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Ministry of Higher Education and Scientific Research
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Course Brochure:

AUTONOMOUS ENERGY SYSTEMS

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PREFACE

In our contemporary world, electricity has become an indispensable element of our daily existence. It not only powers our technological advancements but also fuels the industrial developments that cater to our evolving needs. As we navigate this reality, there is an increasing necessity to explore alternative technologies that ensure a reliable supply of electricity, especially in areas isolated from the conventional power grid. The generation of electricity encompasses a multitude of methods, each shaped by the diverse array of available energy resources. These methods give rise to various types of power plants, with thermal and hydraulic power plants holding prominence among them. Energy resources can be categorized into two primary groups: non-renewable and renewable. Non-renewable energy sources, which encompass fossil fuels and nuclear power, are characterized by finite reserves that continue to deplete over time. In contrast, renewable energy sources, including hydroelectric, biomass, geothermal, wind, and photovoltaic power, harness the abundance of natural resources, rendering them sustainable and virtually inexhaustible. As we grapple with the diminishing reserves of fossil energy resources and the environmental repercussions of harmful emissions, there is an urgent imperative to diversify our energy sources and place a growing emphasis on renewable alternatives. The emission of greenhouse gases is a significant contributor to global warming, underscoring the urgency of cleaner, more sustainable solutions. Renewable energies, which draw upon the power of natural resources like sunlight, water, wind, and geothermal heat, offer a path forward that is environmentally conscious, in stark contrast to the finite nature of fossil and nuclear energies. Within the pages of this course brochure, the diverse methods of electrical energy production are presented, including wind energy, hybrid energy, and photovoltaic energy. This course material has been thoughtfully compiled to provide a clear and accessible resource aimed at facilitating student comprehension, grounded in carefully gathered information.

ABREVIATIONS LIST

AC	Alternating current
BWR	Boiling water reactor
EG	Electric generators
EMC	Electromagnetic compatibility
EMEC	European marine energy center
CdTe	Cadmium telluride
CIGS	Copper indium gallium selenide
CIS	Copper indium selenide
DC	Direct current
GaAs	Gallium arsenide
GHG	Greenhouse gas
LPG	Liquefied petroleum gas
MPP	Maximum power point
NGV	Natural gas for vehicle
PTO	Power Take-Off
PV	Photovoltaic
PVG	Photovoltaic generator
SCADA	Supervisory control and data acquisition

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CHAPTER 1 :

ELECTRICAL ENERGY PRODUCTION METHODS

I.1. Introduction

The initial phase for obvious advancements in the understanding and elaboration of electricity began with the laws of interactions developed in 1785 by Charles-Augustin Coulomb (1736 – 1806). The creation of the electric battery in 1800 by Alessandro Volta (1745 – 1827) was another important phase in the history of science. It was then possible to generate DC currents more powerfully than before with electrostatic machines, which encouraged 19th century researchers to accelerate electrical energy research and inventions. Another interesting phase was reached, in 1820, through the experiment of Danish physicist Hans Christian Ørsted (1777 – 1851), which made it possible to understand electromagnetism. This experiment was immediately redone by André-Marie Ampère (1775 – 1836) which allowed him to explain and formulate the fact. He continued his experiments by assembling magnetic and electric effects, which led to important advances in electrodynamics. However, he missed the electromagnetic induction effect, which was seen in 1821 by the English physicist Michael Faraday (1791 – 1867). In 1821, Thomas Johann Seebeck (1770-1831) noted the thermoelectric effects employed to intercept heat to produce electrical energy. The German physicist Georg Simon Ohm (1787 – 1854) found in 1826 the law connecting the difference of potential and the electric current which crosses a resistance. The mesh for the calculation of electrical circuits had been laid down by the German physicist Gustav Robert Kirchhoff (1824–1887). The designer of modern electromagnetism James Clerk Maxwell (1831 – 1879), born in Scotland, was able to unify the laws of electricity and magnetism into a single set of equations by including the notion of the displacement current. The invention of the rechargeable lead-acid battery is credited to Gaston Planté (1834-1889) in the year 1860. This battery is still used today [1-3]. Nowadays, electricity has become unavailable in our daily life, and for technological and industrial developments to meet our needs. Following this historical overview, the subsequent sections will delve into the methods of generating electrical energy, concepts of energy transformation, various modes of electric power generation, and an exploration of both non-renewable and renewable energy sources.

I.2. From dynamos to alternators for electrical power plants

A dynamo, or electro-dynamo generator, is employed to transform rotating mechanical energy into electricity, maintaining pseudo-constant currents and voltages. This is notably the case with bicycle dynamos. This concept is used in the majority of power plants, where the device is called an alternator which is used to generate alternating currents. The alternator is mainly composed of a [4-5]:

1. Rotor, is a moving mechanism consisting of a magnet;
2. Stator, is a non-moving mechanism consisting of a copper coil.

The alternator is used to transform rotating mechanical energy into electricity with variable currents and voltages.

I.3. Notions on energy transformations

Energy is defined as the capacity to bring about changes, generate motion, alter the temperature of an object, or transform substances, among other effects. Energy is generated from various sources available in nature and can manifest itself in several aspects (movement, chemical reaction, radiation, heat release, fission of an atom, etc.). It can also be transferred from one device to another and transformed by modifying its nature. For instance, petroleum fuel, a form of chemical energy, can be transformed into thermal energy in the form of heat [6-7].

I.4. Electric power generation modes

There are different ways to produce electricity depending on the types of resources. Accordingly, there are different plants. Among these, two significant types of power plants stand out: thermal power plants and hydraulic power plants.

I.4.1 Thermal power plant

Thermal energy can be transformed into mechanical energy, which can subsequently be transformed into electricity for various applications. The energy cycle begins by converting the heat released by burning fuel. Therefore, steam pressure actuates electric generators (EG) that generate electrical energy [8].

- **Steam power plant:** these plants burn fuel either coal, oil, or gas to heat and volatilize water in the boiler. The turbine converts the kinetic energy of a pressurized steam flow into mechanical energy, prompting the alternator to produce electrical energy. The steam is converted again into water which is returned to the boiler and a new phase of energy transformation is reproduced [8-10]. This process of energy transformation is represented in Figure (I.1).

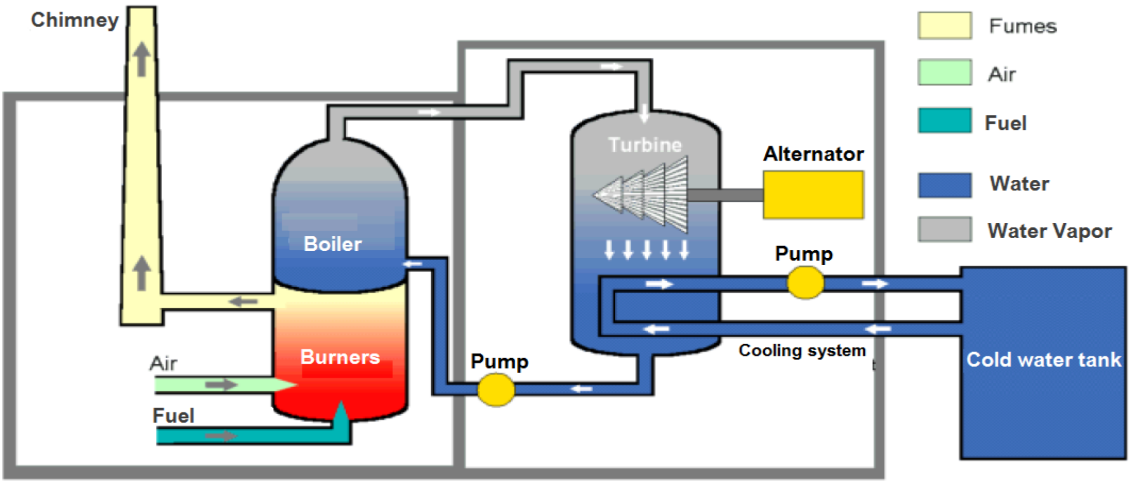

Figure (I.1) : Working principle of steam power plant [10].

- **Hybrid power plant:** it combines two types of turbines: combustion (fueled by gas) and thermal steam, as shown in Figure (I.2). It is based on tow cycles: the gas cycle and steam cycle. In the gas cycle, the gas turbine, which accounts for nearly 67% of the electrical energy generated by the plant, converts the kinetic energy released during the combustion of gas into mechanical energy. This mechanical energy is further transformed into electricity by an alternator. The purified air is enclosed and directed to the combustion chamber. The gases released from the combustion cell energize this turbine, where the gases pass through it and give up a rotating torque to its support which is attached to the support of the alternator which subsequently produces electrical power. Gases exit through the chimney if recovery is not complete. In the steam cycle, the exhaust gas generates superheated steam which makes the steam turbine generator work. The steam then proceeds through a steam turbine, responsible for producing approximately 33% of the electrical energy generated by the plant. In the turbine, the kinetic energy of the steam is transformed into mechanical energy, which is used to generate additional electrical power through the alternator. After the turbine, the steam passes through a tube condenser through which cooling water is run to convert it back into water. The assembly of these thermodynamic phases, a good yield is achieved [8-9,11].

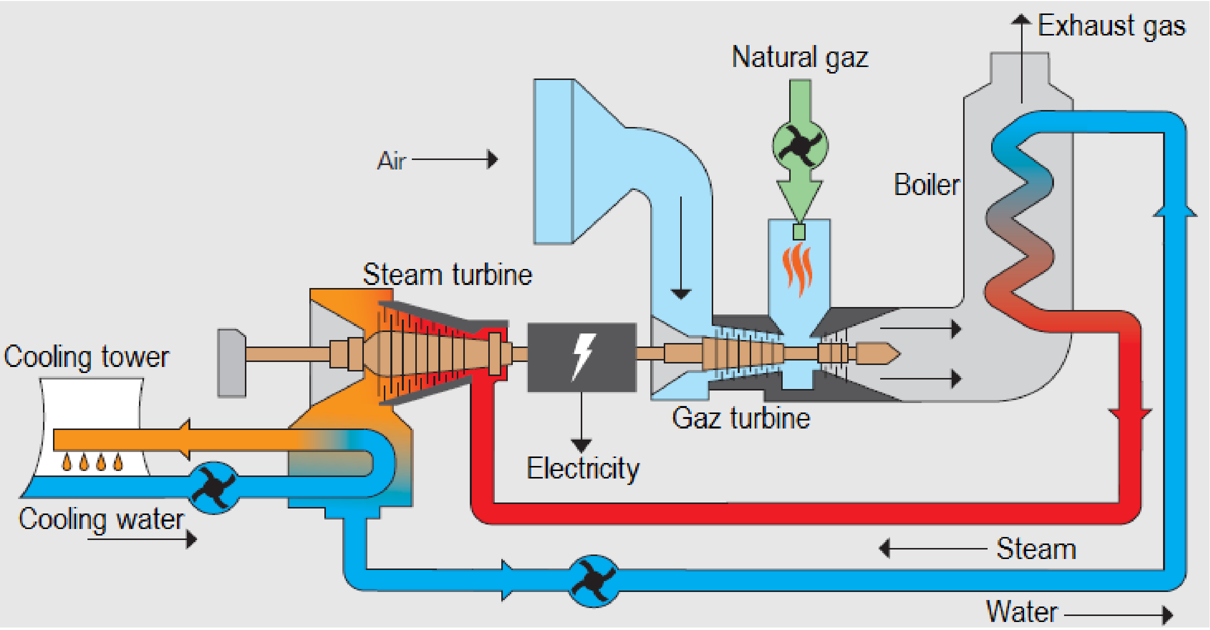

Figure (I.2) : Principle of hybrid power plant [11].

I.4.2 Hydropower plants

The choice of hydropower is directly related to its advantages such as availability, accessibility, low maintenance costs, reliability, and dual exploitation. In practice, the water used to generate electricity is reused for other uses such as irrigation and as purified drinking water. This type of plant is used especially during periods of high energy demand, so as not to operate other expensive types of electricity production plants granted to the same electrical distribution grid [8]. As shown in Figure (I.3), a hydropower plant is mainly composed of a storage basin, a water transport pipe, and a hydraulic turbine connected to a generator. The energy cycle begins with water evaporating from the sun that returns to a higher place compared to where it evaporated, so there is energy power. Under the action of the gravity, this energy is then converted into the kinetic energy of the water flow [12]. The waterfall excites the hydraulic turbine that allows electricity to be generated by the EG. The role of the transformer is to adjust the voltage as needed [8, 13-15].

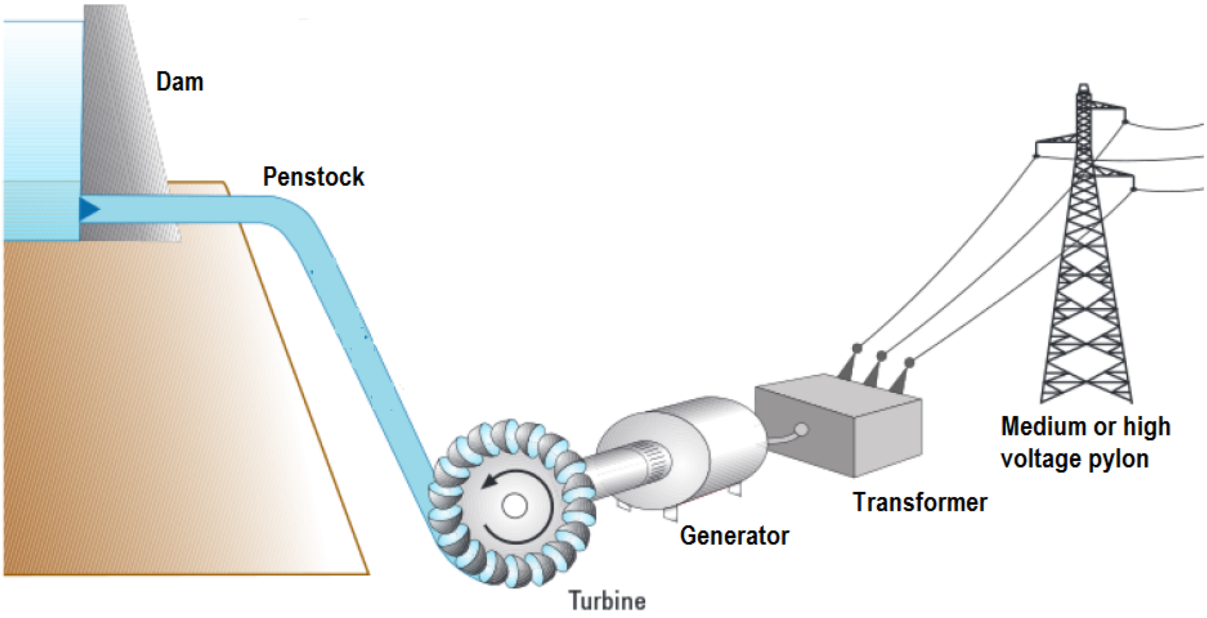

Figure (I.3): Working principle of hydropower plant [15].

Two principal hydropower plants can be distinguished [13-15]:

1. Gravity plant: In this system, the release of water from reservoirs primarily occurs through the force of gravity, driven by the Earth's gravitational attraction.
2. Pumping plant and turbines: This system operates on the principle of moving water between two reservoirs, one located above and the other below the turbine, as shown in Figure (I.4). The operation of this plant necessitates the use of electrical power to pump water, which is subsequently harnessed by turbines. Water can be pumped and utilized by the turbines to meet varying needs, such as responding to surge periods and power demand fluctuations.

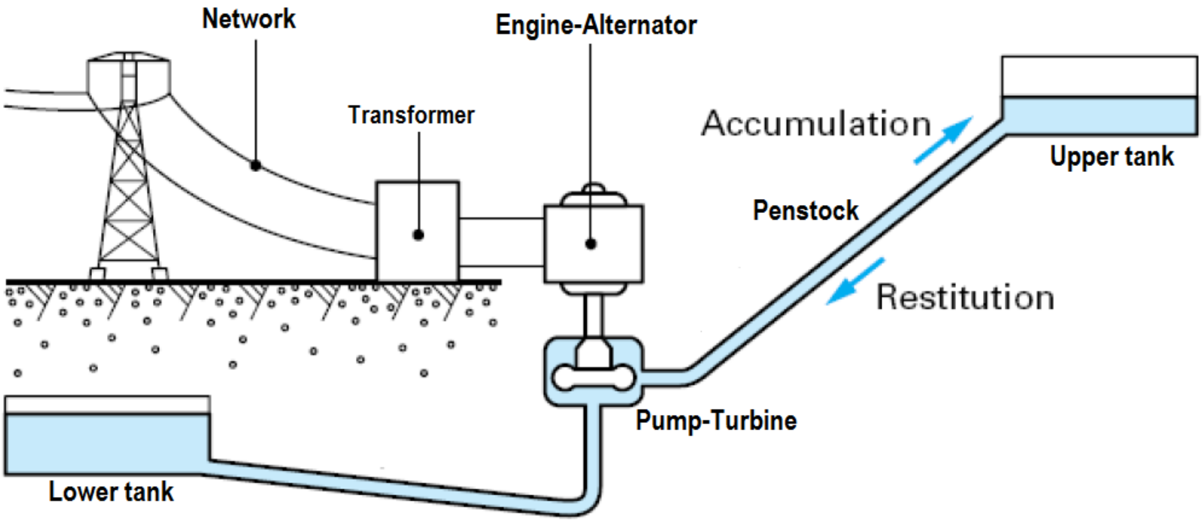

Figure (I.4): Principle of a pumping plant and turbines [14].

Despite the excessive investment in development and construction, which is spread over the years, the hydropower plant provides an important and enormous resource of energy. Its production has the privilege of being cheaper and durable, and its maintenance is at reasonable costs and its service life is very considerable. Compared to other resources, only hydropower plants provide a significant amount of energy [8, 13, 15].

I.5. Different sources of energy

Two main categories of energy resources can be distinguished [16]:

1. Non-renewable energies, whose reserves are exhaustible (fossil and nuclear),
2. Renewable energies, whose reserves are inexhaustible (hydroelectric, biomass, wind, and photovoltaic).

I.5.1. Non-renewable energies

I.5.1.1. Fossil energies

Fossil energies are exhaustible energies that cannot be renewed in a short period and come from oil, coal and gas. These energies have a dramatic influence on the surroundings and generate carbon dioxide and the greenhouse gas (GHG) that stick to the atmosphere [17].

Sedimentary rocks that contain more than half of the carbon are called coal. It is generated by the dissociation of plant remains under the influence of its environment and climatic changes, over millions of years. The formation of organic stratification over many years causes a reduction in volatile organic matter and carbon condensation. Petroleum is produced through the dissociation of marine elements, beings, animals, or plants over millions of years. This fuel is composed of hydrocarbons, organic sulfur elements, oxygen and nitrogen. It is found in sedimentary reservoirs and in porous rock voids [18-19].

