechanisms, installed power capacity, disturbance handling, frequency modulation, voltage regulation, and more. The extant standards, serving as regulatory benchmarks, are meticulously formulated to underwrite the proficient operation of the prevailing distribution network paradigm. It is imperative to acknowledge that in the event of distribution networks undergoing paradigm shifts towards alternative architectures and operational modalities, the extant standards are susceptible to revision [11].

The integration of Distributed Power Generation (PD) from any user demands a thorough investigation to discern an optimal solution that precisely aligns with the connectivity requisites of the applicant. Concurrently, it is imperative to ascertain that this connection remains devoid of any deleterious implications on the functionality of the public network and the quality of energy provisioned to pre-existing users within the network [11].

The connectivity procedure is intricately embedded within the framework of the extant or designated distribution network for the pertinent region, leveraging the available or prospective distribution infrastructures possessing the requisite hosting capacity [11].

III.4.1. Interactions between distributed generation and the electrical grid

III.4.1.1. Grid connection

A) Connection techniques : Decentralized generation installations must be connected to the electrical grid in a way that minimizes disruptions. This includes the use of transformers, inverters, and protection devices.

B) Power quality : The quality of the power injected by decentralized generators must meet the grid’s standards for voltage, frequency, and harmonics to avoid disturbances that could impact other consumers.

III.4.1.2. Load and production management

A) Balancing supply and demand : Network operators must manage the variability of decentralized generation, especially for intermittent sources like wind and solar. Energy storage systems and smart grids can assist in balancing supply and demand.

B) Forecasting and planning : The integration of decentralized generation requires accurate forecasts of production and consumption to plan network operations.

III.4.1.3. Network stability and reliability

A) Voltage and frequency stability : Rapid fluctuations in renewable energy production can impact network stability. Advanced control devices and regulation services are necessary to maintain stability.

B) Security and protection : Protection devices must be implemented to quickly detect and isolate faults, ensuring the safety of both decentralized generation facilities and the main grid.

III.4.2. Applicable standards

III.4.2.1. Technical and safety standards

A) IEC 61727 and IEEE 1547 : These international standards specify the requirements for connecting decentralized generation systems to distribution networks. They cover aspects of protection, performance, and safety.

B) Grid codes : National grid codes define specific criteria for the connection and operation of decentralized generators. For example, in Europe, the ENTSO-E grid code is applied.

III.4.2.2. Regulations and support policies

A) Feed-in tariffs and Power Purchase Agreements (PPA) : Governments establish financial mechanisms such as guaranteed feed-in tariffs and PPAs to encourage investment in decentralized generation.

B) Incentives and subsidies : Grants, tax credits, and other financial incentives are often available for decentralized generation projects.

III.4.2.3. Environmental standards

A) Emission reduction : Decentralized generation facilities are often required to comply with strict standards for reducing greenhouse gas emissions, in line with international commitments such as the Paris Agreement.

B) Environmental Impact Assessment (EIA) : New decentralized generation projects typically need to conduct an EIA to assess and mitigate their environmental impacts.

Chapter IV : Critical Infrastructure of the Electrical System

IV.1. Critical infrastructures and critical electric system infrastructures

Critical infrastructures encompass systems and structures that are vital for the proper functioning of a state, ensuring the safety and well-being of its citizens. Their unavailability or destruction would have a debilitating impact on national security or the economy. These include electric networks, telecommunications, healthcare, water supply, fuel infrastructure, food, transportation, banking and financial systems, public administrations, and more [31].

These infrastructures require special attention to ensure their operation even in unusual circumstances (such as conflict, pandemic, earthquake, etc.), with their electrical power supply being a key area.

The electrical system infrastructure consists of all the means of production, transportation, and distribution of electrical energy, and it is divided into the transmission network, generation network, and distribution network. In addition to purely electrotechnical components such as generators, transformers, and lines, this electrical infrastructure also requires a control system belonging to the information and communication infrastructure. Its functions are to manage and regulate the physical parameters of the electrical system infrastructure and enable reconfigurations in emergency situations [31].

The main characteristics of the electrical infrastructure are that it consists of networks comprising thousands of nodes with an irregular and complex structure that dynamically evolves over time. This evolution occurs at faster time scales [31].

IV.2. Management in the presence of a high rate of PD insertion

Managing critical situations for an electrical system with a high penetration rate of decentralized production is complex due to the variability and intermittency inherent in renewable energy sources, such as solar and wind energy.

In the previous chapter, we explored various impacts of decentralized production on electrical networks (HVA). As long as decentralized production remains marginal, it has no significant influence on the operation or service quality of the network. However, a major challenge arises with the widespread introduction of decentralized production into the network, particularly in the management of critical situations. This introduction contributes to increased uncertainties and hazards, making the network more fragile due to its sensitivity [32].

IV.2.1. Challenges of management with distributed generation (DG)

IV.2.1.1. Network stability

Distributed energy sources can introduce variability in electricity production due to their reliance on weather conditions. This can affect the stability of the grid, which must maintain a constant balance between electricity generation and consumption.

IV.2.1.2. Power quality

A high penetration of DG can influence the quality of electricity, particularly in terms of voltage and frequency. Fluctuations may occur, necessitating compensation devices or sophisticated management systems to maintain quality.

IV.2.1.3. Load management

With decentralized production, energy flow management becomes more complex. Network operators need to integrate advanced monitoring and control tools to manage bidirectional flows, where electricity can be injected into the grid from multiple points.

IV.2.1.4. Technological integration

It is essential to implement smart technologies, such as smart grids, to efficiently manage production and consumption in real-time. This includes advanced metering devices, energy storage systems, and algorithms for production forecasting.

IV.2.1.5. Regulation and standards

Regulations must evolve to allow for the seamless integration of DG. This includes connection standards, financial support mechanisms, and policies to encourage grid balancing.

IV.2.2. Potential solutions

IV.2.2.1. Grid flexibility

Develop solutions for flexibility to respond to production variations. This may include energy storage, demand management, and the integration of fast-response generation sources.

IV.2.2.2. Dynamic regulation

Adapt regulations to allow for rapid and adaptable responses to real-time grid conditions.

IV.2.2.3. Collaboration

Encourage collaboration between grid operators, decentralized energy producers, and consumers to optimize grid management and stability.

IV.3. The technical additional costs associated with intermittency

Renewable energy production is ensured by technologies with radically different technical characteristics. For instance, electricity production technologies from biomass exhibit good flexibility due to the ability to store the resource, whereas micro-hydropower, solar with its two types, and wind energy are inherently intermittent. This means that their production cannot be precisely scheduled from one day to the next, as it varies depending on the availability of the resource. Their integration into electrical systems will pose challenges due to the intermittent nature of production, which does not align with the technical culture of producers, network managers, or regulators [33].

The challenges inherent in the integration of intermittent production give rise to additional technical costs, stemming from increased requirements for production capacities and reserves. These costs are attributed to the risks associated with non-availability during peak periods and the fluctuation of production, necessary to maintain instantaneous balance between supply and demand [33].

The magnitude of the additional costs arising from substantial integration of intermittent production varies significantly depending on the envisaged technological mix, their penetration level, and the spatial distribution of these production units within the electrical system [33, 34].

A British assessment indicates that an expansion of renewable energies in electricity production from 10%, as envisaged from 2010, to 20% could increase system costs by approximately £150 million (lowest cost) to £400 million per year (highest cost) (€225 million to €600 million per year in real terms, April 2002 prices). Additionally, additional costs of approximately £200 million to £500 million per year (€300 million to €750 million per year) are projected for a 30% level [33, 34].