Among hydrocarbons, natural gas is the lightest and results in lower carbon dioxide emissions during the production of electrical energy. Two main types of gas are recognized: liquefied petroleum gas (LPG), which comprises butane and propane, and natural gas for vehicles (NGV), primarily composed of methane [19-20]. In Figure (I.5), the depiction showcases the utilization of fossil fuels to drive a steam turbine, which, in turn, generates electricity.

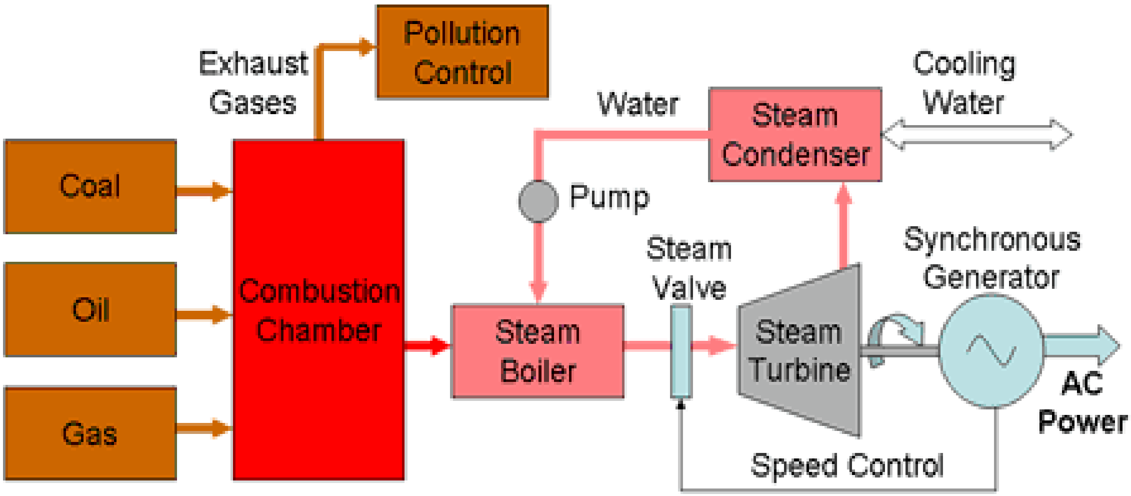

Figure (I.5): Electricity generation using fossil fuel-powered steam turbines [21].

I.5.1.2. Nuclear energy

The objectives of nuclear energy production are to generate significant power with a strong emphasis on safety and minimizing radioactive waste on a large scale. This form of energy is harnessed through two distinct reaction processes [19]:

1. Fusion: It is naturally occur in space and are the driving force behind stars. On Earth, scientists are actively researching and experimenting with controlled fusion reactions for potential energy generation.
2. Fission: It takes place primarily within nuclear reactors. These reactions involve the splitting of atomic nuclei, resulting in the release of energy.

A boiling water reactor (BWR), as depicted in Figure (I.6), is a type of nuclear reactor used for electricity production. In a BWR, uranium fuel is utilized to generate heat through a nuclear fission process. The generated heat causes the water surrounding the fuel rods to boil, converting it into steam. This steam is subsequently utilized to drive turbines that are connected to generators. The spinning turbines generate electricity. In essence, BWRs use the heat from nuclear reactions to produce steam and, in turn, generate electrical power [22].

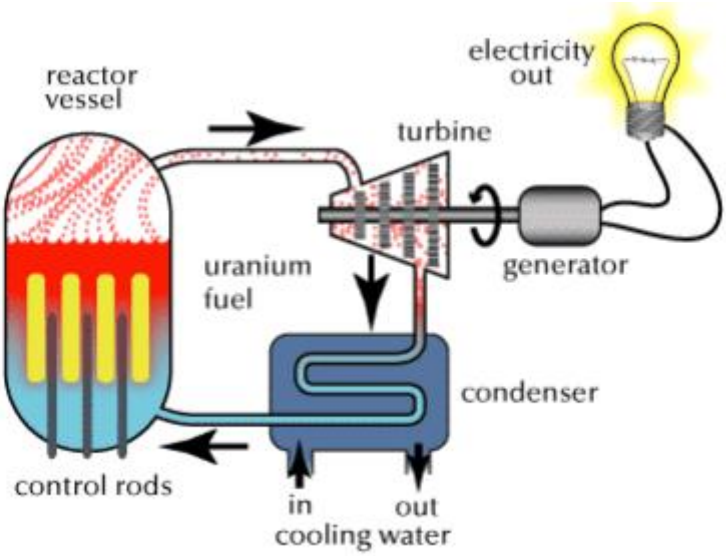

Figure (I.6): BWR for electricity production [22].

I.5.2. Renewable energies

Renewable energies are regularly renewed, reasonably available and accessible, where the sources are natural and conceivable without causing risks to the surrounding environment. These energies can be converted into electrical or thermal energy. These resources can guarantee everything that is included in the usual sources. Renewable energies are currently on the rise and wind turbines and photovoltaic (PV) solar panels are the main sources of this progression. Among the main disadvantages of these types of energy are: less significant efficiencies and huge investments, great dependence on the weather, large space requirements, etc. [23-24]. Renewable energies can be classified into three categories: mechanical energy of kinetic origin, electrical energy or thermal energy. Since it is very difficult to deliver mechanical energy over long distances, it is only usable locally which is usually converted into electricity [25]. Solar energy, wind energy, hydraulic energy, biomass, and geothermal energy are sources of renewable energies. Figure (I.7) illustrates the various types of renewable energy resources.

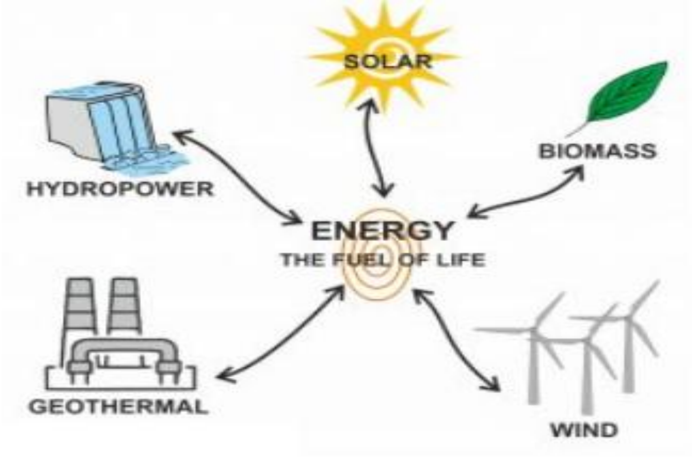

Figure (I.7) : Renewable energy resources [26].

I.5.2.1. Solar energy

Solar energy, which is collected on earth, each year represents about 15,000 times the energy exploited by humanity. As shown in Figure (I.8), there are two common types of solar energy systems [27]:

1. Solar thermal systems: use thermal collectors for the conversion of solar energy into thermal energy;
2. PV solar systems: use PV panels for the direct conversion of light into electrical energy.

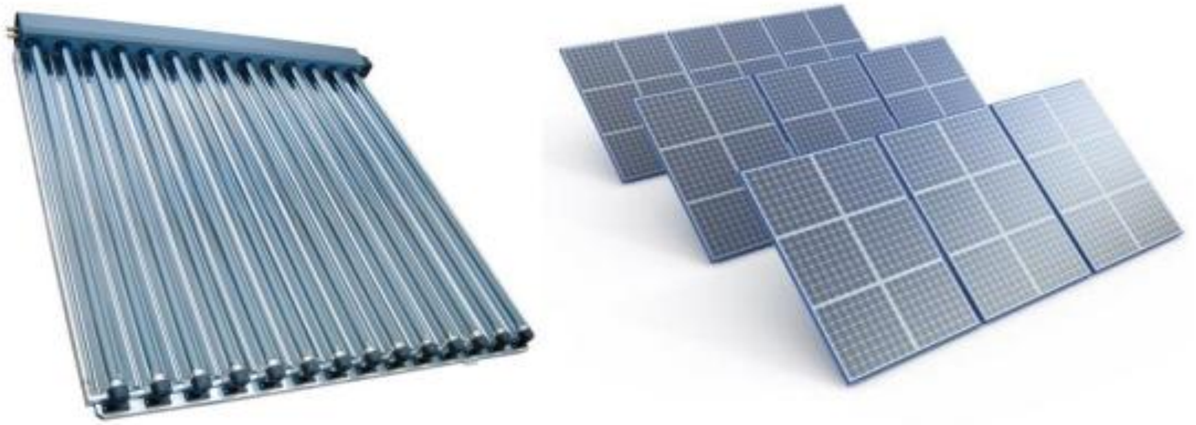

Figure (I.8) : Solar thermal collectors (left) and solar PV panels (right) [28].

Solar thermal collectors have an efficiently coated dark surface that readily absorbs sunlight, causing the material to heat up. Broadly, there are two primary categories of collectors employed. The first is the non-concentrating or flat plate type, utilized for low-temperature applications, while the second category encompasses concentrating or focusing type collectors, such as parabolic trough collectors, which find application in medium to high-temperature scenarios. The absorbed solar energy is transformed into heat energy when high-energy photons from sunlight transfer their energy to the collector's atoms or molecules. In these systems, a heat transfer fluid circulates through the collector, absorbing the generated heat and flowing through a closed-loop setup. Some systems include heat storage components for using excess heat during periods with limited sunlight. The heated fluid is directed for various applications, like providing hot water or space heating in residential settings and industrial processes or electricity generation through steam turbines. Control mechanisms such as sensors, pumps, and valves ensure efficient operation and prevent overheating. The implementation of the largest thermal solar collector is the idea of solar thermal energy. For good production, the collectors should be oriented in the direction of the sun [29]. In Figure (I.9), the process of generating electricity through the utilization of solar collectors in conjunction with steam turbines is elucidated.

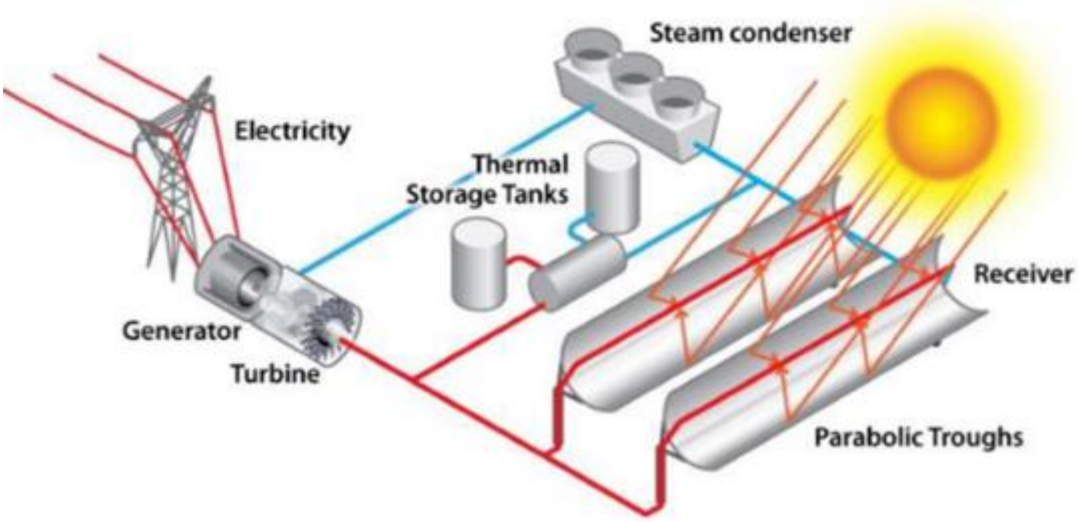

Figure (I.9) : Electricity generation using solar collectors in steam turbines [30].

Solar PV panels, on the other hand, convert sunlight directly into electricity by using semiconductor materials, such as silicon, to create electron-hole pairs when photons strike the material. Electrons freed during this process move through the semiconductor, generating an electric current, which is collected by metal contacts on the panel's surface. The electricity is then directed to power homes, tied to the existing grid, businesses, or stored in batteries for later use. the produced electricity depends on the intensity and duration of illumination and the orientation of the PV module against the direction of the sun [28,29]. Figure (I.10) provides a visual representation of the electricity generation process through the utilization of solar PV panels. Within this system, an array disconnect serves as a crucial safety device, enabling the disconnection of the solar panel array from the broader system and allowing for the deactivation of the DC power generated by the solar panels. Inverters play a pivotal role in ensuring the compatibility of electricity produced by the solar panels with both the electrical grid and household appliances. The responsibility of distributing the AC electricity to various electrical circuits within a home or facility falls to the AC breaker box, which houses circuit breakers that serve the dual purpose of control and protection for different segments of the electrical system. Simultaneously, the electric meter accurately measures the quantity of electricity generated by the solar panels and tracks its consumption [31].

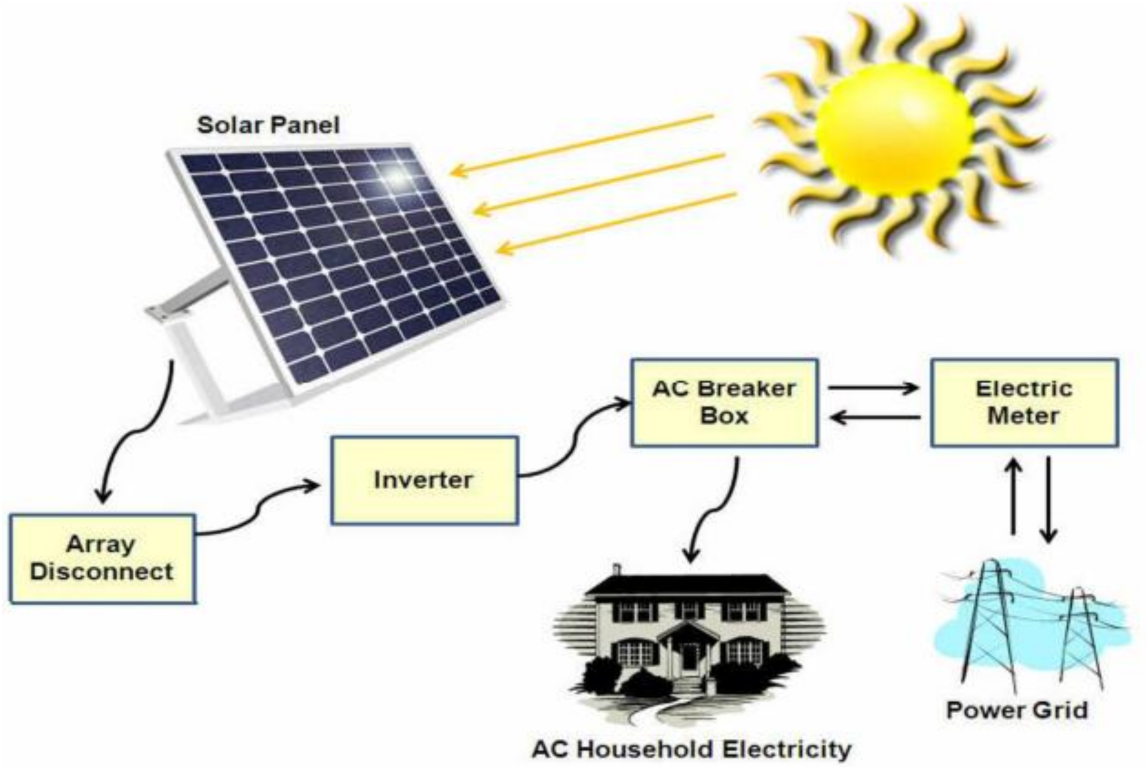

Figure (I.10) : PV solar panels for generating electricity [31].

Solar thermal systems outperform PV systems in terms of efficiency, capturing up to 70% of solar energy, while PV collectors convert only about 12% of incident sunlight into electricity. The advantage of PV energy is its ease of implementation and use, which makes it employable, especially in emerging countries that do not have an interesting electrical grid. However, its effectiveness is still very weak [32,33].

I.5.2.2. Wind energy

Wind represents the displacement of air masses resulting from differences in temperature and differences in the level of pressure resulting from the increase in the temperature of some regions of the globe and the cooling of others. As a consequence, the resulting wind initiates the rotation of the blades, effectively converting wind's kinetic energy into mechanical energy. These rotating blades are then connected to a rotor and EG, which in turn transforms the mechanical energy into electrical energy. Wind energy is considered a sustainable and environmentally friendly source of electrical power, making it a part of the traditional energy mix. However, it is random due to climate change and its interception is still a bit complicated, and it requires towers and blades of large sizes which impose quite significant costs [34-37]. Figure (I.11) depicts the production of electricity through a wind turbine.

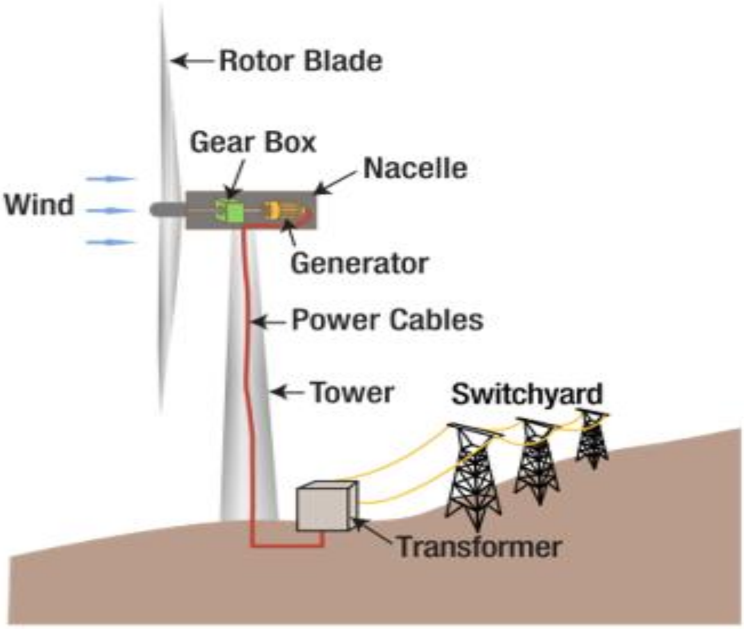

Figure (I.11) : Wind turbine [38].

I.5.2.3. Hydro-electric energy

Hydroelectricity consists of generating electrical energy by exploiting the flow of water, where the greatest power of this flow is a reflection of a high-energy resource. This type of energy is mainly generated through a water tank which helps in creating a large reserve of electricity. Hydraulic stations have an interesting energy reserve for developed countries which thus exploit a non-polluting and cumulative energy resource. The privilege of small stations, whose power does not exceed 10 kW, is that they are valuable for personal and local production. The primordial privilege of this energy is that it is regular and a continuous flow, unlike energies that depend heavily on climate. It is interesting to note that water flows are easier to predict than wind due to water reservoirs that ensure continuous flow. Without forgetting the tidal resources of marine flows which are also interesting, the utilization of these resources is currently possible [27, 32, 36]. Figure (I.12) illustrates the fundamental generation of electricity through the utilization of hydropower energy

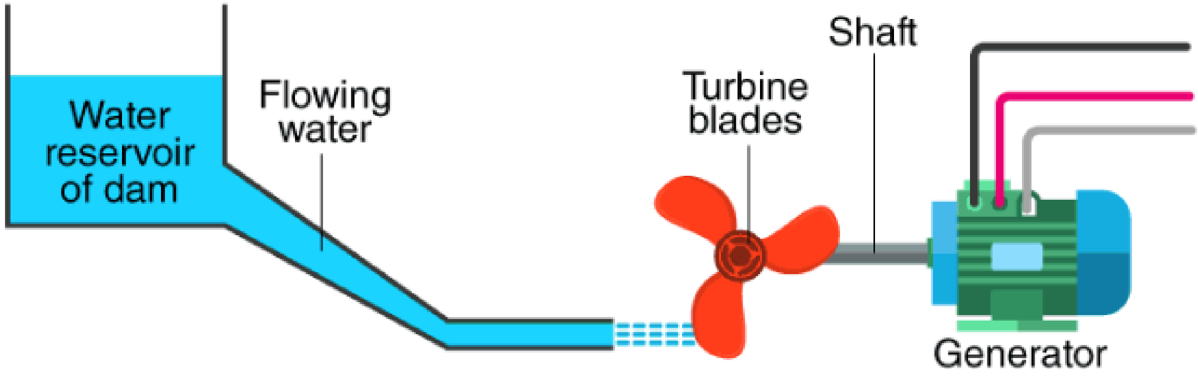

Figure (I.12) : Utilizing hydropower for electricity production [39].

I.5.2.4. Biomass energy

Biomass, a versatile resource derived from all living matter of plant or animal origin through photosynthesis, is found worldwide. It offers diversification of energy resources, reducing dependence on fossil fuels. Comprising mainly carbon, oxygen, and hydrogen, along with nitrogen and mineral elements [40], biomass occurs naturally (e.g., wood, algae) and as agricultural or even household waste. Wood energy significantly contributes to global energy usage, with more than 50% of wood traded worldwide destined for energy purposes. The other half is used in manufacturing. Biomass energy conversion involves biological and thermochemical processes, both with specific requirements. The biological or wet process converts biomass into gases or fuel additives, while the thermochemical or dry process transforms low-energy biomass into liquids or gases, generating heat and electricity [41, 42]. Biomass power plants are designed to utilize a range of organic materials such as wood chips, agricultural residues, and even animal manure. These raw materials are gathered, transported, and subjected to various processing steps, which can include shredding, chipping, and drying to optimize their combustion potential. Once the biomass is prepared, it is introduced into a specialized combustion chamber. Inside this chamber, the biomass is combusted, which results in the generation of high-pressure steam or hot oil, as depicted in Figure (I.13). The produced high-pressure steam or hot oil is then harnessed in a boiler system. This system is crucial in driving a steam turbine, which is a key component in the power generation process. The steam turbine's mechanical energy, generated by the force of the steam, is utilized to power an electrical generator. As the turbine rotates, it induces electromagnetic induction within the generator, leading to the production of electricity. This newly generated electricity is subsequently transmitted to the power grid for distribution to consumers, providing a source of renewable energy. Upon exiting the turbine, a portion of the steam is reclaimed for heating purposes, a practice commonly referred to as cogeneration [43].

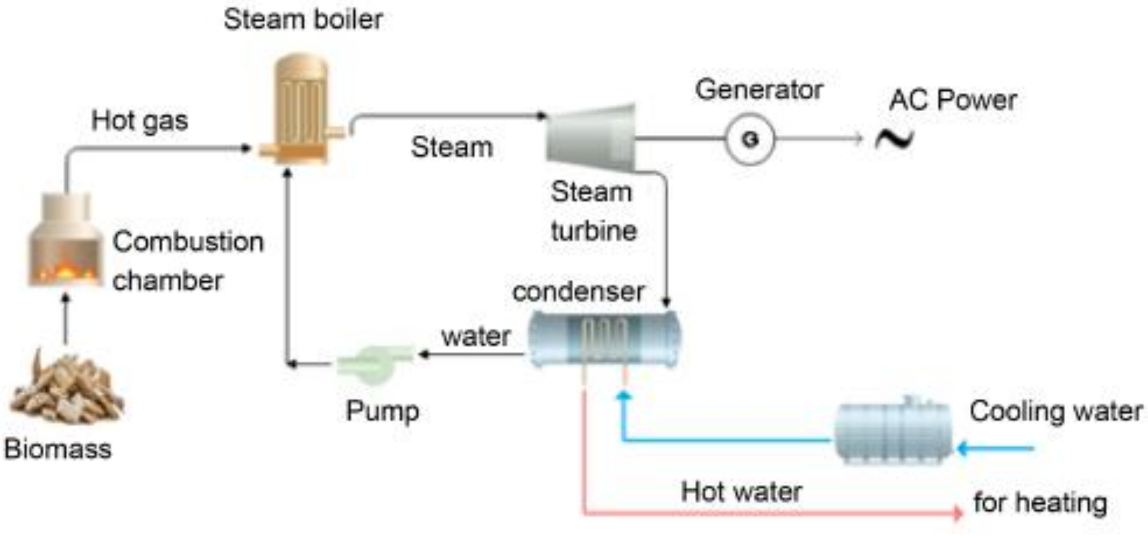

Figure (I.13) : Steam turbine biomass cogeneration plant [43].

I.5.2.5. Geothermal energy

Geothermal energy, classified as a sustainable energy source, involves harnessing subsurface thermal energy from within the Earth for the purposes of both heating and electricity generation. As you delve deeper into the Earth's crust, temperatures rise at an average rate of approximately 2.78°C per 100 meters. The effective utilization of geothermal energy relies on the permeability of geological materials. This renewable energy source is categorized into four groups based on temperature. High and medium-temperature geothermal sources are primarily utilized for electricity generation through geothermal power plants, while low-temperature sources find applications in district heating and industrial processes. The efficiency of energy extraction often benefits from heat pumps [27, 44, 45]. One key advantage of geothermal energy is its continuous availability, independent of climatic conditions, making it a cost-effective choice. However, the precision of the extraction process is of utmost importance [25, 27]. Figure (I.14) illustrates the operation of geothermal power plants, where a process involves extracting hot water or steam from deep underground using high-pressure well production. When this heated fluid reaches the surface, a drop in pressure induces its conversion into steam. The resulting steam powers a turbine linked to a generator, ultimately generating electricity. After this stage, the steam undergoes cooling in a designated tower and condenses back into water. The cooled water is then cycled back into the Earth to initiate the process once again [46].

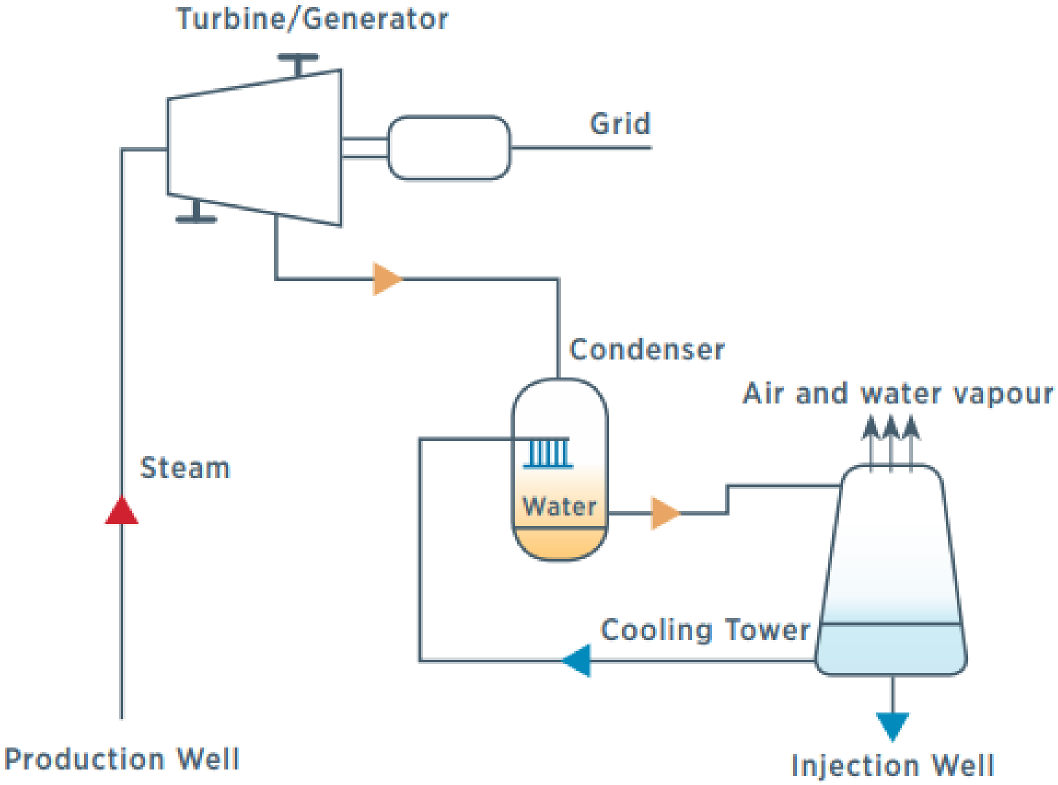

Figure (I.14) : Steam geothermal power plant [46].

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CHAPTER 2 :

WIND ENERGY

II.1 Introduction

Wind energy is the first renewable energy used, after wood energy, to produce mechanical energy, approximately 3000 years ago. Since antiquity, it has been used to move boats forward, grind grain, or pump water. It was around the year 2000 before Jesus Christ that Hammurabi, the king of Babylon, created an irrigation system for agriculture by harnessing the energy of the wind. In medieval Europe, windmills were used to grind grain and/or to wipe areas covered with water. Around the 19th century, the number of windmills in use was approximately two hundred thousand mills listed. An abundance of these types of mills was seen after the invention of steam engines. Water pumping mills were used in the Netherlands to wipe areas below sea level, and this technique was used approximately around the year 1350. The first assembly of wind turbines into a generator was introduced by Danish Meteorologist Poul La Cour in 1891 after the discovery of electricity. Then wind energy could be re-exploited in the 1940's especially in Denmark with 1300 wind turbines. About a million wind turbines were operating around the world in the 1960's. The first oil shock of 1973 gave a sudden awakening to this type of energy. At the beginning of the 20th century, wind turbines strongly marked their arrival, with about six million wind turbines built. At present, the risks and dangers caused by global warming give a new spirit to the use of this type of energy [1-3]. After a brief presentation of national wind resources and wind farms, this chapter is devoted to the presentation of wind energy, namely: its operating principle and energy conversion, standards, advantages, and disadvantages. A detailed description of the different components of a wind turbine is also introduced. Before ending this chapter, an example application of wind energy is presented.

II.2 Algerian wind energy map

Figure (II.1) represents the annual wind speed at a height of 10 meters from the ground over the entire Algerian territory. It shows that average annual wind speeds vary with geographical location and range between 1.2 and 6.3 m/s in all regions of the country. The highest peaks in annual speed are recorded in the south. In the southwest region, the wind speed is greater than 4 m/s and reaches 6.3 m/s in Adrar. The Hassi R'Mel site ranks second with an annual speed of about 6.1 m/s. Tindouf area follows with an average speed of about 6 m/s. Speed up to 5.8 m/s can be recorded in the far south, especially in In-Salah, Bordj-Badji-Mokhtar, Timimoun, and Ain-Amenas. On the borders with Tunisia and Libya, the wind speed is about 3 m/s. The Beni-Saf area has high wind power (860 W/m^2 annually), which makes it possible to generate the necessary electricity and even transmit this energy to neighboring areas. Northern Algeria is characterized by moderate winds, with an average speed of 1 to 4 m/s. Except for the ports of Oran and Algiers which have an average annual speed of about 4 m/s, Tell-Atlas and the Sahel do not contain any area with an average annual speed exceeding 4 m/s. It should also be noted that the city of Tizi Ouzou, which is located in a basin at an altitude of 187 meters from the sea, and the city center of Maghnia, which is surrounded by a large concentration of high-rise buildings, are characterized by wind speeds, with an annual average speed not exceeding 1.2 m/s [4–6].

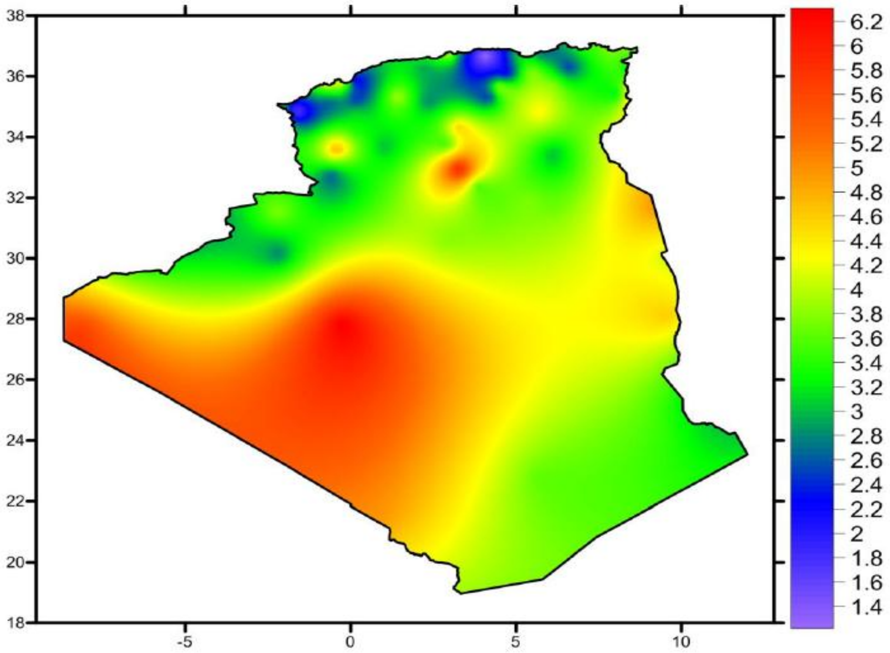

Figure (II.1) : Annual wind speed at 10m from the ground [7].

Seasonal wind speeds are shown in Figure (II.2).

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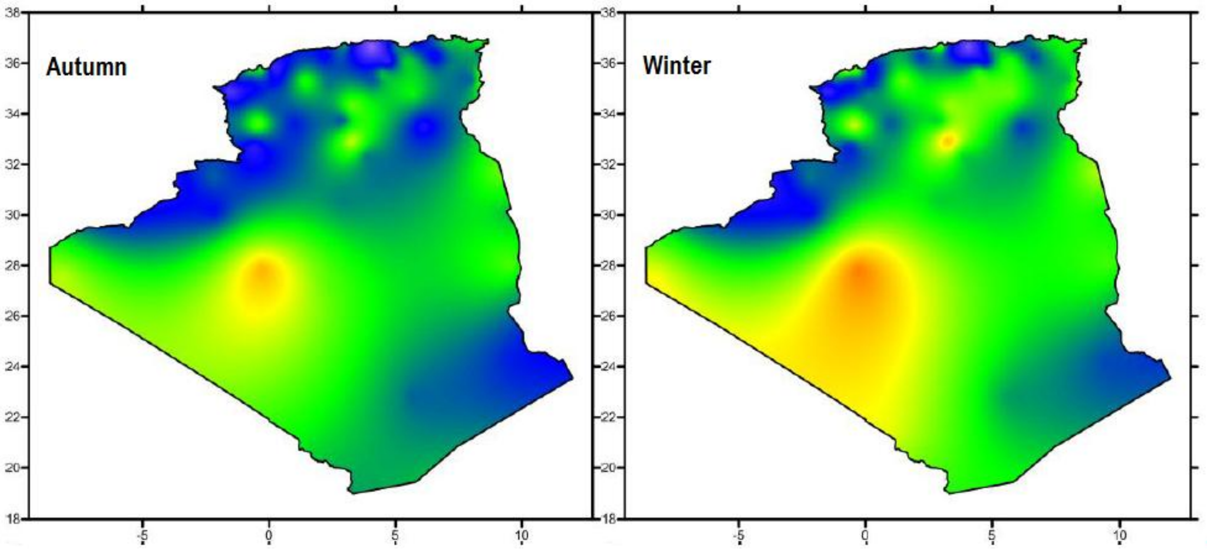


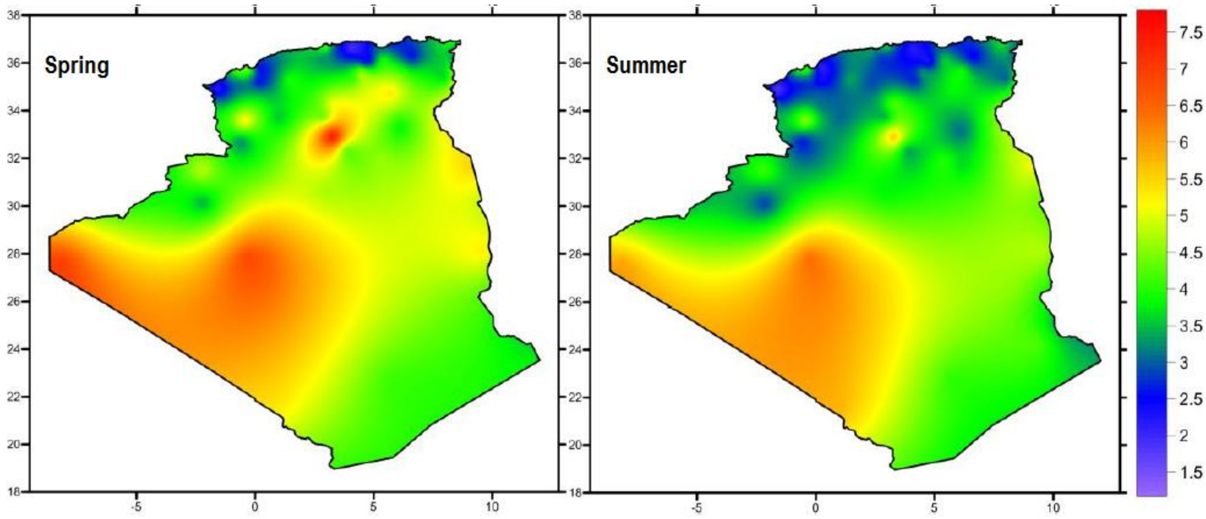


Figure (II.2) : Seasonal wind speeds at 10m from the ground (m/s) [7].