As we have just mentioned, the widespread integration of non-programmable sources generates additional technical costs, attributable to :

IV.3.1. Requirements for additional production capacities

The need for additional production capacities arises from the uncertainty regarding the contribution of intermittent sources to peak power. The probability of failure in wind production, for example, is higher during peak periods than that of conventional thermal production. Thus, even though wind energy can contribute to available capacity during peak periods, this contribution cannot be guaranteed in the same way as conventional production. As the share of wind energy in peak demand increases, the risk becomes more significant, and the volume of production capacities to be held in reserve to ensure system security grows. While this risk can be mitigated by the geographical dispersion of intermittent production units, there is indeed an additional cost to ensure power [33].

IV.3.2. Balancing the electrical system

In an electrical system primarily powered by conventional thermal generation, demand variations are the main sources of imbalance. However, with the increasing integration of intermittent sources into the system, unforeseen fluctuations in producers' output become a progressively significant uncertainty that needs to be addressed. It is no longer merely a matter of planning reserve production capacities to meet demand during peak periods in case of intermittent source failures due to the uncertainty of their contributions. It is also crucial to continuously maintain the balance between supply and demand to uphold the quality of the supply. To achieve this, the electrical network manager must have rotating or immediately available reserves, the cost of which increases as the volume of imbalances becomes more substantial [33].

☼ **Important Note**

Three types of reserves are distinguished based on their activation duration : [33]

a) Primary reserve : Automatically activated, it allows for a response within 1 or 2 seconds.

b) Secondary reserve : Designed to replenish the used reserves and restore the availability of the consumed primary reserve. These production means are also automatically mobilized within a timeframe of 30 seconds.

c) Tertiary reserve : This category encompasses a set of "peak" means that the electrical network manager can activate with considerably longer delays (from 30 minutes to half a day) to replenish the consumed secondary reserve.

✷ The combination of primary and secondary reserves constitutes the system services provided by the transmission network manager. Meanwhile, tertiary reserve can be secured in a liberalized market through the competitive bidding of offers by market participants.

Given that demand can be predictable to some extent, forecast errors can ultimately lead to managing reserve capacities exceeding approximately 5 to 10% of thermal capacity if predictions are inaccurate [35].

IV.4. Methodology of critical situations management

The critical situation management methodology for an electrical system with a high penetration rate of decentralized production may vary depending on the size and complexity of the system, as well as the available resources. However, the following is a general methodology that can be adapted to many situations :

① **Continuous monitoring**

- Implementation of advanced monitoring systems to collect real-time data on decentralized production, load, voltage, frequency, and other key network parameters.

② **Forecasting**

- Use of meteorological forecasting models to anticipate renewable energy production, especially for intermittent sources such as solar and wind.
- Forecasting electrical demand using statistical models and historical data.

③ **Resource planning**

- Allocation of sufficient resources to cope with variations in decentralized production and demand.
- Energy storage capacity to absorb excess production and provide energy during demand peaks.

④ **Load management**

- Use of load management systems to reduce demand during periods of insufficient renewable energy production.
- Promotion of load flexibility among customers through incentive-based tariffs.

⑤ **Active network control**

- Deployment of advanced network control technologies, such as battery management, voltage and frequency regulation, and energy flow management.

⑥ **Coordination among stakeholders**

- Close collaboration between decentralized energy producers, network managers, regulators, and other stakeholders to share real-time information and make coordinated decisions.

⑦ **Contingency plan**

- Development of emergency plans to address critical situations, such as unexpected decentralized production failures or demand spikes.

⑧ **Integration of information technologies**

- Use of advanced information management systems to make decisions based on real-time data and improve network responsiveness.

⑨ **Awareness and education**

- Raising awareness among end-users about energy management issues and the need to reduce consumption during critical periods.

⑩ **Testing and simulations**

- Regular conduct of tests and simulations to assess the system's resilience against potential critical scenarios.

It is important to note that managing critical situations for an electrical system with high penetration of decentralized production is a constantly evolving field, as new technologies and methods regularly emerge to optimize network stability and reliability. Local regulations and standards can also have a significant impact on management methodology. Therefore, close collaboration among stakeholders and constant adaptation to changes are essential to ensure the proper functioning of the electrical grid.

IV.5. Interest in energy storage

With the growing development of renewable energies, electrical grids must now contend with highly intermittent production, such as wind and photovoltaic energy. Figure (IV.1) depicts the production of a 300 kW wind turbine over a 5-minute period, revealing substantial variability with fluctuations of 100 kW in just 3 seconds. Figure (IV.2), on the other hand, illustrates the production of a photovoltaic installation over a day, demonstrating how the presence of clouds can lead to significant variability in production [36].

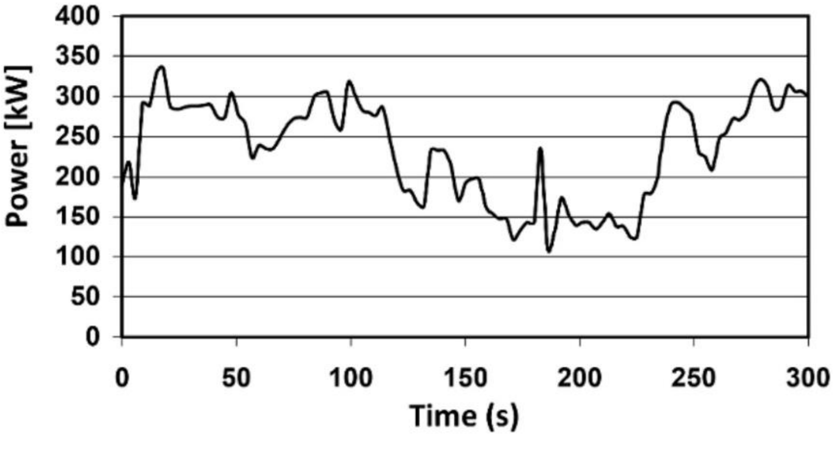


Fig. IV.1. Example of power produced by a wind turbine of 300 kW operating at a constant speed [36].

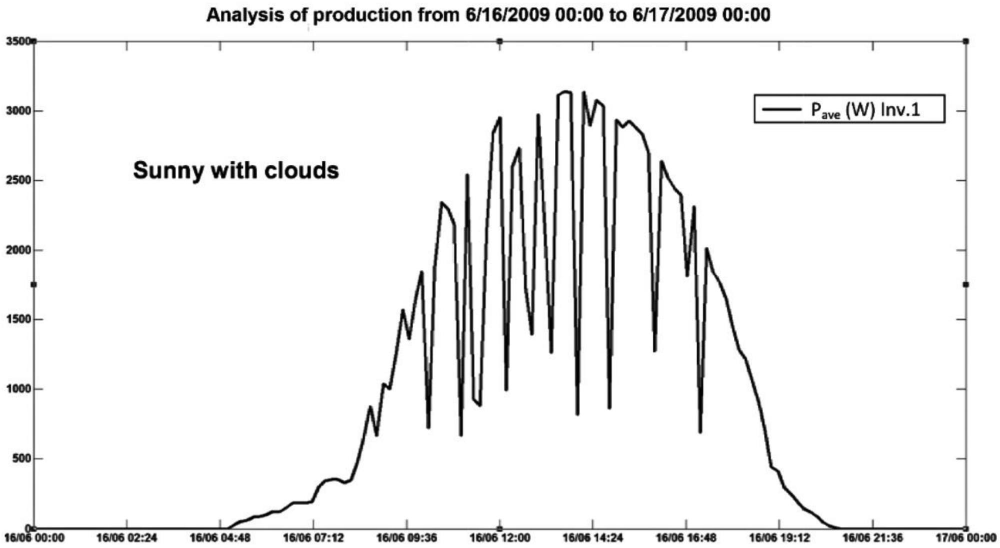


Fig. IV.2. Profile of a sunny day with clouds [36].