We observe that the spring period (figure (II-2.c)) remains the season in which the speed reaches its ceilings, escorted by the summer season, Figure (II.2d). However, in Autumn, the wind speed does not exceed a ceiling of 3m/s over a large area of the country (Figure II.2a)). The winter season (figure II.2a)) provides an average wind speed between the two seasons of Autumn and Summer. Some areas are still areas where the wind speed is considerable throughout the year, especially in the southwest in Adrar, in the center of the territory (Hassi-R'Mel), and the west of the high plateaus (Mechria). Wind potentials on the western Sahel remain fairly regular throughout the year at a speed of around 4.5m/sec. In conclusion, we note that the winds in the south of the country are stronger than those of the high plateaus, while the latter have stronger wind speeds than those of the north of the national territory [7].

II.3 Wind farms and capacities

The first three leaders of wind energy in Africa in 2020 were: South Africa (2636 MW), Morocco (1405 MW) followed by Egypt (1375 MW). Algeria is ranked 10th with a power of 10.2 MW generated in the Kabertene park (72 km north of Adrar) using twelve turbines [8]. The continental census of July 2022 is presented in table (II.1).

Tableau (II.1) : Power and continental wind farms [8].

Continent	Total number of parks	Total power	Offshore power	Onshore power
Africa	104	9.3 GW	0	7.44 GW
Americas	2 866	313.2 GW	0.04 GW	184.19 GW
Asia	3961	474.8 GW	24.82	186.06 GW
Europe	15871	478.5 GW	26.19 GW	195.53 GW
Oceania	192	65.2 GW	0 GW	10.72 GW

The Algerian government has initiated research to identify regions with a good wind source to invest in wind farms for an appreciated power of about 1.7 GW by 2030 [9 ,10]. At worldwide, the wind power market has not stopped progressing since the 2000's. A new installation of about 102 GW has been added to the international reserve in 2021 (among this new installation, 19 GW is Offshore and 83 GW is Onshore). At the end of 2021, approximately 845 GW was available worldwide with an increase of 13.5%. Currently, the most progress in this technology is in China with a new power of 55.9 GW; a total power of around 346.7 GW was estimated in 2021, which exceeds the United States which installed 13.4 GW increasing its reserve to 135 GW. Brazil ranked third in terms of newly installed capacity. The Brazilian market has increased by more than 60% compared to 2020 (3.8 GW installed in 2021 increasing its total capacity to about 21.6 GW). Taking into account new installations, Vietnam ranked fourth in the world in 2021. By the end of 2021, the Vietnamese market had recorded about 4.1 GW of installed capacity. The top three European countries in terms of capacity increase in 2021 are the United Kingdom (2.6 GW), Sweden (2.1 GW), and Germany (1.9 GW). The UK has regained its position as the leading European installer by adding 2.6 GW to its reserve, increasing its total capacity to around 26.8 GW. Sweden led the European Union for new installations in 2021 (2.1 GW). Germany ranked third in Europe in terms of new capacity (1.9 GW); this has increased its total capacity to about 63.8 GW at the end of 2021. In Europe, most of the power reached until 2021 is mainly distributed among the five countries: Germany (63.8 GW), Spain (28.2 GW), United Kingdom (26.8 GW), France (19.1 GW), and Sweden (12.1 GW) [11].

II.4 Principle and structure of wind turbines

The wind turbine, a successor to traditional windmills, serves as a converter designed to transform wind's kinetic energy, which is essentially the movement of a mass of air, into mechanical energy. This mechanical energy is subsequently converted into electricity, which is either supplied to local consumers or integrated into the electrical grid [12]. Figure (II.3) provides a visual representation of this process. This transformation is completed in two stages [13]:

1. The transformation of wind's kinetic energy into mechanical energy by the turbine,
2. The transformation of the mechanical energy generated by the turbine into electricity is achieved by EG, which delivers the electricity to the electrical grid.

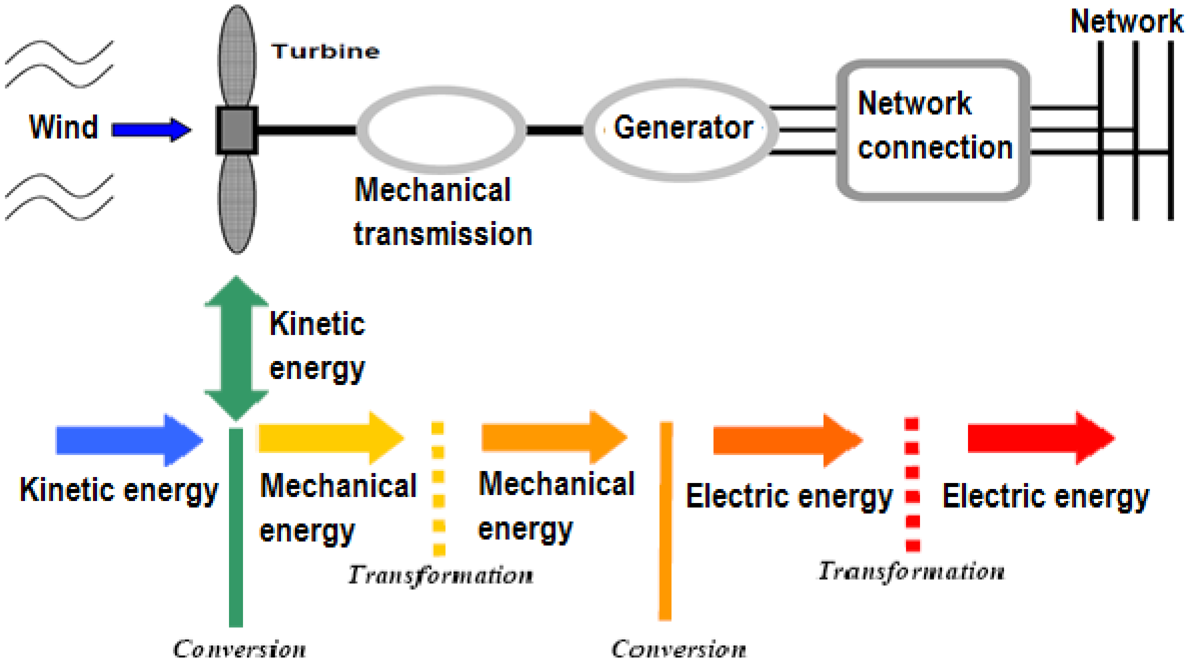
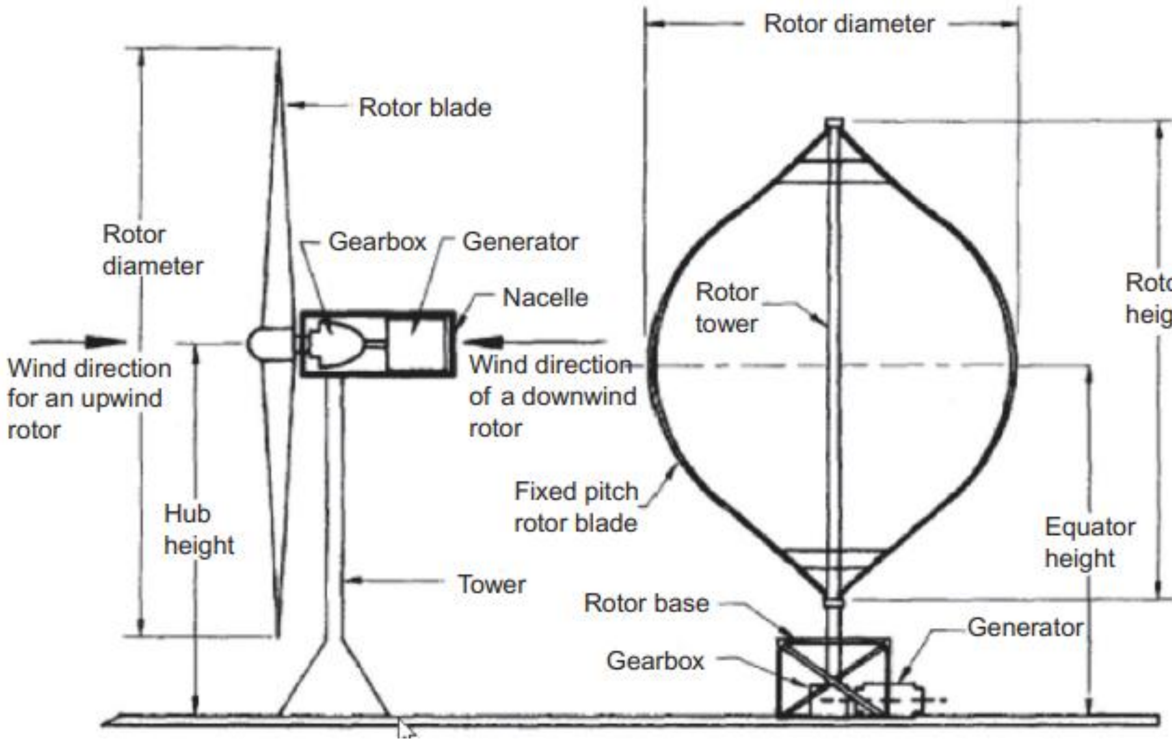


Figure (II.3) : Transformation stages of the wind kinetic energy in wind turbines [14].

A wind turbine consists of a rotor with two or three blades (generally three blades to balance wind speed between up and down) that intercept the wind's kinetic energy. The nacelle comprises all the components used to produce electrical energy. Among these devices we mention: EG, speed multiplier, blade blockers in the event of high wind speeds, an orientation device, and also a cabinet for the coupling to the electrical grid, as shown in Figure (II.4). The rotational energy generated is either converted into hydraulic power by a pump, or into electricity by means of a EG. The multiplier is used to reduce the torque and/or to multiply the rotational speed of the rotor to around 90,000 revolutions per hour for a two-blade rotor. Depending on the speed, the blades make about 600 and 1500 revolutions / hour. The grid connection cabinet ensures that the generated power can be combined with that of the electrical grid using a transformer. Typically, wind turbines support wind speeds of no more than 90 km/h. Moreover, they are constantly stopped to avoid system damage and degradation [13, 15–16].



(a) **(b)**

Figure (II.4) : Wind turbine structure: **(a)** wind turbine of horizontal axis, **(b)** wind turbine of vertical axis [17].

The available power of the air passing through the turbine is given analytically by the following formula [18]:

$$P_{air} = \frac{\chi_{air} \times \mathcal{E} \times V_{wind}{}^{3}}{2} \qquad (\text{II}.1)$$

Where χ_{air} represents the density of the air (*Kg/m*^{3}); Ƨ represents the circular area swept by the turbine (*m*^{2}); and V_{wind} represents the wind flow speed (*m/s*). The aerodynamic power appearing at the rotor is given as a function of the aerodynamic efficiency of the wind turbine R_{aer} (also called the power coefficient) and the power available of the air P_{air} by the formula [18]:

$$P_{aer} = R_{aer} \times P_{air} \qquad (\text{II}.2)$$

The ratio between blade tip speed and wind flow speed is named speed ratio [18]:

$$\gamma_{air} = \frac{\vartheta \times r}{V_{wind}} \qquad (\text{II}.3)$$

Where r represents the radius of the turbine; ϑ represents the rotational speed of the turbine (*rad/s*); and V_{wind} represents the wind flow speed (*m/s*).

II.5 Characteristics and sizing

Considering the place of positioning, wind turbines can be classified into three categories: onshore wind turbines, fixed offshore wind turbines, and floating offshore wind turbines [19]. The categories of wind turbines are shown in Figure (II.5).

Figure (II.5) : Wind turbines categories [19].

Two types of wind turbines can be distinguished according to size: large wind turbines and small wind turbines [15].

1. Large wind turbines, characterized by a vertical tower twice as tall as the blades. These wind turbines generate a power of a few megawatts, which is enough to supply electricity to thousands of homes.
2. Small wind turbines, ranging in height from 10 to 35 m, generate powers ranging between 100 W and 36 MW to operate isolated houses connected or not connected to the electrical grid.

Additionally, there are two distinct types of wind turbines: vertical-axis wind turbines and horizontal-axis wind turbines (as shown in Figure (II.6)). However, the latter is the more prevalent choice, despite the need for a turbine control device. Typically, they exhibit higher aerodynamic efficiency and operate autonomously. Whereas, vertical-axis wind turbines do not require a blade controller and have a mechanical device on the ground, which makes maintenance easier. On the other hand, the pylon is usually very bulky and very heavy. For this reason, vertical-axis wind turbines are not specifically approved for considerable power [15,20].

(a) (b)

Figure (II.6) : Photos of main categories of wind turbines, **(a)** horizontal-axis wind turbine, **(b)** vertical-axis wind turbine [13].

Wind turbines can also be classified into three types according to their nominal power and rotor diameter [20]:

1. Small-power wind turbines characterized by a rotor diameter of less than 12 m and providing a nominal power of less than 0.04 MW.
2. Medium-power wind turbines characterized by a rotor diameter of between 12 m and 45 m and provide a nominal power of between 0.04 MW and a few hundred kW.
3. High-power wind turbines characterized by a rotor diameter greater than 46 m and providing a nominal power greater than 10 MW.

The wind turbine tower must be self-supporting, self-resistant, and reinforced with steel or reinforced concrete, but generally, steel is used for high-power wind turbines. Certain materials and composites are used for the fabrication of the blades because of their good properties: lightness, robustness, and resistance to corrosion. Wind farms or parks consist of hundreds of wind turbines that work collectively to generate electrical energy [21].

II.6 Advantages and disadvantages of wind energy

The main advantages and importunities of wind energy are [13,22]:

Advantages

- It is non-polluting energy and does not generate hazardous waste. It is renewable (the wind is inexhaustible) and less expensive,
- The use of this type of energy can be conveniently stopped - as needed -.
- The operation of the wind turbine is not complicated, it can be easily connected to the available network, and it stands out squarely without leaving any traces.
- It is energy primarily intended for local or regional consumption, particularly in remote areas, which results in a reduction in the cost of energy distribution.

- Winter in which wind is important (high earning season) is the season when consumption and demand for electricity are important.

Disadvantages

- Electrical power generated by wind turbines is unstable and not constantly useful (which depends on wind speed which is difficult to predict),

- Especially in places with low wind speed, the cost of wind energy remains more expensive compared to other usual energy resources,

- Blades could naturally be considered as a risk organ. In fact, there is little possibility of damage and accidents caused by blade fracture.

- Wind turbines can cause potential interferences to transmission waves.

- Two main sources of noise can be identified in wind turbines: the aerodynamic noise generated by the passage of air along the blades, which is the least annoying and commonly reduced by a good selection of the place of installation and the mechanical noise caused by the rotary motion of mechanical devices, which begins to disappear due to the improvements made on the multiplier.

II.7 Standards

A new form of computer interconnection and communication has become essential for managing wind farms. This new form of communication helps to check the status of the wind system at any time and to send instructions in the form of commands to manage the system remotely. A SCADA (Supervision, Control, and Data Acquisition) system is well-suited to ensure these needs. The transmission of commands by the SCADA system can be based on one of the types of binding rules, such as European standards IEC 61850 and IEC 61400-25. The standard IEC 61850 describes all exchanges at source substations and IEC 61400-25 covers exchanges at a wind farm. Used for data exchange in transformer substations, the international protocol IEC 61850 is applied to integrate all control, measurement, and protection activities in a substation. The standard IEC 61400-25 is a new version of IEC 61850 for bonding in wind farms. The definition of these protocols will [23]:

- Ensure interconnection in order to exchange the necessary data;
- Maintain the set of configurations used, such as centralized configurations or decentralized configurations;
- Adapting to new developments in interconnection technology and data exchange.

II.8 Example of a wind turbine application

It has been centuries since wind energy was harnessed to pump water, especially in the agricultural sector. Currently, two types of wind pumping are used in practice: windmills (mechanical pumping) and wind turbines (electrical pumping). In the first system, the rotating energy of about twenty blades (which are controlled by a crank rotor) activates a piston pump submerged at the bottom of the well which pushes water from the source. While in the second system, a rotor (having 2 to 3 blades) is connected to a generator to operate a centrifugal pump that inhales water and pushes it out. Electric pumping is the most widely used, mainly in deep wells with high flow rates [24-25]. Figure (II.7) displays the block diagrams of the two wind-driven water pumping systems: one mechanical and the other electrical.

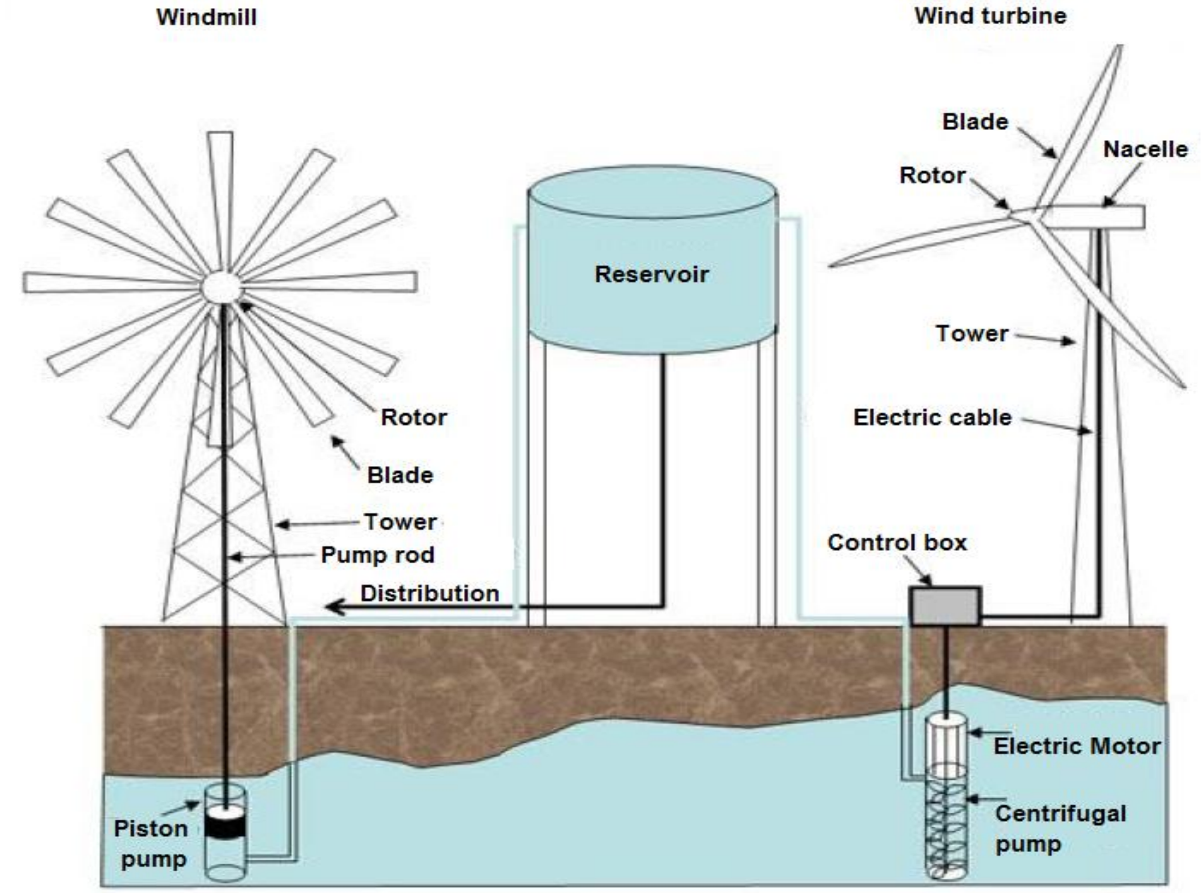


Figure (II.7): Wind energy based water pumping system [25].