The two previous examples demonstrate that achieving a balance between energy production and consumption does not occur naturally and proves to be a complex undertaking, largely due to the increasing penetration of renewable energy sources with substantial variability. The implementation of electrical energy storage mechanisms generated by these renewable sources provides the opportunity to mitigate the inherent fluctuations in their production, thereby promoting their alignment with the energy demand requirements [36].

The transportation infrastructure, including railway networks, metro systems, and tram lines, places a significant demand on electrical grids characterized by intermittent energy needs resulting from the frequent acceleration and deceleration of traction vehicles, as well as variations in passenger traffic levels throughout the day [36].

In the effort to enhance the cost-effectiveness of energy storage, a highly relevant approach lies in the sharing of services provided by a storage system among various stakeholders, including energy managers, producers, and consumers. These services encompass a range of crucial functionalities, including but not limited to : [36, 37]

1. Precise and dynamic local voltage control, enabling effective adjustment of electrical parameters to maintain network stability.
2. Network support in case of degraded operation, ensuring the continuity of energy supply even during disruptions.
3. The ability to inject energy back into network sections, thereby contributing to load balancing and reducing disturbances.

4. Reactive compensation for network managers and clients, promoting the optimization of delivered energy quality.
5. Reducing transport losses by minimizing energy dissipation during long-distance transportation.
6. Improving the quality of electrical power, ensuring stable voltage free from disturbances for end users.
7. Energy shifting and support for production units, facilitating the seamless integration of intermittent renewable energies into the grid.
8. Primary frequency control and frequency stability for islanded grids, ensuring consistent and reliable operation of isolated systems.
9. Resolving energy congestion by enabling more efficient balancing between supply and demand.
10. Supporting participation in ancillary network services, strengthening the flexibility and resilience of the electrical system.
11. Recovery after curtailment, quickly restoring the supply in the event of a planned energy outage.
12. Ensuring a stable production profile, allowing producers to plan and deliver a consistent amount of energy.
13. Smoothing demand peaks, helping to avoid network overloads during consumption spikes.
14. Consumption shifting, allowing consumers to optimize their energy usage based on costs and availability.
15. Improving the quality and continuity of energy supply, ensuring a reliable and uninterrupted service to users.

IV.6. Islanding

Islanding, in the context of microgrid management, refers to the condition where the microgrid is intentionally or unintentionally disconnected from the main distribution grid at the Point of Common Coupling (PCC). In this configuration, distributed generators (DG), energy storage devices (ES), as well as internal loads within the microgrid operate autonomously and independently of the main grid. In islanded mode, it is noteworthy that the electrical production capacity of the microgrid is often limited and insufficient to meet the entire energy demand of connected loads. Therefore, it becomes imperative to establish a prioritization strategy for loads based on their importance, ensuring a continuous and uninterrupted power supply for critical loads and infrastructure such as hospitals, data centers, facilities, military bases, chemical and pharmaceutical production plants, etc., where a power outage can have serious consequences [38].

Transitions of microgrids from an interconnected operational state to an islanded operational state, and vice versa, can lead to substantial disparities between energy production and demands, thereby causing significant imbalances in fundamental electrical parameters such as frequency and voltage. This oscillation between microgrid operating modes can result in significant disturbances in the electrical system, having a considerable impact on the overall stability and reliability of the electrical network [39].

Chapter V : Self-production in renewable energies (Microgrids)

V.1. Concept and operation of microgrids

V.1.1. Concept of microgrids

Microgrids are small-scale electrical networks designed specifically to provide low-voltage (LV) electrical supply to a small number of consumers. These networks include : [39, 40]

- ❶ Different local production units (distributed energy resources) such as micro-turbines, fuel cells, small diesel generators, photovoltaic panels, mini wind turbines, and small hydropower.
- ❷ Storage devices such as flywheels, energy capacitors, and batteries.
- ❸ Controllable local flexible loads with the capability to be controlled in relation to network operation.

A microgrid is often located at low voltage (LV) and typically has an installed micro-generation capacity of less than a few megawatts (MW). However, there may be exceptions, especially when parts of the medium-voltage (MV) network are included for interconnection purposes [40].

V.1.2. Operating modes of a microgrid

A microgrid must have the ability to operate optimally when connected to the main grid under normal conditions (operation in connected mode), while also being capable of isolating itself and operating autonomously in case of emergencies (operation in islanded mode) [40].

V.1.2.1. Operation in connected mode to the grid

In connected mode to the grid, the microgrid is connected and exchanges energy with the public electrical distribution system through the Point of Common Coupling (PCC) [39].

V.1.2.2. Operation in islanded mode

Islanded mode operation in a microgrid involves disconnecting from the main grid in the event of a power outage or according to a predetermined plan. In this configuration, distributed generators, energy storage devices, and loads operate autonomously. However, since electricity production within the microgrid is typically limited, it is essential to prioritize the power supply to critical loads to ensure a constant energy supply for them [39].

To achieve long-term islanded operation, a microgrid must meet high requirements in terms of storage size and rated capacity of micro generators for a continuous supply to all loads, or it must rely on significant demand flexibility [39].

A microgrid has three essential characteristics: local load, local micro-sources, and intelligent control. In many nations, there is a focus on environmental preservation by incentivizing the adoption of low-carbon footprint technologies such as renewable energies (RE) and cogeneration through carbon credits (for more information, refer to appendix B). It would be wise to incorporate this component as a fundamental feature of microgrids. The absence of one or more of these elements can be more precisely described through distributed generation (DG) interconnection scenarios or demand-side integration (DSI) scenarios [39].

V.1.3. Debunking misconceptions about microgrids

In the following, we will dispel some misconceptions about microgrids : [39]

- ✗ Microgrids are exclusively isolated (islanded) systems.
- ✓ Microgrids have the capability to transition to islanded operation in case of an emergency, but they are mostly operated interconnected with the upstream distribution network.
- ✗ Microgrids are established by customers who own micro-sources.
- ✓ While the presence of Distributed Generation (DG) is a distinct feature of a microgrid, it goes beyond passive tolerance and demands active supervision, control, and optimization.
- ✗ Microgrids comprise intermittent renewable energy sources, implying reduced reliability and increased vulnerability to interruptions and complete outages.
- ✓ A microgrid can mitigate variations in renewable energy sources (RES) by using its own energy storage devices (when operating in islanded mode) or by tapping into external production reserves (when interconnected to the main grid). Moreover, the ability of the microgrid to transition from interconnected mode to islanded mode effectively enhances the resilience and reliability of the energy supply.
- ✗ Due to high construction costs, the implementation of microgrids is often limited to field trials or remote sites.
- ✓ The global penetration of Distributed Energy Resources (DER) is increasing, supported by financial incentives for renewable energy and cogeneration. Microgeneration and storage costs are expected to decrease, strengthening the commercial competitiveness of microgrids. Additional costs for transforming distribution lines into microgrids typically involve control and communication systems, often offset by savings resulting from coordinated DER management.