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CHAPTER 3 :

HYBRID SYSTEMS

III.1 Introduction

Currently, it is necessary to give more importance to the development of new technologies for the stable production of electricity. Tidal energy, which is generated from the kinetic energy of tidal currents, provides a very significant energy resource compared to wind energy [1]. The first introduction and exploitation of this type of energy did not occur until the end of the 20th century. This type of energy resource has a mechanism similar to that of a wind turbine, where a rotating system is placed underwater to harness the kinetic energy of the marine currents. The world's first tidal turbine prototype was designed and tested in 1994 by IT Power Consulting Ltd with a power of 15kW in Loch Linnhe, Scotland. It comprised two-blade horizontal axis turbines with a radius of 1.75 m as shown in Figure (III.1) [2].

Figure (III.1) : World's first tidal turbine of IT Power Consulting Ltd [3].

Four years later, IT Power proposed the Seaflow tidal turbine (Figure (III.2)) with a horizontal axis fixed below the sea surface using cylindrical support. This tidal turbine has a nominal electrical power of 0.3 MW with 2 blades with a radius of 5.5 m. In 2003, this turbine was established at a depth of 25 m on the north shore of Devon, England [2].

Figure (III.2): SeaFlow tidal turbine installed in north of Duvon, England [4].

The SeaGen installed at Strangford Loch in Northern Ireland in 2008 was the first commercialized grid-connected tidal turbine prototype (Figure (III.3)). It consists of two horizontal axis double blades with a radius of 8 m and a power of 0.6 MW (per turbine) with intake blades attached to two shafts connected in turn to a main cylindrical shaft [2,5].

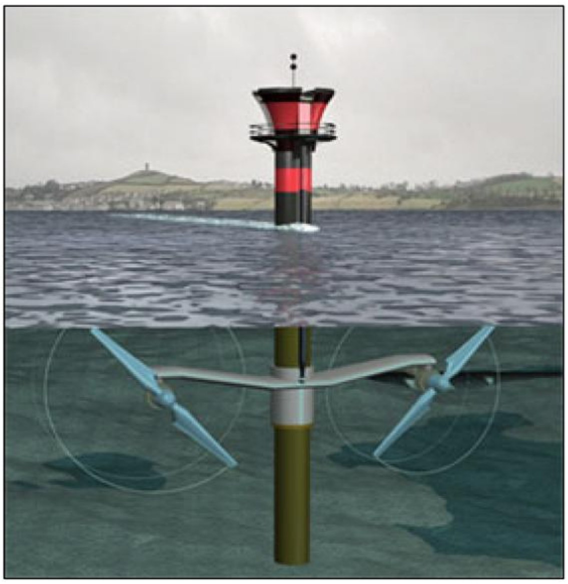
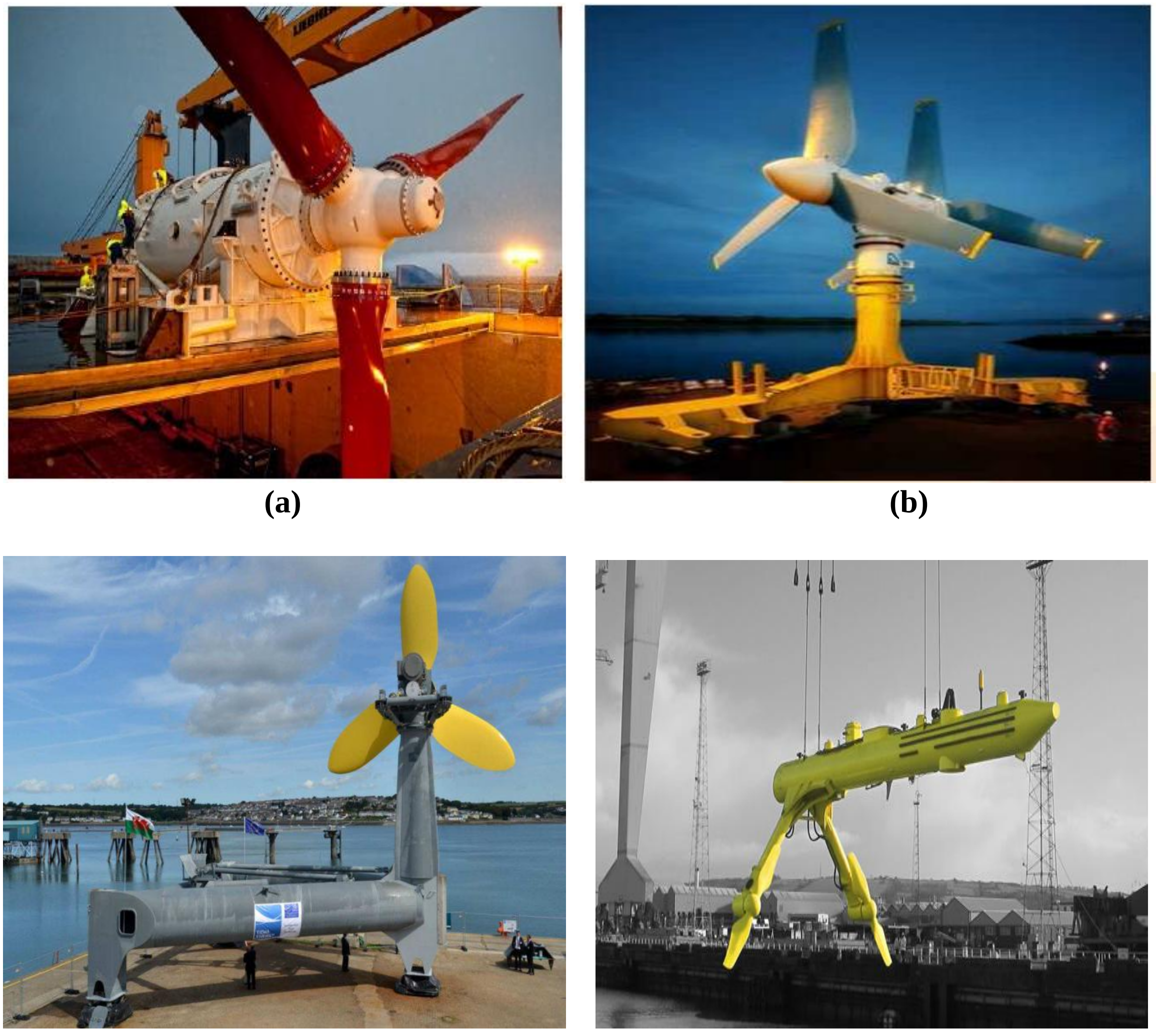


Figure (III.3): SeaGen tidal turbine installed in Strangford Lochn, Ireland [6].

In 2011, Andritz Hydro Hammerfest presented its tidal turbine (Figure (III.4a)) with a power of 1 MW, with a blade radius of 11.5 m. In the same year, Atlantis Resources Corporation similarly presented its tidal turbine (Figure (III.4b)) with the same power and a blade radius of 9 m. Five years later, in 2016, Tidal Energy Ltd unveiled its 0.4 MW tidal turbine (Figure (III.4c)), with a blade radius of 6 m, in Ramsey Sound, Wales. Whereas tidal turbines offered by Andritz, Atlantis or Tidal Energy are all horizontal axis based on three blades installed and emerging below the sea surface. Scotrenewables Tidal Power Ltd uses another technique by fixing two blades (fixed at two tips) totally emerged to a semi-submerged main shaft [2] as shown in Figure (III.4d).



(a) **(b)**

(c) **(d)**

Figure (III.4): Tidal turbines designed by some companies (a) Andritz Hydro Hammerfest [7], (b) Atlantis Resources Corporation [8], (c) Tidal Energy Ltd [9], (d) Scotrenewables Tidal Power Ltd [10].

Most of the founders of this technology have adopted the 3-blade horizontal-axis tidal turbine, while Openhydro has chosen another tidal turbine structure with a half-open middle and many wings, with water crossing it through its middle. In 2006, a prototype, 0.25 MW and 3 m rotor radius was built and tested by the European Marine Energy Center (EMEC) in the Orkney Isles in Scotland and connected to the UK electrical grid in 2008. The initial prototype of Openhydro with a power of 0.5 MW, 85×10^4 Kg and a radius of 8 m, Figure (III.5), was tested in 2011 in Brest, France. In 2013, Openhydro installed several test stations in Paimpol-Brehat in Brittany, France [2,7].

Figure (III.5): Tidal turbine of Openhydro [7].

In this chapter, tidal turbines and their principle of operation, the main existing technologies, operators, advantages, and disadvantages of this energy resource will be presented.

III.2 Principle of Operating of tidal turbines

A tidal turbine is a floating or underwater plant that exploits the energy of water flows, similar to a wind turbine that exploits the kinetic energy of air to generate electricity. Generally, tidal turbines can be stabilized by underwater shafts (fully submerged or attached to a mast that emerges) or by buoys on the sea surface [11–12]. Figure (III.6) shows the different stages of energy transmission as well as the operation of the tidal turbine.

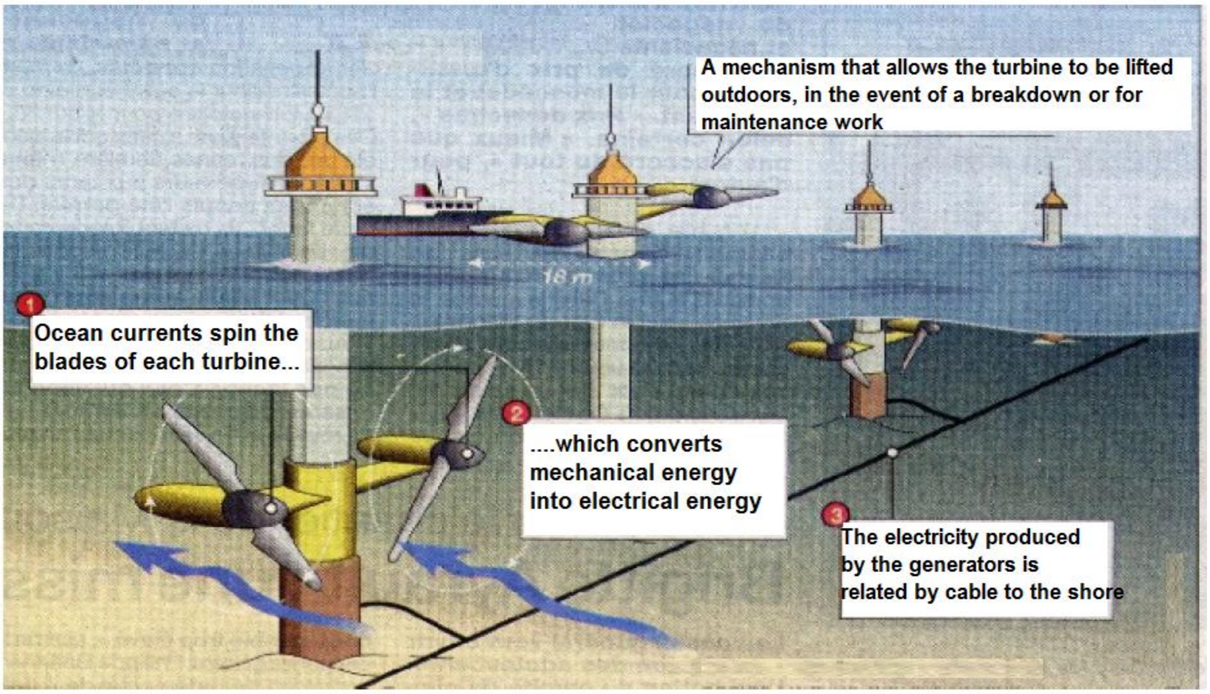


Figure (III.6) : The principle of operation of tidal turbines [13].

The primary components of tidal turbine systems are illustrated in Figure (III.7). This includes the core components such as the turbine rotor, responsible for capturing kinetic energy from tidal currents and transforming it into mechanical power. The mechanical power generated at the turbine shaft is then transformed into electricity through a Power Take-Off (PTO) system. The PTO system comprises several key elements, including a mechanical drive train, which transfers power from the turbine to a generator. The generator plays a pivotal role in converting mechanical power into electrical energy. This electrical energy is further managed through a power electronic interface and a transformer, ensuring the seamless integration of electricity production into the main grid [14-16].

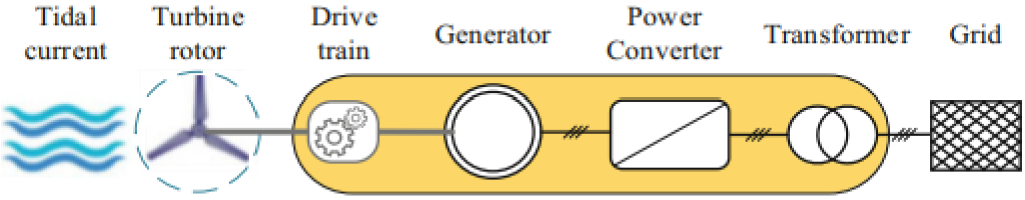


Figure (III.7) : Main components of a tidal turbine [16].

The pressure difference between the blades of the tidal turbine, caused by the kinetic energy of the ocean currents, generates a rotating movement of the blades (mechanical energy). The mechanic rotation (mechanical energy) produced is transformed, in turn, into electricity through a generator related to the rotating shaft [2].

The aerodynamic power appearing at the rotor of the tidal turbine is given as a function of the aerodynamic efficiency of the turbine R_{aer} and the power of the fluid P_{fluide} by the formula [17]:

$$P_{aer} = R_{aer} \times P_{fluid} = R_{aer} \times \frac{\chi_{fluid} \times \text{Ƨ} \times V_{fluid}^{3}}{2} \qquad (\text{III}.1)$$

Where χ_{fluide} represents the density of the fluid (*Kg/m*^{3}); Ƨ represents the circular area swept by the blades (*m*^{2}); and V_{fluid} represents the fluid flow speed (m/s).

The ratio between the blade tip speed and the fluid flow speed is named velocity ratio [17]:

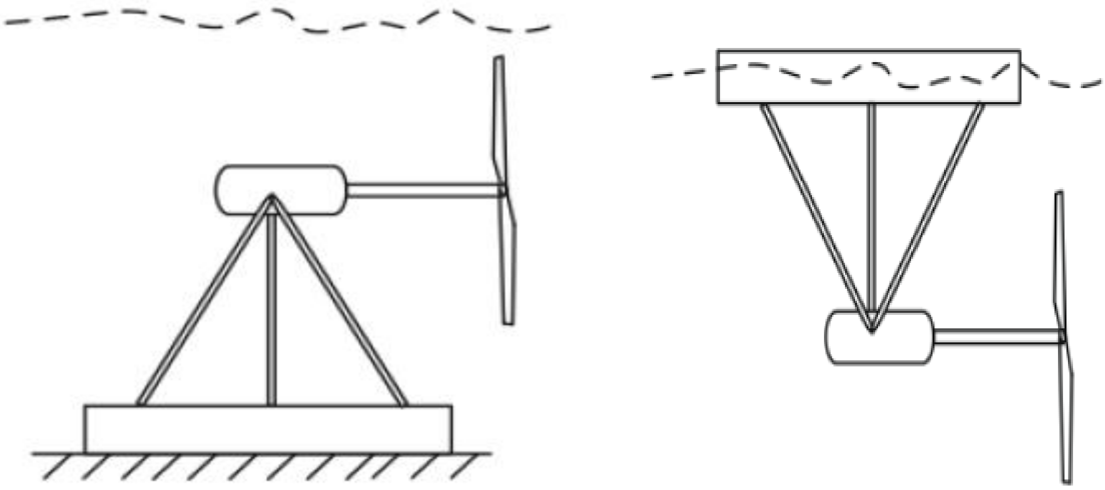
$$\gamma_{Fluid} = \frac{\vartheta \times r}{V_{fluid}} \qquad (\text{III}.2)$$

Where r represents the radius of the turbine; and ϑ represents the rotational speed of the turbine (*rad/s*).

III.3. Different types of tidal turbines

III.3.1. Horizontal axis turbines

The concept of this tidal turbine closely resembles the operating principle of traditional horizontal-axis wind turbines, where the rotation axis aligns with the direction of the sea current, as depicted in Figure (III.8). One of its key advantages lies in its high electrical energy production efficiency compared to alternative technologies [12,18,19]. The kinetic energy of the marine flow sets the blades in motion, generating electrical energy through the EG. Certain prototypes may require adjustment, rotating into a semi-circle to optimize energy conversion efficiency based on the flow direction [19].



(a) **(b)**

Figure (III.8) : Horizontal axis tidal turbine, (a) totally submerged, (b) partially submerged [20].

III.3.2 Vertical axis tidal turbines

Vertical axis tidal turbines exploit the aerodynamic movement of their blades to convert the kinetic energy of the marine flow into mechanical energy with vertical rotation (its axis is perpendicular to the marine flow), which stimulates the EG to generate electric power. This technology is particularly favored for dams. Typically, a EG has a booster accelerator attached to it [19]. The advantage of this system is that it is independent concerning the direction of the incoming marine flow. The restart of this tidal turbine is not as automatic as a horizontal axis tidal turbine, which thus requires a restart system that can affect the turning efficiency of the tidal turbine. There are different types of vertical axis technology [15], as shown in Figure (III.9).