- ✗ The concept of a microgrid is so innovative that systems operators must completely rethink the structure of their network.
- ✓ While the installation of new metering, communication, and control devices is necessary, the transformation of a conventional distribution network into a microgrid doesn't impose substantial infrastructure costs on the network operator. In fact, a microgrid can effectively defer the investment expenses for device replacement.
- ✗ Loads within the microgrid are ensured to never experience supply interruptions.
- ✓ A smooth transition to islanded operation, meaning without power interruptions, requires considerable redundancy in storage or production capacities within the microgrid. Therefore, an islanded microgrid will likely need to adjust non-essential loads based on the instantaneous availability of resources.

V.2. Operation and control of microgrids

V.2.1. Controllable elements in a microgrid

In addition to the fundamental elements governing the interplay between supply and demand, a microgrid could be enhanced by the establishment of dedicated infrastructure for energy balancing. Among these infrastructures are dispatchable loads, such as electric vehicles, as well as storage units within substations. These devices could potentially contribute either to minimizing energy flows or maximizing them in a context of increased profitability, given energy exchanges conducted under favorable tariff conditions [39].

V.2.1.1. Intermittent RES units

Intermittent energy production units from renewable sources have controllability constraints due to the physical nature of their primary energy source. Restricting their production is generally not preferable due to the high investment costs, low operating costs, and environmental benefits they provide compared to carbon emissions. However, a reduction may be considered in the case of line overload or overvoltage issues to ensure the stability of the electrical network [39].

The operation strategy for intermittent Renewable Energy Source (RES) units can be characterized as « priority dispatch ». In essence, these units are typically excluded from the unit commitment schedule, given that they do not violate system constraints. However, units with independent reactive power interfaces (decoupled from active power output) may be incorporated into reactive power management to enhance the overall technical performance of the microgrid [39].

V.2.1.2. Dispatchable microsource and cogeneration (CHP) units

The controllability of cogeneration units (CHP : Combined Heat and Power) depends on their responsiveness to local heat demands, whether they can be operated in heat-only, electricity-only, or hybrid mode. Since most of these microsource and cogeneration units rely on rotating machinery technology, their controllability in terms of reactive power is inherently limited by active and apparent power [39].

Due to the better controllability of dispatchable microsource units, a microgrid equipped with several of these units will have to solve the traditional unit commitment problem but on a much smaller scale. However, the microgrid operator will have to deal with significantly higher load variations due to fluctuations in intermittent renewable energy production [39].

V.2.1.3. Storage units

From a technical perspective, a storage unit can operate either following the load (for balancing) or following prices (for arbitrage), depending on its objective. These storage units can also provide balancing reserves, ranging from short-term to long-term applications. Direct current storage technologies, such as batteries and supercapacitors, can contribute to balancing the reactive power of the system without significant operational costs [39].

V.2.2. Microgrid operation strategies

The efficient operation of microgrids relies on the utilization of Distributed Generation (DG) technologies for active and reactive power generation. However, the configurations and operation schemes of microgrids are influenced by sometimes divergent interests of stakeholders, including system operators, DG owners, DG operators, energy suppliers, customers, and regulators. The optimal planning of these microgrids must therefore take into account economic, technical, and environmental objectives to ensure their overall performance [39].

According to stakeholders engaged in planning or operation, microgrids have four distinct operational objectives : economic option, technical option, environmental option, and the combined option of these objectives [39].

The economic option aims to reduce costs without considering the impact on the network or the environment. It is favored by owners of Distributed Generators (DG) who operate without concern for network or environmental constraints, often limiting themselves to the physical constraints of the DG [39].

The technical option focuses on optimizing network performance by minimizing power losses, voltage variations, and device loads, without considering the financial aspects related to the production of Distributed Generators (DG). This approach may be favored by system operators [39].

The environmental option gives preference to Distributed Generation (DG) units with reduced emissions, disregarding financial and technical considerations. It is often employed to achieve environmental goals, typically supported by regulations. Decisions regarding DG are primarily dictated by emission quotas, considering exclusively the physical limits of the DG [39].

The combined option comprehensively addresses the management of Distributed Generation (DG) by considering economic, technical, and environmental criteria. It balances these dimensions while taking into account network constraints and the limits of DG. This approach is relevant for stakeholders participating in various markets, including energy, network services, and emission certificates [39].

V.3. Hybrid microgrids with distributed generation and storage

Hybrid Micro-Grid Systems, also known as HMGS, represent a complex configuration that combines multiple decentralized (renewable) sources and traditional sources, interconnected through electronic control mechanisms. These systems are characterized by their ability to operate in autonomous mode (islanded mode), forming an isolated microgrid, while also being capable of connecting to the main electrical grid (connected mode). The use of HMGS powered by renewable energy sources (RES) emerges as an economically viable solution to address the electricity supply challenge in remote areas geographically distant from traditional energy distribution infrastructure [40].

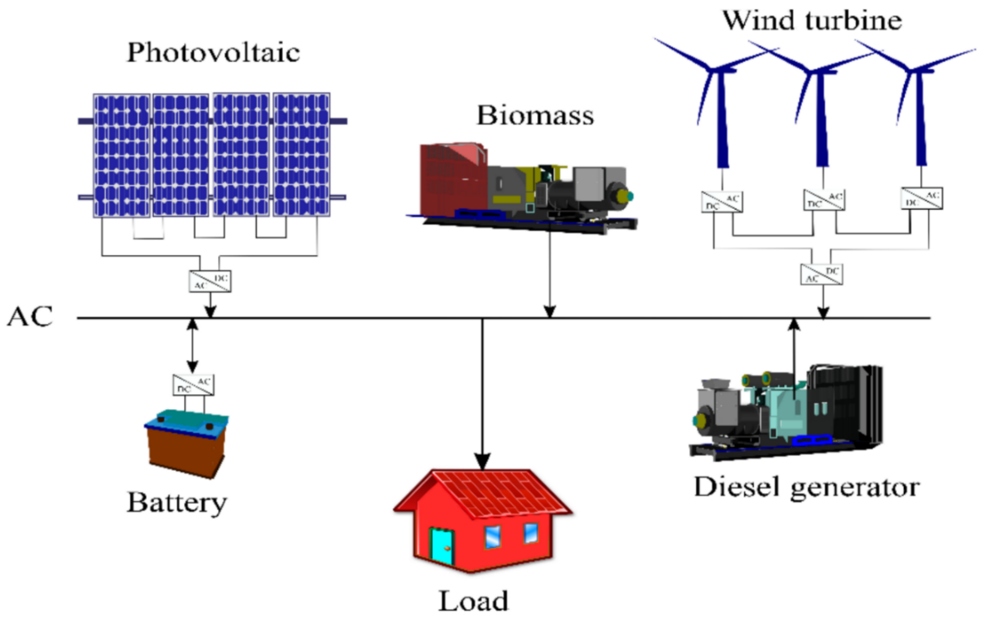


Fig.V.1. Components of a Hybrid Microgrid System [41].

Among the main characteristics of hybrid microgrid systems, we can identify :

1. **Combination of Energy Sources :** Hybrid microgrids typically integrate renewable energy sources such as solar, wind, or hydroelectric power with conventional energy sources like diesel or gas generators. This combination allows for maximizing the use of renewable energies while ensuring a stable power supply.
2. **Operational Flexibility :** HMGS can operate in islanded mode, meaning autonomously, disconnected from the main electrical grid, or in connected mode to the grid. This flexibility allows them to adapt to local needs and conditions, especially in the event of a power outage.
3. **Energy Reliability :** Hybrid microgrids are designed to enhance the reliability of electrical power, especially in remote or underserved areas with limited access to traditional grids. They reduce dependence on external energy sources and can operate continuously using locally available resources.
4. **Energy Efficiency :** By utilizing various energy sources and optimizing their use, HMGS aim to enhance overall energy efficiency, thereby reducing the consumption of fossil fuels and greenhouse gas emissions.
5. **Diverse Applications :** Hybrid microgrids are used in a variety of applications, including rural areas, remote communities, military bases, industrial facilities, national parks, and even in sustainable development projects.
6. **Advanced Management Technologies :** To ensure optimal management of resources and electrical load, hybrid microgrids use advanced control and management systems that incorporate technologies such as energy storage systems, demand management, and energy flow optimization.

Hybrid microgrids play a crucial role in the transition to cleaner and more sustainable energy production, providing reliable and flexible energy solutions for remote regions and areas experiencing frequent power disruptions.

A prime example of a hybrid microgrid is the « Princess Elisabeth » research station in Antarctica, operated by Belgium. This scientific research station is not connected to an electrical grid due to its location in extreme Antarctic conditions (air temperatures ranging from -5°C to -50°C, maximum wind speed per month: 125 km/h). Thanks to the implementation of a hybrid microgrid, the station is energy self-sufficient. For electricity production, this hybrid microgrid combines 379.5 m^2 of solar panels and 9 wind turbines (each with a capacity of 6 kWh) [42, 43], with the generated energy stored in lead-acid batteries with a capacity of 6,000 Ah. Heating is produced using 22 m^2 of solar thermal panels. Additionally, two diesel generators (44 kWh) are available as backup sources.

Fig.V.2. The Princess Elisabeth research station in Antarctica powered by a hybrid microgrid [44].

V.4. Monitoring and data logging

The systematic monitoring process serves to constantly verify the operational status of all equipment while maintaining continuous control over their functioning. This is crucial to ensure their intrinsic safety and the stability of the overall electrical system. It is imperative that the monitoring system remains at the forefront of technology, ensuring its ability to operate in real-time continuously through the integration of software and hardware specifically designed for microgrids [45]. Monitoring and data logging in microgrids serve several important objectives :

1. **Real-time monitoring :** Real-time monitoring of electrical parameters, such as voltage, current, frequency, active and reactive power, is crucial for ensuring the proper operation of the microgrid. This allows for the rapid detection of issues and fluctuations, enabling corrective measures to be taken [46].
2. **Load management :** Real-time monitoring of loads enables microgrid operators to effectively manage electricity demand, distribute the load among various energy sources (such as solar panels, wind turbines, diesel generators, etc.), and plan battery recharge.

3. **Energy optimization :** Data monitoring enables informed decision-making regarding the use and distribution of energy. It can assist in optimizing energy production based on weather conditions, resource availability, and demand.
4. **Fault detection :** By recording performance data and monitoring in real-time, it is possible to quickly detect faults or malfunctions in the microgrid, allowing for prompt reactions to minimize service interruptions [46].
5. **Performance Analysis :** Long-term data recording enables in-depth analysis of microgrid performance. Historical data is valuable for identifying trends, assessing energy efficiency, and planning improvements.

To implement monitoring and data recording in an electrical microgrid, several components and systems are required, including :

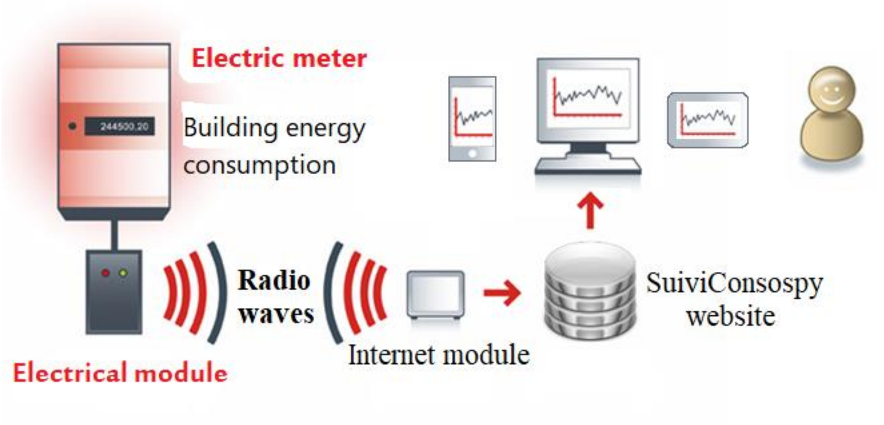
- **Sensors :** They measure electrical parameters and transmit data to the microgrid management system.
- **Microgrid Management System (MGMS) :** It collects, processes, and analyzes real-time data while making microgrid management decisions.
- **Data storage system :** The collected data is stored in databases for future use and performance analysis.
- **User interfaces :** Microgrid operators and managers can access data through user-friendly interfaces to monitor and manage the system.
- **Communication :** Data is typically transmitted through communication networks, such as wired or wireless networks, to enable remote monitoring.

The selection of equipment and software for monitoring and data recording will depend on the specifications of the microgrid, its size, complexity, and specific objectives.

Among examples of monitoring and data recording products are :

a) Consospy : The CONSOSPY Electricity module is a device that connects to the electronic electricity meter. With its memory capacity, it records the meter's power at regular intervals (every minute, 10 minutes, or hourly). With this module, it is possible to track either our electricity consumption or production. Communication is wireless (radio waves). The energy evolution over different periods is viewable with the tracking software « SuiviConsoSpy ».

(a)



(b)

Fig.V.3. (a) Consospy Electricity Module ; (b) Schematic diagram [47].

b) WebdynSun : serves as a pivotal conduit dedicated to the surveillance and acquisition of data emanating from solar power infrastructures. Within a singular apparatus, this gateway intricately consolidates a myriad of metrics sourced from inverters, electrical gauges, and environmental sensors, encompassing variables such as solar irradiance, ambient temperature, and wind velocity. Employing a meticulous protocol, the device adeptly transcribes the gathered data into the universally embraced CSV (Comma-Separated Values) format. These formatted datasets undergo periodic transmission, facilitated by mobile networks, Ethernet infrastructure, or the venerable switched telephone network (RTC), directed towards a central server repository. The installation process, characterized by its simplicity and user-centric design, leverages an embedded web server, affording the additional capability of remote deployment. Furthermore, this gateway empowers localized actions by exercising control over pertinent files originating from the central server [48].