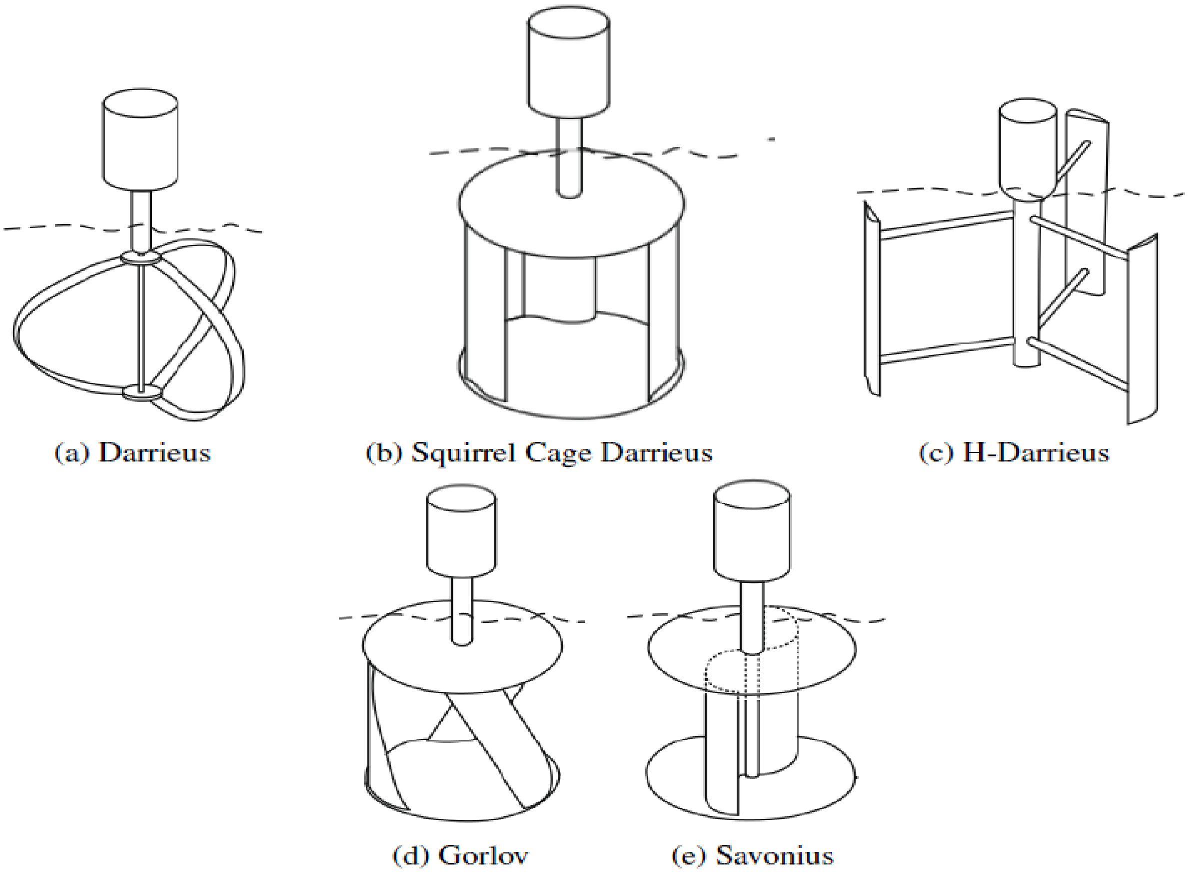


Figure (III.9) : Types of vertical axis tidal turbines [20].

Darrieus turbines, Figure (III.8a), were originally designed for wind turbines, however, they have been used to harness the power of marine flows. Some modifications have been made to this type of turbine to overcome the initial structure design problems, as shown in Figures (III.8b) and (III.8c). H-Darrieus turbines are very useful primarily where mechanical resistance is crucial. While Darius squirrel-cage turbines, Figure (III.8e), are preferred for lower power. However, the main drawback of Darrieus turbines is the automatic restart once their operation is interrupted. The Savonius turbine is one of the simpler turbines designed to overcome the shortcomings of the automatic restart of the Darrieus turbine. This turbine has a high restart torque that can be selected for low-flow sea currents. However, one of the drawbacks of this turbine is the low efficiency [20]. The Gorlov turbine, proposed by Professor Alexander Gorlov of Northeastern University in the United States, consists of blades with spiral shapes around a cylindrical surface, as shown in Figure (III.2d). This turbine was manufactured and tested between the years 1994-1997 to overcome the auto-restart problem that occurred in Darrieus offshore flow turbines to obtain good efficiency [20-21].

III.3.3 Tidal turbine with oscillating wings

In this turbine, two dynamically controlled arms are installed to control the angle of capture (Figure (III.10)). The movements of the arms are parallel to the tidal movements of the hydraulic pistons. Entry of the pistons within their cylinders enables hydraulic fluid to be sent at powerful pressure toward the hydraulic turbine to excite the EG and generate electrical power. This turbine is designed to be installed under the sea surface [19].

Figure (III.10) : Oscillating wings tidal turbine structure [22].

III.3.4 Tidal turbine with Venturi Effect

Lunar Energy's tidal turbines are designed to be installed under the sea (so as not to impede marine traffic) and use the Venturi effect to exploit the strength of the sea current by boosting the speed of the sea current in a conical tube that becomes a narrower radius. To obtain high conversion efficiency, the propeller is placed in the center of the tube (where the tube radius is narrow) to increase the rotational speed of the propeller, Figure (III.11). This type of tidal turbine can be installed in places with strong marine flows to increase the efficiency of electricity production [18, 23].

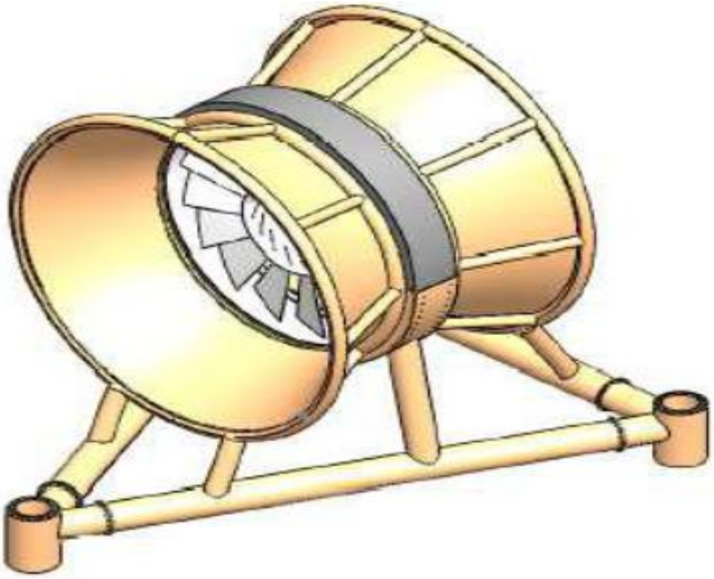


Figure (III.11) : Tidal turbine structure with Venturi effect [18].

III.3.5. Other technologies

Buoy point technology is a floating turbine intended to generate electric power from wave energy [24]. There are different types of this technology in which the designs differ from one manufacturer to another, Figure (III.12). This turbine is a balancer that oscillates through a wave. Its role is to intercept the energy generated by the perpendicular passage of the wave to generate electric power. Generally, this turbine can be installed about 22 km Offshore [19].

Figure (III.12) : Floating tidal turbine structure [23].

Another floating tidal turbine with a linear structure is designed to produce electrical energy from wave energies, Figure (III.13). It consists of several hinged segments of floating cylindrical sections, and it is fixed at one end. Its oscillation forces the hydraulic arms to suck the oil into the reservoir. The oil is released from the reservoir to drive a hydraulic motor which excites the EG to generate electrical power. These tidal turbines are often installed about 5 to 10 km offshore for high productivity [19,25].

Figure (III.13) : Floating tidal turbine with linear structure.

River tidal turbine (Figure (III.14)) consists of a dual vertical axis and fairing to increase conversion efficiency. This type of tidal turbine is manufactured to be placed on the river surface. In particular, from an environmental point of view, it is best to keep these turbines out of sight as much as possible. This type of tidal turbine has an insignificant impact on marine life because fish can circulate under it [27].

Figure (III.14) : River tidal turbines structure [27].

III.4 Advantages and disadvantages

The main advantages and challenges of this technology are:

Advantages

- Tidal energy is renewable, natural, non-polluting (no carbon dioxide, no radioactive waste), and production is free (marine flows are inexhaustible, and production power is predictable during the year, which is not the case with wind on land (wind turbines) [28 -30],
- Underwater tidal turbines are designed to pose no danger to marine life. In addition, the blades are not dangerous because they rotate at a rate of 600 to 900 revolutions per hour; ten times slower than those of ships [29],
- Tidal turbines generate electricity with a power greater than or equal to the power that can be generated by conventional wind turbines of more than three times the size; this is due to the density of water, which is much greater than the density of air (more than 800 times greater) [29–30],

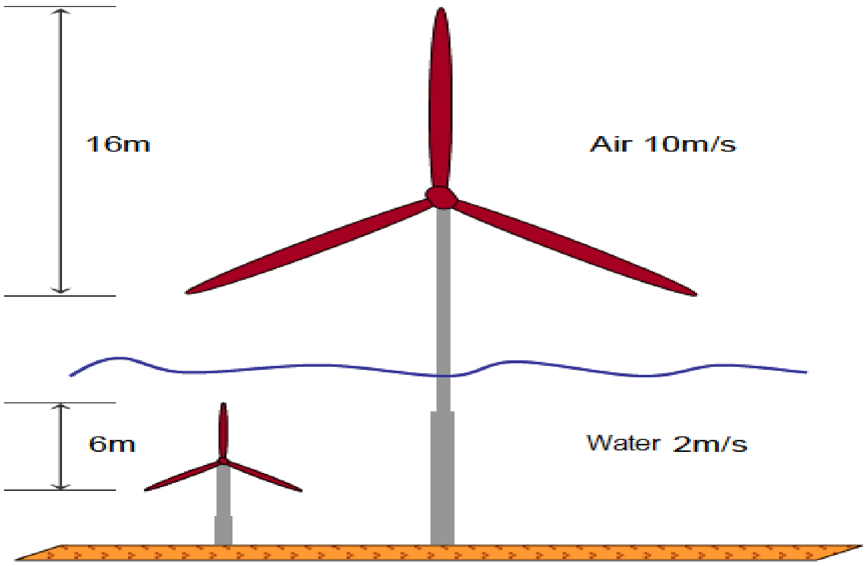


Figure (III.15) : A comparison of a tidal turbine and a wind turbine placed offshore to generate the same energy [21].

- Placed in the open sea, they are usually invisible and do not disturb vision [29].

Disadvantages

- Corrosion of immersed elements in sand and seawater makes them very brittle [29],
- The installation and maintenance of some underwater devices require huge investments [29, 31],
- Tidal turbine parks can interfere with other sectors such as: fishing, maritime entertainment, underwater means of communication, etc. [19].

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CHAPTER 4 :

PHOTOVOLTAIC SOLAR ENERGY

IV.1 Introduction

If a semiconductor material is illuminated by a light ray, then additional electron-hole pairs are produced depending on the light intensity. This fact is called the photovoltaic effect [1]. The term photovoltaic comes from Greek and is constituted of two words: Photos: Light. Volt: Unit of electrical voltage, the surname of physicist Alessandro Volta. The photovoltaic effect was detected by the French physicist Alexandre Edmond Becquerel in 1839. The initial prototype of a PV cell was designed in 1954 for space application, but investments in terrestrial applications did not begin until the 1970's [2]. Photovoltaic energy is estimable, credible, clean, and inexhaustible. Currently, most photovoltaic panels can operate for up to twenty years and even more [3]. Two main photovoltaic power plants can be distinguished: autonomous (not connected to the grid) and coupled to the grid [4]. In this chapter, we will present, the solar energy potential in Algeria, the basic notions of photovoltaic renewable energies: photovoltaic cell technologies, photovoltaic installation, and the different applications whether autonomous or connected to the grid... This chapter ends by presenting an example of PV energy application.

IV.2 Assessing solar energy potential in Algeria

Algeria collects one of the most eminent solar potentials of the Mediterranean basin due to its privileged geographical location. The sunshine on the country territory attains an equivalent of 83 days annually and can reach an equivalent of 162 days annually (almost double) in the highlands and Sahara. The weekly energy collected for each 1 m^2 (horizontally) is around 35 KWh in large regions of the country. In the desert, this solar energy potential can be beneficial to the country's economy [5] (table (IV.1)).

Table (IV.1) : Percentage of sunshine for each region of the national territory [5].

Areas	Coastal areas	Highlands	Desert
Area surface	4%	10%	86%
Average sunshine duration (Days/year)	110.5	125	146
Average energy collected (GJ/m^2/year)	6.12	6.84	9,54

In Algeria, solar energy is exploited only by PV panels. On the other hand, the two energies: thermal and thermodynamic, remain under test [5]. As shown in figure (IV.1), the south contains the most important solar energy potential on the Algerian territory.

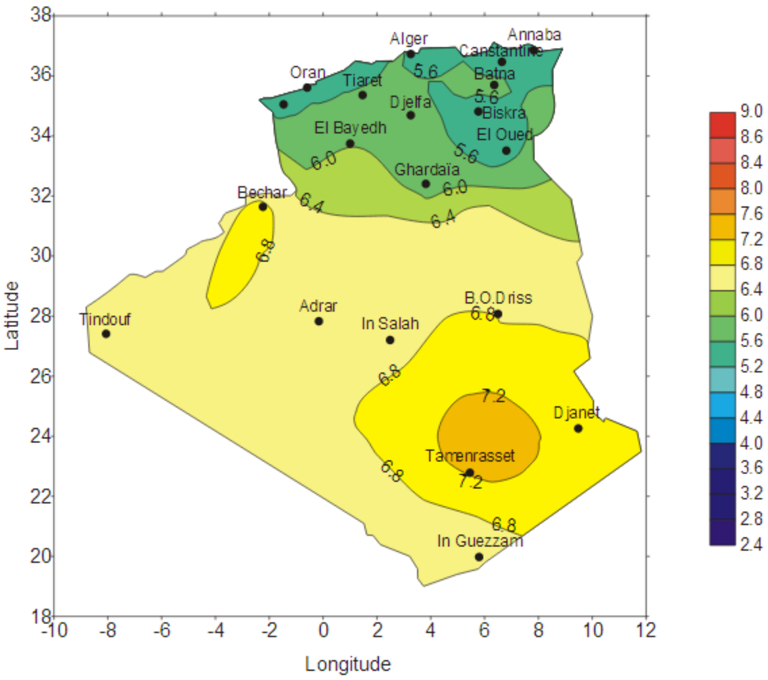


Figure (IV.1) : Annual solar energy received on the territory of Algeria [6].

The national energy plan aims to promote the utilization of this valuable energy resource. To achieve this goal, the Algerian Ministry of Energy Transition and Renewable Energies has planned and initiated numerous investments, as documented in references [7-8].

IV.3 Technologies of photovoltaic cells

Solar PV panels function through the direct conversion of sunlight into electrical energy, a process facilitated by semiconductor materials, commonly silicon. This conversion is made possible by harnessing the PV effect, which takes place when semiconductor materials absorb photons emitted by the sun. When a photon contacts the semiconductor material within a PV panel, it possesses the potential to energize an electron, thereby liberating it from its atomic structure. This excitation of electrons and their subsequent release creates voids known as "holes" within the material, leading to the formation of electron-hole pairs. The dislodged electrons are now mobile within the semiconductor. Due to the inherent electrical properties of the semiconductor, electrons are channeled along a predefined electrical pathway. This movement of electrons within this designated path results in the generation of an electric current. This flow of electrons is captured and utilized as electricity. To gain a deeper comprehension of this conversion process, it is important to consider the structure of the elementary cell, as illustrated in Figure (IV.2). Typically, this basic unit consists of two primary layers: one is positively doped, signifying a deficiency of electrons, while the other is negatively doped, indicating an excess of electrons. These two layers unite to form what is termed a PN junction. When sunlight strikes the PV cell, it imparts its energy to the atoms situated at the PN junction, leading to the detachment of electrons and the concurrent creation of both negatively charged electrons and positively charged holes. This sequence results in the emergence of a separation barrier between the two layers of the photovoltaic cell. The n-type region is crafted through the negative electrode and negatively doped silicon, while the p-type region is achieved through the positive doping of silicon and the application of a positive electrode. The crux of this operation lies in the p-n junction, positioned between the n-type and p-type layers. This junction plays a pivotal role by establishing an internal electric field, which facilitates the segregation of charge carriers, specifically electrons and holes. This process, catalyzed by exposure to sunlight, culminates in the creation of an electric current. This entire process embodies the fundamental mechanism through which a PV cell converts solar energy into electrical power.

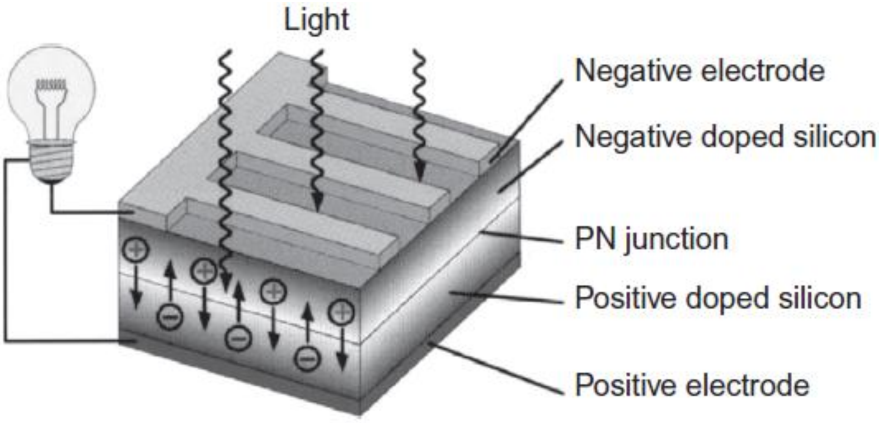


Figure (IV.2) : Composition of a PV cell [10].

There are several constituent materials for PV cells [11-12]: crystalline silicon and amorphous silicon which make up the majority of global production (more than 80%) destined for terrestrial applications, GaAs, CdTe, CIS, and CIGS.

- **Monocrystalline silicon:** It is made into expanded bars. Their cells are the most efficient with an efficiency of between 15% and 20% (at high and medium illumination), but they are very expensive.
- **Polycrystalline silicon:** Its cells with a low efficiency of 12% to 17% have greatly helped in reducing the cost of the modules.
- **Amorphous silicon:** Its realization is less expensive and allows for the manufacture of short ratios. However, its cells are deposited in a very thin film and have a very low efficiency of 5% to 7%. This type of silicon seems to be suitable for devices that require little power, such as powering clocks or calculators, etc.
- **Gallium arsenide (GaAs):** It has a very high efficiency of 25-40%, but it is very expensive and is only used for satellite solar modules or on centralized equipment where efficiency and mass are the most important factors, not cost!
- **Cadmium telluride (CdTe):** It is the leader in thin films and has the lowest cost. However, its efficacy is not encouraging, it ranges from 8% to 10%. It includes a

hypothetically risky component that has already been ruled out in several countries (cadmium 1). This type of silicon seems particularly suitable for solar power stations.