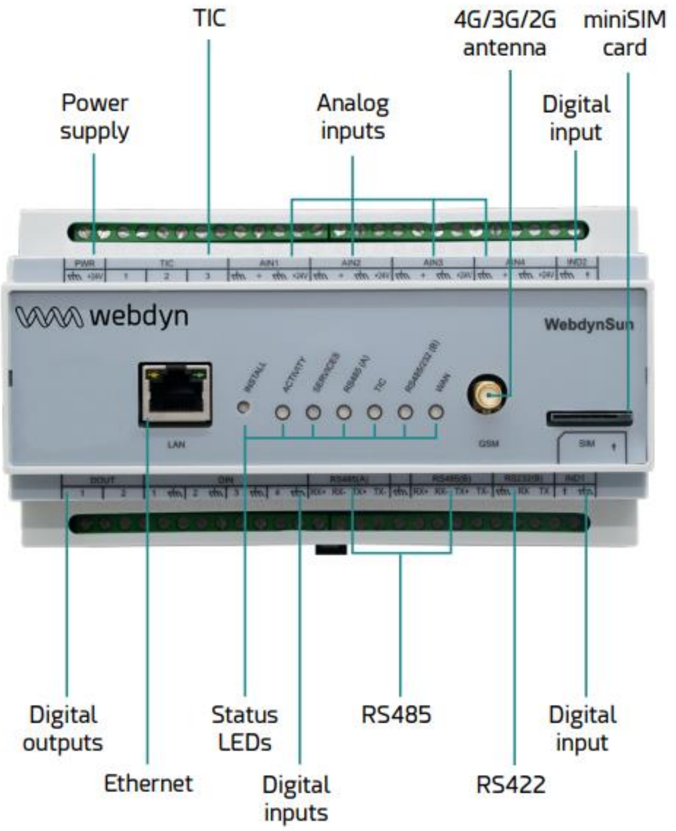


Fig. V.4. Photograph of a WebdynSun module (gateway) [48].

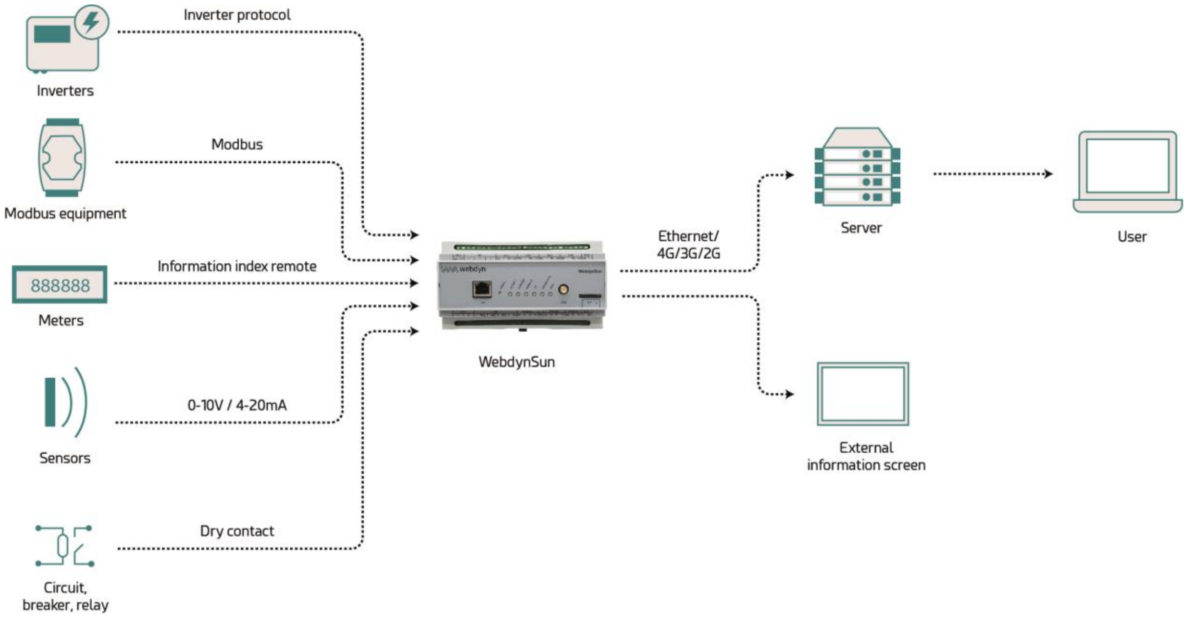


Fig. V.5. WebdynSun Principle Schematic [48].

General Conclusion

In conclusion, this course has been designed with the aim of providing a comprehensive understanding of the fundamental principles of centralized production (CP) and decentralized production (DP) in the field of electricity. We have embarked on a journey through five chapters, each aimed at deepening our knowledge of these crucial concepts.

In the first chapter, we explored general techniques for electricity production by examining various conventional power plants, their management, and efficiency. This chapter laid the groundwork for our understanding of centralized production.

The second chapter was devoted to decentralized electrical production (DP). We studied the underlying technologies, from conventional sources to new and renewable sources such as geothermal, biomass, solar, and wind. This exploration allowed us to grasp the extent of decentralized production.

The third chapter addressed the connection of DP to the electrical grid, covering connection conditions, regulatory and organizational aspects, as well as technical aspects of connection to high-voltage networks (HVA).

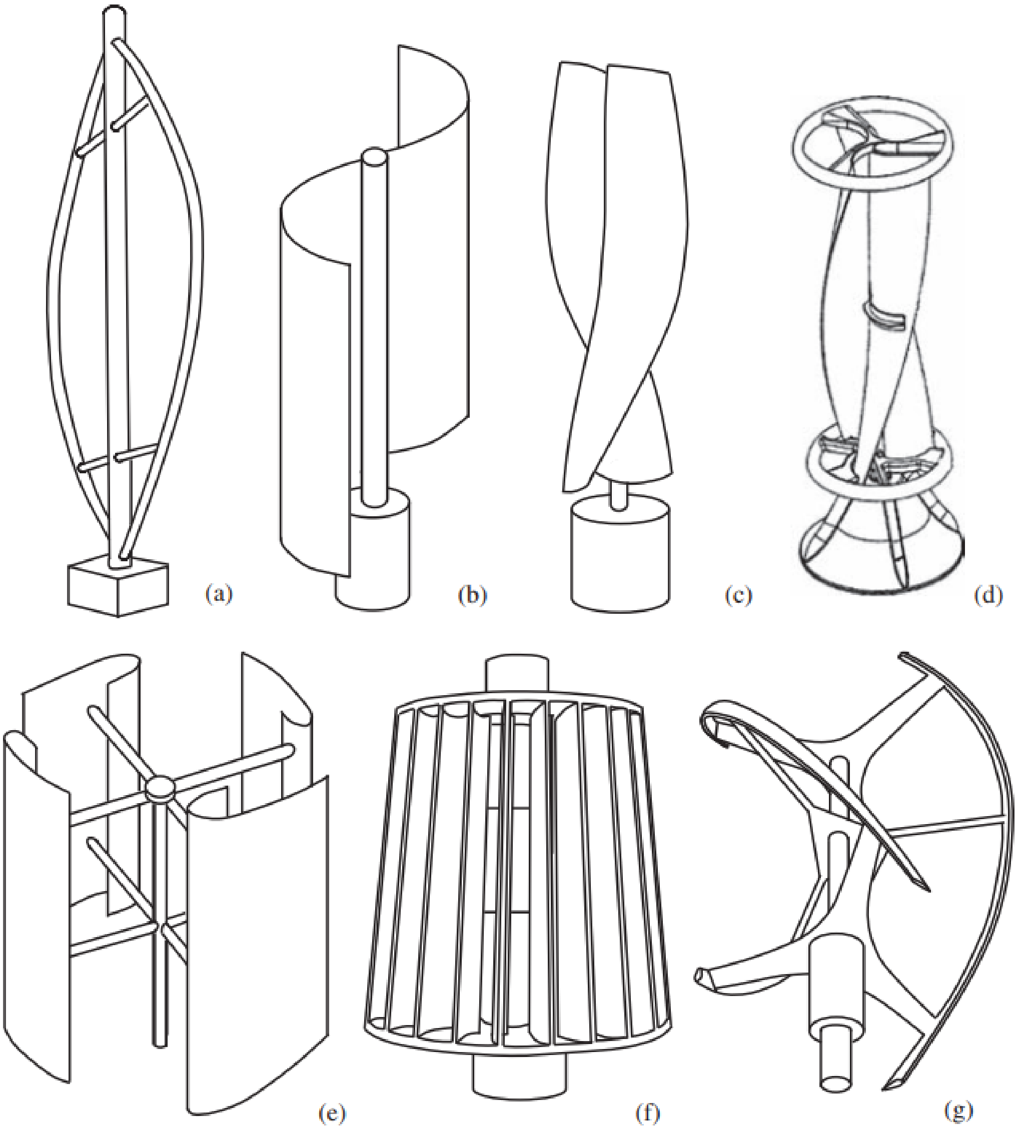
The fourth chapter focused on critical infrastructures of the electrical system, delving into management in the presence of a high penetration rate of DP, challenges and technical costs related to intermittency, methodologies for managing critical situations, as well as the importance of energy storage and islanding.