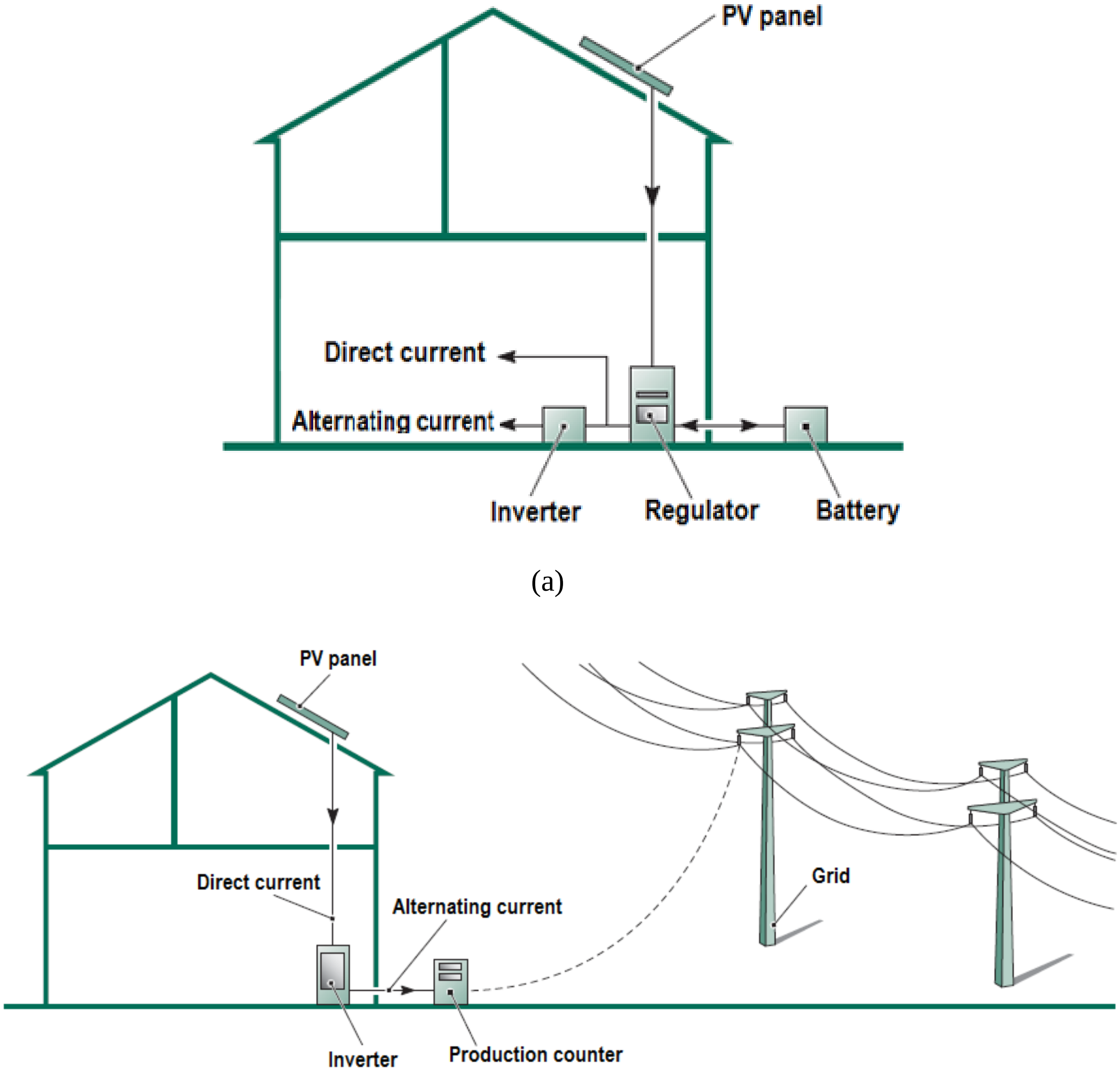
- **Copper indium selenide (CIS) and copper indium gallium selenide (CIGS):** Their cells have a lower efficiency of 10%-12% and benefit from the same ease of preparation as amorphous silicon. However, this material is relatively little exploited, due to manufacturing problems and climatic requirements, and mainly also because of the cadmium it has. This type of silicone seems to be mainly suitable for housings connected to the grid.

IV.4 Principle of a photovoltaic installation

Solar photovoltaic conversion is the process of promptly converting solar energy into electrical energy by harnessing light to stimulate the PN junction, thereby generating electricity. These modules comprise multiple cells, enhancing the overall efficiency of the energy transformation. To power AC devices or to connect the electrical energy generated by photovoltaic modules (in the form of direct current electricity) to the grid, the use of inverters is essential. Inverters are responsible for converting DC to AC [13]. The PV systems are categorized into two main types [13]:

1. Autonomous PV systems
2. Grid-coupled PV systems

The design and structure of autonomous PV systems are different from that of PV coupled systems to the grid. Unconnected systems – which must ensure an appropriate stock – usually store electrical energy in accumulators (batteries) [14], (see figure (IV.3(a)). The unconnected PV system (figure (IV .3)) generates electrical power for locations not connected to the grid and ordinarily stores the electricity in storage batteries for use when needed. For use with DC current, an electronic regulator guarantees the charging of the accumulator. Its role is to stop the recharging of the accumulator before they are fully charged (to avoid overcharging) and to interrupt the current in the circuit before the accumulators are completely discharged so as not to deteriorate the accumulator. Often, lead-acid batteries are the most used due to their price (less expensive) and their ease of operation. The PV system can be connected to the grid via an inverter which is used to convert the DC current delivered by the photovoltaic modules into AC current appropriate for the characteristics of the grid. Moreover, this type of photovoltaic system does not require an accumulator of energy (figure (IV.3(b))) [15].



(a)

(b)

Figure (IV.3) : Principle of a PV system (a) with storage, (b) with direct coupling with the grid [15].

Table (IV.2) : Advantages and disadvantages of a PV system [14].

Advantages	Disadvantages
➢ Direct transformation of energy from the sun which is inexhaustible. ➢ PV systems are non-polluting and silent ➢ The maintenance cost is minimal, often requiring no maintenance at all. ➢ Guaranteed reliability for low-power applications.	➢ The initial cost of the investment in PV panels is very expensive. ➢ The energy storage system requires additional cost and periodic maintenance. ➢ The installation must be done by experts to avoid any errors and to guarantee good productivity. ➢ PV electrical energy is not

➢ The dimensions of the PV installation can be adjusted according to the energy needs. ➢ Limited risk of electric shock and a low risk of fire. If all sockets are installed in accordance with the standards, the security of the system will be absolute.	competitive and not persistent for thermal exploitation.

IV.5 Photovoltaic panels

IV.5.1 Photovoltaic cell

The photovoltaic cell, as depicted in Figure (IV.4), serves as an electronic component designed to directly convert light rays into electrical energy. It is a key building block of a photovoltaic generator (PVG), typically characterized by modest power output, suitable for various applications [16].

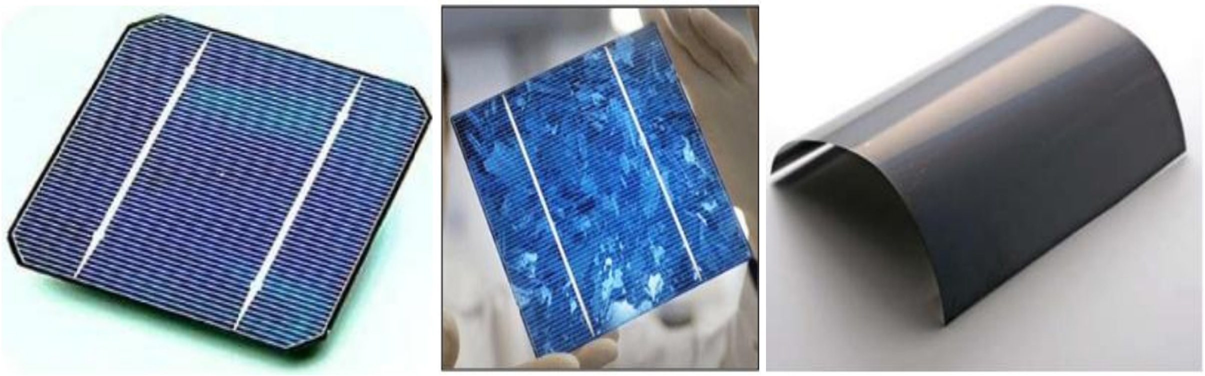


Figure (IV.4): Primordial silicon solar cells (a) mono-crystalline, (b) poly-crystalline, (c) amorphous [8].

IV.5.2 Photovoltaic modules

A photovoltaic module is created by assembling individual PV cells into a single unit enclosed within glass. This assembly includes essential components, such as encapsulants and glass, on both sides of the module. One side provides protection for the module, while the other is typically covered with either glass or a polymer film, often made from materials like Tedlar [17-18], as shown in Figure (IV.5). A collection of PV modules collectively forms a PV panel

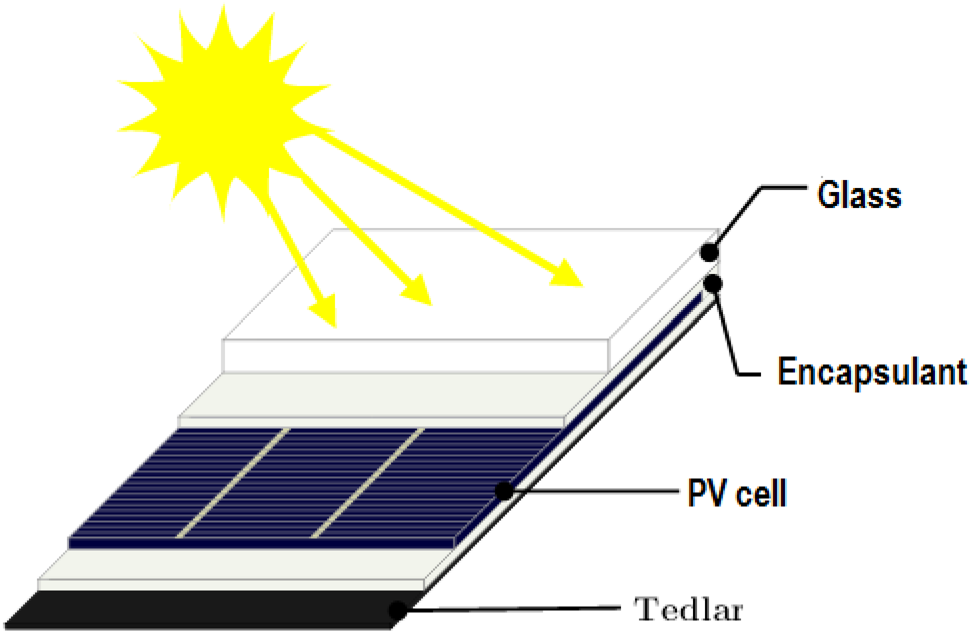


Figure (IV.5): Section of a PV module [18].

The modules are placed on a metal structure that helps to maintain the photovoltaic panel with a given slope angle [16]. To produce more power (the best efficiency), a multitude of modules are assembled in parallel series to form a PV field [13], (figure (IV.6)).

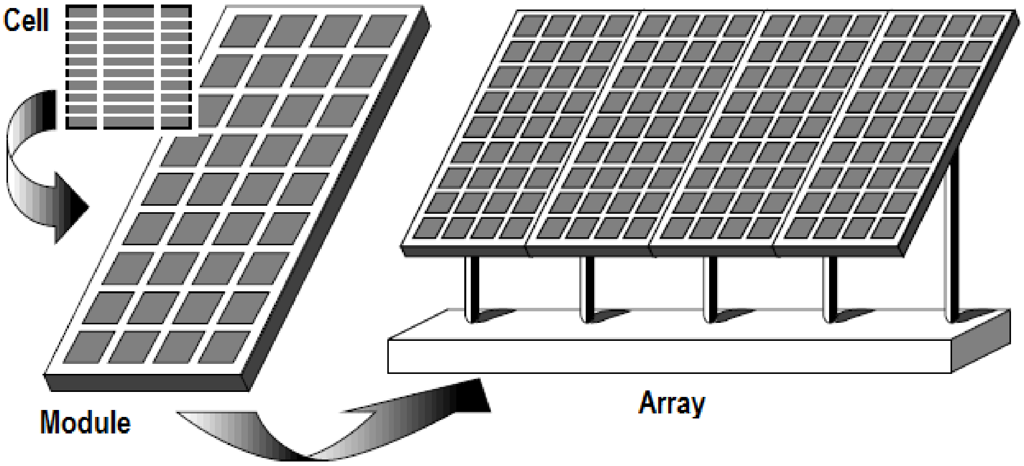
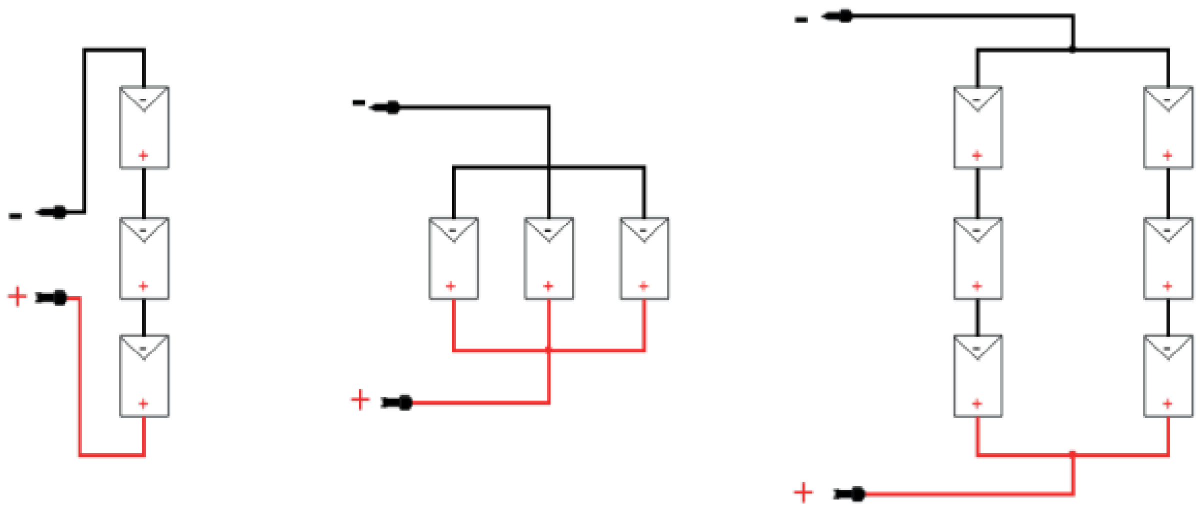


Figure (IV.6): Going from the cell to the PV field [19].

Various methods for assembling PV modules are illustrated in Figure (IV.7). For enhancing the power output of a PV system, a mixed installation, combining series and parallel configurations, is commonly favored.



(a) (b) (c)

Figure (IV.7): Assembly of PV modules, (a) in series, (b) in parallel, and (c) mixed [20].

IV.5.3 PV Cell protection: bypass diodes and anti-return diodes

To ensure safety and proper functioning of the PV installations, protective devices must be incorporated into the system, as depicted in Figure (IV.8). To serve this purpose, two essential components can be employed [16]:

1. Parallel diodes (or by-pass) are used to separate a module if an error occurs in one or more cells or shading occurs in certain cells.
2. Anti-reverse diode does not allow reverse currents to enter the PV modules.

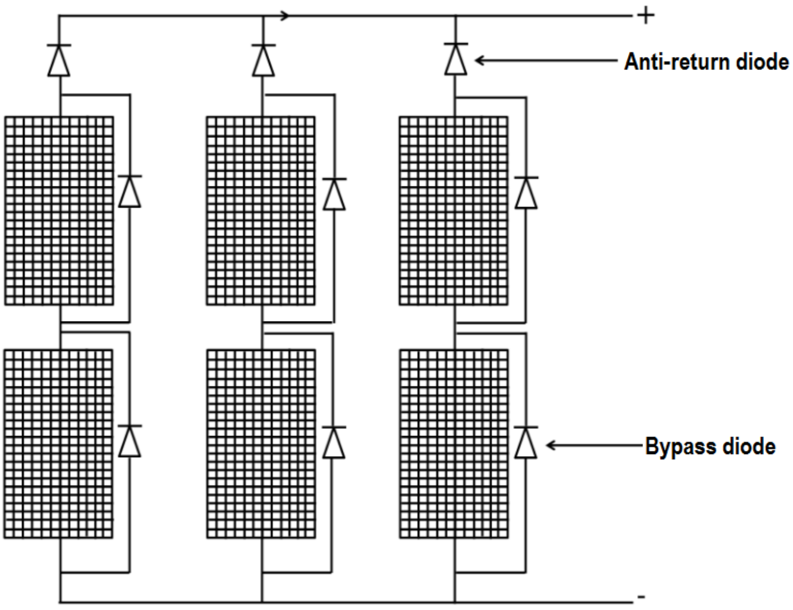


Figure (IV.8): Types of diodes used for the protection of PV modules [16].

IV.5.4 Maximum Power Point (MPP)

The output current curve of the PV module as a function of the output voltage (red curve) is not linear. This characteristic depends instantaneously on the incident ray intensity and temperature [16-21]. Similarly, the output power curve is plotted as a function of the output voltage (blue curve), and the maximum power point (MPP) can be determined. The black line shows the characteristic of a resistive load connected to the GPV. The intersection of I(V) of GPV and the load will give the MPP (figure (IV.9)). Maximum power point tracer is used to ensure good assembly performance by providing maximum power [21].

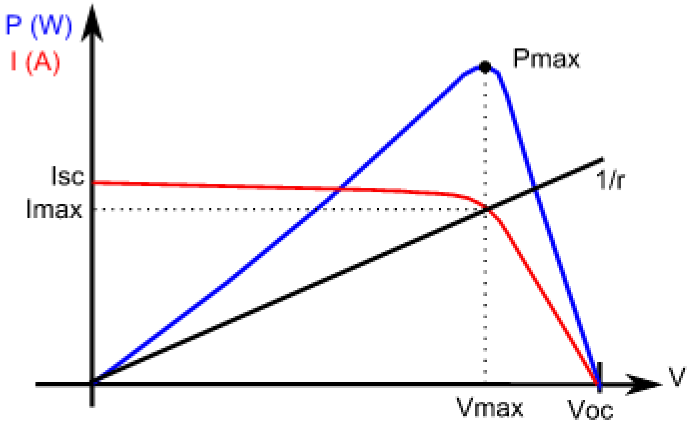


Figure (IV.9): Presentation of the I(V) and P(V) characteristics of a PVG [21].