Finally, in the last chapter, we explored self-production in renewable energy through microgrids. We demystified misconceptions about them and studied their operation, exploitation, control, as well as simplified explanations of hybrid microgrids with distributed generation and storage. Emphasis was placed on monitoring and data recording.

This course has been enriched with numerous explanatory examples, images, photos, and additional information in the appendix to further clarify the acquired concepts.

Finally, I would like to express my gratitude to all the students, professors, and researchers who have participated in this course. Your remarks and constructive criticisms are welcome as they will contribute to revising and enhancing this work even further. The aim of this course is to equip you with the essential knowledge to understand and contribute to the constantly evolving field of electricity production, whether it be centralized or decentralized.

APPENDIX A : Various types of vertical axis wind turbines.



(a) Darrieus;

(b) Savonius;

(c) Solarwind;

(d) Helical;

(e) Noguchi;

(f) Maglev;

(g) Cochrane.

APPENDIX B : Carbon Credits

In many countries, environmental protection is encouraged by incentivizing businesses and organizations to reduce their greenhouse gas emissions, particularly carbon dioxide (CO_2), which contribute to climate change. This encouragement is done by allocating "carbon credits" to entities that implement renewable energy (RE) and cogeneration technologies.

Carbon credits, also known as emission credits or emission certificates, represent a unit of measurement used to quantify the reduction of CO_2 emissions. When a company adopts RE technologies, such as solar or wind energy, or employs cogeneration, producing electricity and heat simultaneously from a single energy source, it can reduce its CO_2 emissions. In reward, it may receive carbon credits, which can be traded on carbon markets or used to comply with environmental regulations.

The use of RE technologies and cogeneration is encouraged because it contributes to the reduction of greenhouse gas emissions, which is beneficial for the environment. Simultaneously, it enables businesses to benefit from carbon credits as a reward for their actions towards environmental sustainability.

Bibliographic References

[1] Sekhane Hocine, « Amélioration de l'Ecoulement des Puissances à Travers les Systèmes FACTS Pour les Réseaux Electriques », doctoral thesis in electrical engineering, Mentouri Brothers University of Constantine 1, 2019, Serial Number: 142/DS/2019, Order Number: 01/Elech/2019

[2] Benoît Robyns, Arnaud Davigny, Bruno François, Antoine Henneton, Jonathan Sprooten, « Electricity Production from Renewable Energies », ISTE and John Wiley & Sons, 2012, ISBN : 978-1-84821-390-6

[3] Anne Maczulak, « Renewable energy: Sources and methods », Green technology, 2010, ISBN 978-0-8160-7203-3 (hardcover), ISBN 978-1-4381-2748-4 (e-book).

[4] Nouredine Hadjsaïd, Jean-Claude Sabonnadière, « Power Systems and Restructuring », John Wiley & Sons, 2009. ISBN 978-1-84821-120-9

[5] Théodore Wildi, Gilbert Sybille, « Electrotechnique », 3rd edition, Quebec, presse de l'université Laval/De Boeck. ISBN 2-8041-3171-8.

[6] A.K. Raja, Amit P. Srivastava, Manish Dwivedi, « Power plant engineering », New Age International Publishers, 2006, ISBN (10) : 81-224-2333-7, ISBN (13):978-81-224-2333-4

[7] M.V. Deshpande, « Elements of Electrical Power Station Design », 1st edition, 2010, PHI Learning. ISBN-10 : 812033647X , ISBN-13 : 978-81-203-3647-6

[8] Gilberto Francisco Martha de Souza, « Thermal Power Plant Performance Analysis », Springer Series in Reliability Engineering, 2012, ISSN 1614-7839, ISBN 978-1-4471-2308-8, e-ISSN 2191-5377, e-ISBN 978-1-4471-2309-5, DOI 10.1007/978-1-4471-2309-5

[9] Dipak K. Sarkar, « Thermal Power Plant-Design and Operation ». Elsevier, 2015, ISBN : 978-0-12-801575-9.

[10] Office of Energy Efficiency, Natural Resources Canada, « Systèmes d'information sur la gestion de l'énergie-Guide et outil de planification », Efficacité Nouveau-Brunswick, 2010, ISBN 978-1-100-95225-3

[11] Naama Bakhta, « La Production Décentralisée », Course Material, Department of Electrical Engineering, University of Science and Technology of Oran (USTO)-Mohamed Boudiaf.

[12] Nouredine Hadjsaïd, Jean-Claude Sabonnadière, « Electrical Distribution Networks », ISTE and John Wiley & Sons, 2011, ISBN 978-1-84821-245-9

[13] Sreedhar R. Guda, C. Wang, and M. H. Nehrir, « A Simulink-Based Microturbine Model for Distributed Generation Studies », Proceedings of the 37th Annual North American Power Symposium, 2005, Ames, IA, USA, DOI: 10.1109/NAPS.2005.1560537

[14] Nourai A., Martin B.P., Fitchett D.R., "Testing the limits", IEEE Power & Energy Magazine, Volume: 3, Issue: 2, 2005, pp. 40-46, DOI: 10.1109/MPAE.2005.1405869

[15] P.F. Ribeiro; B.K. Johnson; M.L. Crow; A. Arsoy; Y. Liu, « Energy storage systems for advanced power applications », Proceedings of the IEEE, Volume: 89, Issue: 12, 2001, pp. 1744 - 1756, DOI: 10.1109/5.975900

[16] G.L. Bullard; H.B. Sierra-Alcazar; H.L. Lee; J.L. Morris, «Operating principles of the ultracapacitor », IEEE Transactions on Magnetics, Volume: 25, Issue: 1, pp. 102-106, 1989, DOI: 10.1109/20.22515

[17] M. Corley, J. Locker, S. Dutton, R. Spee, « Ultracapacitor-based ride-through system for adjustable speed drives », 30th Annual IEEE Power Electronics Specialists Conference. Record. (Cat. No.99CH36321), pp. 26–31, Charleston, SC, USA, 1999, Print ISBN : 0-7803-5421-4, Print ISSN : 0275-9306, DOI: 10.1109/PESC.1999.788976

[18] P. Pillay; R.M. Samudio; M. Ahmed; R.T. Patel, « A chopper-controlled SRM drive for reduced acoustic noise and improved ride-through capability using supercapacitors », IEEE Transactions on Industry Applications, Volume: 31, Issue: 5, pp. 1029-1038, 1995, DOI: 10.1109/28.464516