The power P_{max} which corresponds to the MPP is given by the formula:

$$P_{max} = V_{max} \times I_{max} \qquad (IV.1)$$

The quality of PV cell is judged by the form factor (FdF) given by the formulas [22]:

$$FdF = \frac{P_{max}}{P_{mm}} \qquad (IV.2)$$

$$FdF = \frac{V_{max} \times I_{max}}{V_{CO} \times I_{SC}} \qquad (IV.3)$$

Where I_{SC} is the short circuit current flowing through the cell under illumination without voltage application and V_{CO} is the open circuit voltage measured when no current is flowing through the cell.

The closer the FdF is to unity, the better the cell.

The power conversion efficiency η_{PV} of the PV cell is given as a function of the maximum power delivered by the cell P_{max} and the incident power P_{in} .

$$\eta_{PV} = \frac{P_{max}}{P_{in}} = \frac{FdF \times V_{CO} \times I_{SC}}{P_{in}} \qquad (\mathrm{IV}.4)$$

Figure (IV.10) shows the equivalent electrical circuit of an illuminated PV cell.

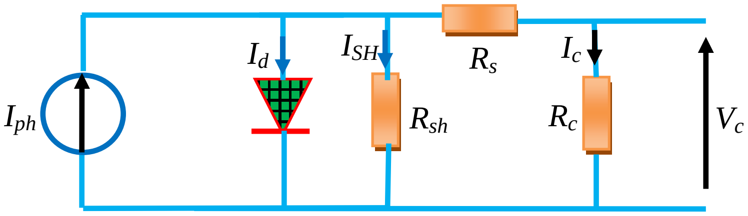


Figure (IV.10): Equivalent circuit of a PV cell with a diode.

The current produced by the cell I_c is given by the formula [23]:

$$I_c = I_{PH} - I_{Sa}\left[Exp\left(\frac{q(V_c + R_s I_c)}{nK_B T}\right) - 1\right] - \frac{V_c + R_S I_c}{R_{SH}} \qquad (\mathrm{IV}.5)$$

With I_{PH} is the photocurrent of the cell, I_{Sa} is the reverse saturation current of the diode, q, n, K_B, and T denote respectively the charge of the electron, ideality factor of the diode ($1 \le n \le 1.5$), Boltzmann constant (1.381 10^{-23} J/K) and the cell temperature (in Kelvin), R_S and R_{SH} are the series and shunt resistances of the cell. The instantaneous efficiency of PV array can be calculated using the following formula [24]:

$$\eta = \frac{P_{ch}}{A \times M \times E} \qquad (\mathrm{IV}.6)$$

P_{ch}: The power generated by a PV array, A : The area of a single module used in a system (m^2); E: Total solar irradiance on an inclined plane (W/m^2); and M : Number of modules in the PV array.

One of the main objectives of a PV installation connected to the grid is to provide all the power supplied by the panel. The converter (DC/DC or/and DC/AC) allows the implementation of an internal MPP tracker control so that maximum power is reproduced permanently [21]. The efficiency of PV panels is inversely proportional to the temperature of PV cells [16].

IV.6. Inverter

The role of the inverter is to convert the DC power generated by a PV panel into AC power. In PV installations connected to the grid, the inverter is composed of: an MPP tracker, a bridge that is used to convert direct power into alternating power, and a transformer [18]. Its internal electric circuit is shown in figure (IV.11).

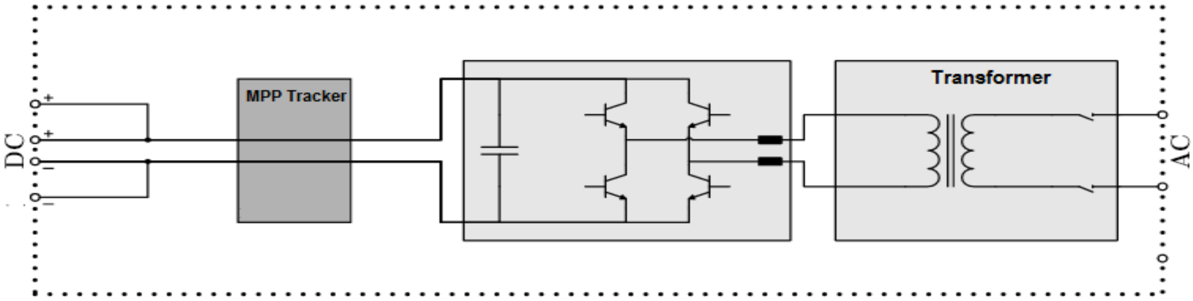
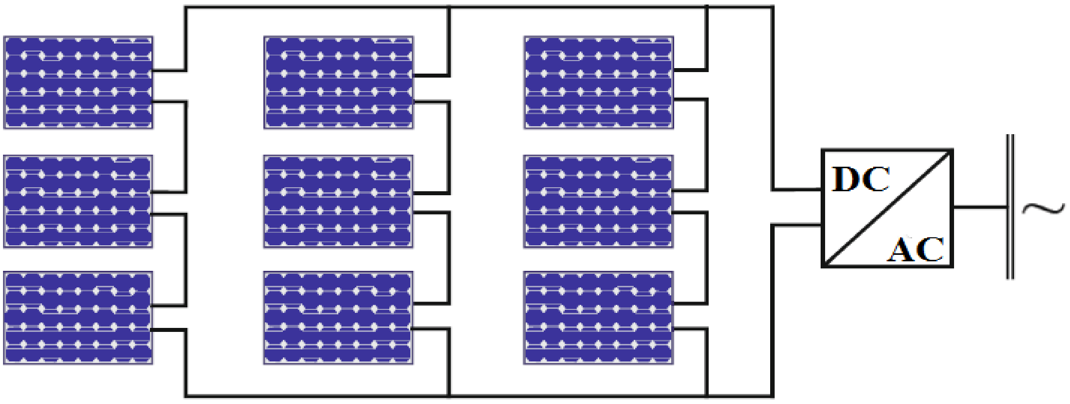


Figure (IV.11) : Internal electrical circuit of an inverter [18].

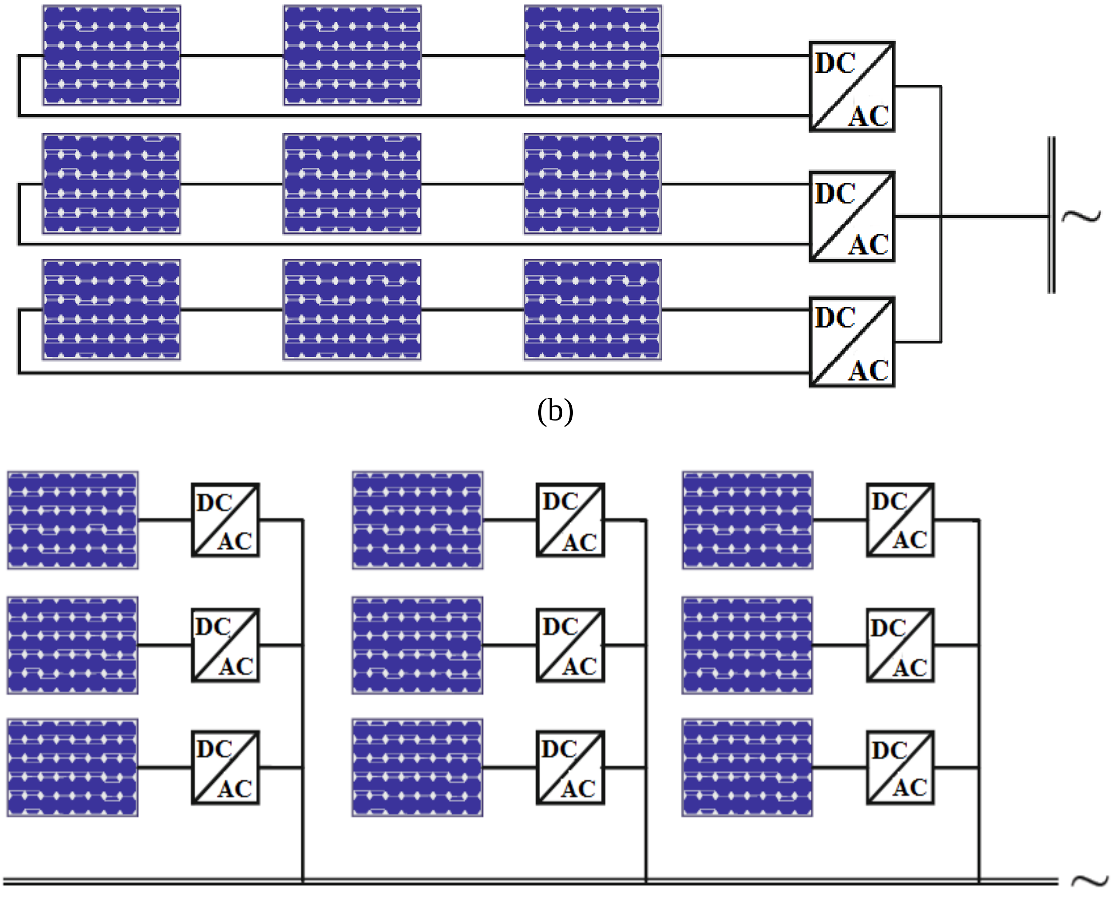
A predetermined power range, specified by the manufacturer, is necessary at the inverter input. If this power exceeds the maximum allowable capacity, the module will only convert and deliver the maximum electrical energy it can generate. On the other hand, in the case when this input power is less than the minimum power, the inverter goes into standby mode and does not generate electrical energy [18]. The Inverters connected to the grid should be [25]:

1. Ensure perfect connection of PV modules to the network,
2. Control the power generated by the PVG by forcing it to operate at the point which provides the maximum power that can be injected into the grid,
3. Ensure permanent protection of the network from failures and stop the system in the event of a sudden accident.

Currently, there are three basic inverter topologies: centralized inverters, string inverters, and integrated inverters.



(a)



(b)

(c)

Figure (IV.12) : Inverter topologies (a) with a centralized inverter (b) with string inverters, (c) with integrated inverters to modules [26].

In the case of a central inverter topology, the PV modules are arranged in "string" chains, and connected in parallel with others using anti-return diodes. As shown in figure (IV.12(a)), this topology requires a single inverter for the whole installation. This topology is especially used in high-power installations (> 0.1 MW). It has economic advantages, but its credibility is limited, especially when an interruption occurs in the central inverter. In the case of a string inverter topology, each string of the PV system is directly connected to its own inverter (Figure (IV.12(b)). This topology avoids low-light issues and allows for increased system reliability. However, the large number of inverters requires additional costs. The string topology is practically convenient and more used for personal installations. As shown in figure (IV.12(c)), in the case of the topology of inverters integrated with modules, each module is equipped with a separate inverter. However, the increase in the number of inverters and connection cables causes additional costs. Usually, this topology is only suitable for low-power systems between 0.05 kW and 0.4 kW [27, 28]. Efficiency for 1500 W to 3000 W power inverters was around 85.5 - 90 % (1988 to 1990) and increased to 90 - 92 % (1995) for inverters with galvanic separation. Inverters of this power without galvanic separation, increase to 92.5 – 94%. Currently, the good efficiency that inverters can achieve is around 98% [25,28]. The inverters guarantee is about ten years.

IV.7 Photovoltaic cables and connectors

Two types of cabling and connectors can be identified in PV installations:

1. DC cables: between the PV modules and the inverters and
2. AC cables: between the inverters and the equipment.

DC cables must mainly meet the electrical requirements of adaptation to the present voltages and currents. In addition, these cables must be designed in such a way that the losses in them are negligible. In addition, the entire installation is established outside, for this the cables and DC connectors need to be sufficiently adapted and resistant to bad weather and external conditions: impermeable to humidity [18].

IV.8 Safety standards

The PV installation must be constructed according to the standards to avoid any risk of damaging the equipment. Some safety procedures and standards should be taken into account [29]:

- Fuses or circuit breakers should be used to protect the cables from excessive currents and overloads in the event of a sudden problem,

- A DC isolation controller is required to protect the PV system from damage.

- Lightning arresters and lightning conductors must be installed to protect metallic elements from overvoltage. In addition, all metallic devices must be connected to the same ground,

- A cut-off mechanism is required in the inverter to avoid any unexpected risks.

- Single conductor cables should be used to reduce the danger of short circuits.

- In a PV installation, the following standards need to be considered: IEC 61215 (design qualification and type approval of crystalline silicon terrestrial PV modules), IEC61646 (design qualification and type approval of thin-film terrestrial PV modules), IEC 61730 (PV module safety qualification), IEC 62108 (design qualification and type approval of PV Concentrators), EN 61000-6 (the immunity and emissivity degrees), and NF EN 50530 (the overall efficiency of grid-connected PV inverters).

IV.9 Example of a photovoltaic application

Photovoltaic energy is possible in several sectors, and we can mention: isolated housing, means of transmission, water analysis, road signs, guidance, search for suspects, urban lighting, etc. [30]. Water pumping is one of the most common solar PV applications. The main components of PV pumping systems are (1) PV panel, (2) panel support, (3) protection box with fuse, (4) inverter, (5) grounding, (6) level detector low water, and (7) submersible pump. The main safety devices that can be found in these pumping systems are: a protection box with a fuse for the main circuit breaker and lightning arrester, a grounding, and a low water level detector (stop the pump if the well is empty) [31]. Figure (IV.13) shows the principle of the photovoltaic pumping system.

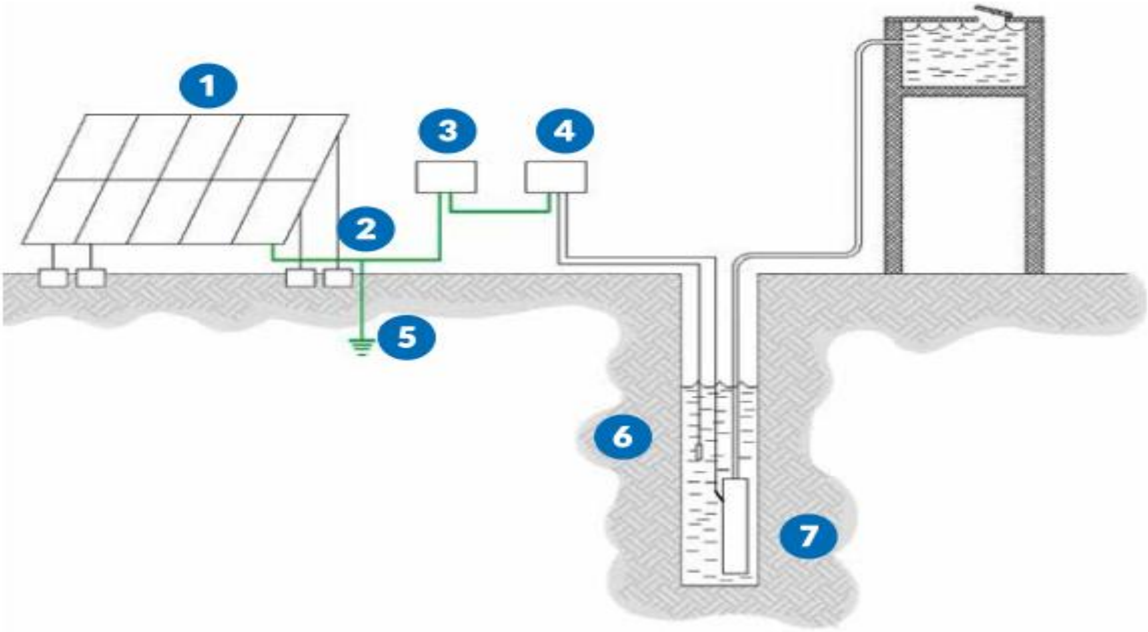


Figure (IV.13) : Operating principle of a PV pumping system [31].

IV.10 Various renewable energies in the world and productivity

During the last decade especially between 2010 and 2020, the use of modern bioenergy for heating increased by about 7% (4.9 EJ) with a contribution of 5.2% for heating buildings worldwide in 2020. While the use of bioenergy for industrial heating increased by 8% to 9.9 EJ between 2015 and 2020. Besides, biofuel production for transportation increased from 2.6 EJ to 4.1 EJ (56%) between 2011 and 2021. Therefore, worldwide biodiesel production almost doubled to 1.5 EJ. Indonesia is currently the world leader in biodiesel production with about 18% of the world total. About 0.3 GW of new geothermal capacity has been connected to the existing grid in 2021, bringing the global total capacity to about 14.5 GW. Until the end of 2021, the first four countries that took part in this extension were the United States, Indonesia, the Philippines and Turkey. In 2021, the PV market continued to reach unprecedented heights, with new installations totaling approximately 0.175 TW, contributing to a global solar PV capacity of 0.942 TW. Notably, the world's top contributors to annual solar PV production are Australia (15.5%), Spain (14.2%), Greece (13.6%), and Honduras (12.9%). About 26 GW of new hydropower capacity was added in 2021, increasing the total installed capacity to about 1.197 MW. The first three countries that participated in this hike were: China, Canada, and India. In 2021, the ocean energy capacity saw a substantial increase of around 4,600 kW, resulting in a total installed capacity of approximately 0.524 GW by the end of the year. The majority of this added capacity can be attributed to two prominent tidal turbines: the La Rance plant in France (0.24 GW) and the Sihwa plant in the Republic of Korea (0.254 GW). Wind power capacity was added to about 0.102 TW to the world's capacity (estimated at about 0.845 TWh) in 2021. Large portions of the additions were consolidated in Asia (61.4%), Europe (15.6%), and North America (13.8%) [32].

In 2022, the global solar power capacity reached 1,185 GW, and wind power capacity reached 0.906 TW. Solar PV constituted the majority of renewable power capacity additions in 2022, making up 70% of the total (0.348 TW). Wind power followed at 77 GW (22%), and hydropower at 22 GW (6.3%). The top contributors to this capacity increase were China, the United States, and India. Solar capacity saw a significant 37% rise in 2022 compared to 2021, led by China at 44%, with the United States and India contributing 8% each. Wind power capacity grew by 77 GW in 2022, a 17% decrease from the prior year, with China and the United States accounting for 47.7% and 15.6%, respectively. In contrast, hydropower capacity additions in 2022 were 22 GW, falling short of the annual 30 GW required to meet environmental goals [33]. In Algeria, the Ministry of Energy Transition and Renewable Energies has planned to achieve starting from 2021 an electricity power of 1 GW, cumulative per year, from renewable sources. This project will increase the new power added to 15 GW by 2035 [34].

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