[19] I. Papic, P. Zunko, A. Krajnc, D. Povh, M. Weinhold, R. Zurowski, « 300 kW battery energy storage system using an IGBT converter », 1999 IEEE Power Engineering Society Summer Meeting. Conference Proceedings (Cat. No.99CH36364), Edmonton, AB, Canada, 1999, DOI: 10.1109/PESS.1999.787491

[20] N.G. Hingorani, « Introducing custom power », IEEE Spectrum, Volume : 32, Issue : 6, pp. 41–48, 1995, DOI: 10.1109/6.387140

[21] Hassan Bevrani, Bruno Francois, Toshifumi Ise, « Microgrid Dynamics and Control », John Wiley & Sons, 2017, ISBN 9781119263692 (pdf), ISBN 9781119359357 (epub), ISBN 9781119263678 (cloth)

[22] F. Blaabjerg; Zhe Chen; S.B. Kjaer, « Power electronics as efficient interface in dispersed power generation systems », IEEE Transactions on Power Electronics, Volume: 19, Issue: 5, pp. 1184–1194, 2004, DOI: 10.1109/TPEL.2004.833453

[23] V. Siva Reddy, S.C. Kaushik, K.R. Ranjan, S.K. Tyagi, « State-of-the-art of solar thermal power plants-A review », Renewable and Sustainable Energy Reviews, 27 (2013) pp. 258–273, http://dx.doi.org/10.1016/j.rser.2013.06.037

[24] Volker Quaschning, Manuel Blanco Muriel, « Solar Power–Photovoltaics or Solar Thermal Power Plants ? », VGB Congress Power Plants 2001 · Brussels · October 10 to 12, 2001

[25] Radu D. Rugescu, « Solar Energy », Intech, 2010, ISBN 978-953-307-052-0

[26] Wei Tong, « Wind Power Generation and Wind Turbine Design », WIT Press, 2010, ISBN: 978-1-84564-205-1

[27] D. Yogi goswami, Frank kreith, « Energy efficiency and renewable energy Handbook », Second edition, 2016 Taylor & Francis Group, LLC, ISBN : 978-1-4665-8508-9, eISBN 13: 978-1-4665-8509-6

[28] Brown, R.C., « Biorenewable Resources : Engineering New Products from Agriculture », Iowa State Press, A Blackwell Publishing Company, Ames, IA, 2003, pp. 59–75.

[29] Olivier Richardot, « Réglage Coordonné de Tension dans les Réseaux de Distribution à l'aide de la Production Décentralisée », Doctoral Thesis, National Polytechnic Institute of Grenoble - INPG, 2006.

[30] Herman Bayem, « Apport des méthodes probabilistes aux études d'intégration des énergies renouvelables aux systèmes électriques », Electrical Energy. Paris-South University - Paris XI, 2009. Français. NNT : . tel-00447151

[31] Benoit Rozel, « La sécurisation des infrastructures critiques : recherche d'une méthodologie d'identification des vulnérabilités et modélisation des interdépendances », Doctoral Thesis, Polytechnic Institute of Grenoble, 2009.

[32] Thi Thu Hà PHAM, « Influences De La Production Décentralisée Sur La Gestion Des Infrastructures Critiques Des Réseaux De Puissance », Doctoral Thesis, Polytechnic Institute of Grenoble, 2006.

[33] Philippe Menanteau, Dominique Finon, Marie-Laure Lamy. « L'intégration de la production intermittente dans les marchés électriques libéralisés : des surcoûts techniques aux pénalités économiques imposées par les règles de fonctionnement des marchés ». 2004. <halshs-00001311>

[34] Ilex Energy Consulting, « Quantifying the system costs of additional renewables in 2020 », A report to the Department of Trade and Industry, In association with Professor Goran Strbac, Manchester Center for Electrical Energy, UMIST, oct. 2002.

[35] Grubb, M., « The integration of renewable electricity sources in power systems », Energy Policy, pp. 670-688, Energy Policy, 19(7), Sep. 1991. https://doi.org/10.1016/0301-4215(91)90100-3

[36] Benoît Robyns, Bruno François, Gauthier Delille, Christophe Saudemont, « Energy Storage in Electric Power Grids », ISTE and John Wiley & Sons, 2015, ISBN 978-1-84821-611-2

[37] Delille G, François B, Malarange G, « Construction d'une offre de services du stockage pour les réseaux de distribution dans un contexte réglementaire dérégulé », European Journal of Electrical Engineering, vol. 12, no. 5–6, pp. 733–762, Septembre 2009.

[38] Li Fusheng, Li Ruisheng, Zhou Fengquan, « Microgrid Technology and Engineering Application », China Electric Power Press. Published by Elsevier, 2016, ISBN : 978-0-12-803598-6

[39] Nikos Hatziargyriou, «Microgrids: Architectures and Control », John Wiley and Sons, 2014, ISBN: 978-1-118-72068-4

[40] Jayachandran. M, Ravi. G, « Design and Optimization of Hybrid Micro-Grid System », 1st International Conference on Power Engineering, Computing and CONtrol, PECCON-2017, 2- 4 March 2017, VIT University, Chennai Campus, Energy Procedia 117 (2017) 95–103, https://doi.org/10.1016/j.egypro.2017.05.111

[41] Mohammed Kharrich, Salah Kamel, Rachid Ellaia, Mohammed Akherraz, Ali S. Alghamdi, Mamdouh Abdel-Akher, Ahmad Eid and Mohamed I. Mosaad, « Economic and Ecological Design of Hybrid Renewable Energy Systems Based on a Developed IWO/BSA Algorithm », Electronics 2021, 10, 687. https://doi.org/10.3390/electronics10060687

[42] Jin Wang ; Yinke Dou ; Guangyu Zuo ; Musheng Lan ; Xiaomin Chang; Bo Yang; Zhiheng Du ; Miaoyuan Yu ; Qingyang Mao, « Application and effect analysis of renewable energy in a small standalone automatic observation system deployed in the polar regions », AIP Advances 12, 125218 (2022); doi: 10.1063/5.0128256

[43] Can Berk Saner, Spyros Skarvelis-Kazakos, « Fuel savings in remote Antarctic microgrids through energy management », 2018 53rd International Universities Power Engineering Conference, 04-07 September 2018, Glasgow, UK, DOI: 10.1109/UPEC.2018.8541935

[44] International Polar Foundation. (n.d.). *Princess Elisabeth Antarctica Research Station*, from https://www.polarfoundation.org/projects/detail/princess_elisabeth_antarctica

[45] Albarakati AJ, Boujoudar Y, Azeroual M, Eliysaouy L, Kotb H, Aljarbouh A, Khalid Alkahtani H, Mostafa SM, Tassaddiq A and Pupkov A (2022), « Microgrid energy management and monitoring systems : A comprehensive review », Frontiers in Energy Research, 10:1097858. doi: 10.3389/fenrg.2022.1097858

[46] Daniel Cadilla, Mireia Gil, Cristian Ros, Cristina Gil, Nicola Bugati, « Micro-réseaux photovoltaïques hybrides : Guide de conception et calcul », Centre Régional pour les Energies Renouvelables et l'Efficacité Energétique (ECREEE), July 2017.

[47] EESmart. (n.d.). Module tableau électrique. EESmart. https://eesmart.fr/modules/module-tableau-electrique/

[48] WebdynSun-datasheet, official website of the specialized company Webdyn Flexitron Group : https://www.webdyn.com