People's Democratic Republic of Algeria
Ministry of Higher Education and Scientific Research
University Of Mustapha Stambouli Mascara

COURSE OF RENEWABLES ENERGIES

FOR LICENCE STUDENTS (L3) OF :
MECHANICAL ENGINEERING,
OPTION: ENERGETIC

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Preface

Humanity faces unprecedented environmental threats, with pollution, water scarcity, and energy security emerging as existential challenges. These fundamental resources form the cornerstone of civilization, yet their degradation through industrial discharge, transportation emissions, and domestic consumption demands immediate action. The past fifty years have revealed alarming climate instability, with global warming triggering catastrophic weather events - from devastating hurricanes to prolonged droughts - all linked to soaring atmospheric CO_2 levels exceeding 420 ppm. This crisis coincides with the rapid depletion of finite fossil fuel reserves, creating an urgent need for systemic change.

Modern solutions employ a multi-pronged approach combining cutting-edge technology with policy reform. Carbon capture innovations like liquefaction and geological sequestration now mitigate industrial emissions, while carbon taxation schemes create economic incentives for greener practices. Most crucially, the global energy transition toward renewables - solar, wind, and geothermal - offers sustainable alternatives to dwindling petroleum reserves. This educational program provides comprehensive analysis of renewable systems, examining their operational principles, technological implementations, and environmental benefits through carefully curated data designed for academic engagement. The curriculum equips students with both theoretical knowledge and practical tools to address these pressing ecological challenges.

Introduction

Introduction

For over a century, fossil fuels-comprising oil, natural gas, and coal-have been the cornerstone of the world's energy supply, fueling industrial growth and serving as vital raw materials for numerous industries, including chemicals. Today, they still account for more than 80% of global energy consumption. However, these resources are inherently finite, having formed over millions of years through intricate biological and geological processes. As a result, they are non-renewable within any meaningful human timeframe, posing significant challenges for long-term energy sustainability.

In stark contrast, renewable energy sources such as solar, wind, geothermal, tidal, and biomass offer a transformative path forward. These resources naturally replenish on human timescales, providing a virtually inexhaustible and sustainable supply of clean energy. The accelerating pace of global industrialization-especially in emerging economies-combined with rising energy demands, highlights the urgent need to transition toward these cleaner alternatives to secure a stable and environmentally responsible energy future.

Unlike fossil fuels, which take millions of years to form and release significant greenhouse gases when burned, renewable energy sources offer a cleaner, more sustainable means of power generation with minimal emissions and reduced ecological impact. For example, solar energy harnesses sunlight through photovoltaic panels, wind energy converts kinetic air flow into electricity via turbines, and hydroelectric power utilizes flowing water to generate electrical energy. Geothermal energy taps into the Earth's internal heat, while biomass converts organic materials into fuel, and ocean energy exploits tidal and wave movements

Beyond their environmental benefits, renewable energy technologies are becoming increasingly cost-competitive as innovation advances and economies of scale improve. They play a critical role in reducing greenhouse gas emissions, mitigating climate change, and avoiding the environmental hazards linked to fossil fuels and nuclear waste. Among them, solar energy stands out as the most abundant and accessible resource, capable of meeting a substantial portion of global energy needs with minimal operational costs and no resource depletion concerns.

The transition to renewable energy is driven by multiple factors: the finite nature of fossil fuels, the urgent need to reduce carbon emissions, technological advancements that lower costs, and the socio-economic benefits of energy independence and job creation in clean energy sectors. As renewable technologies mature and scale, they are becoming increasingly cost-competitive and integral to modern energy systems worldwide

This academic course on renewable energies will provide an in-depth exploration of the scientific principles, technological innovations, and practical applications of various renewable energy sources. It will cover system design, integration into power grids, energy storage solutions, and policy frameworks that support sustainable energy transitions.

Chapter 1

Solar Astronomy

Chapter 1: Solar Astronomy

1.1.Fundamental Concepts

Renewable energy encompasses naturally replenished power sources that are sustainably available within human timeframes. Unlike finite resources such as fossil fuels (petroleum, coal, natural gas) and nuclear materials (uranium), these energies stem from ongoing celestial and terrestrial processes. Most renewable energy systems are driven by solar radiation, either directly (as in photovoltaics) or indirectly (as seen in wind and hydroelectric power). The main categories of renewable energy include (See Figure 1.1):

- Solar (photovoltaic and thermal)
- Wind energy
- Hydropower
- Marine energy (including tidal and wave)
- Geothermal systems
- Biomass conversion

Technologies developed by humans harness these natural processes, necessitating careful evaluation of environmental impacts, economic feasibility, and geopolitical considerations (Sayigh, 2019; Judge, 2018).

Figure 1.1 *A comparative overview of renewable and non-renewable energy sources. (Bahman Z and M. Patrick, 2021)*

1.2.Comparative Analysis of Renewable Systems

Key Advantages:

- Continuous availability through natural cycles
- Minimal greenhouse gas emissions during operation

- Lower risk of catastrophic failures compared to traditional power plants
- Cost structures primarily influenced by infrastructure rather than fuel
- Easier decommissioning processes

Technical Challenges:

- Intermittent generation capacity (excluding geothermal systems)
- Extensive land use requirements
- Potential environmental trade-offs (e.g., biomass carbon neutrality reliant on regrowth rates)
- Visual impacts on landscapes
- The need for energy storage solutions to match generation with demand

The fluctuating nature of solar and wind resources is increasingly managed through smart grid technologies and hybrid system designs. These advancements, coupled with heightened environmental concerns, suggest that renewable energy will likely form the cornerstone of future global energy systems (Moussa, 2020).

Category of Impact	**Relationship to Conventional Sources**	**Comment**
Exposure to Harmful Chemicals		
Emissions of Hg, Cd, and other toxic elements	Reduced emissions	Emissions reduced by several hundred times
Emissions of particles	Reduced emissions	Much lower emissions
Exposure to Harmful Gases		
CO_2 emissions	Reduced emissions	Major advantage
Acid rain-SO_2, NO_x	Reduced emissions	Reduced by more than 25 times
Other greenhouse gases	Reduced greenhouse gas emissions	Major advantage-mitigates global warming
Other		
Spills of fossil fuels	Total or partial elimination of oil spills	Heavy fuel oil and other petroleum product spills avoided
Water quality	Better water quality	Reduced water pollution
Soil erosion	Smaller loss of land	In most cases, no deep penetration into the earth

Table 1.1 *Summary of environmental impacts (Vezmar et al, 2014)*

1.3.Energy Conversion Classifications

Renewable energy systems transform natural phenomena through four primary mechanisms:

1. Thermodynamic processes (solar thermal, geothermal)
2. Aerodynamic conversion (wind turbines)
3. Hydrodynamic systems (tidal generators, hydroelectric dams)
4. Photonic/radio-dynamic transformation (photovoltaic cells)

1.4.Solar Energy Fundamentals

Solar energy, the most prevalent renewable resource, is converted primarily through two methods:

1. The photovoltaic effect (which generates electricity directly)
2. Thermal absorption (which produces heat)

Solar power systems are remarkably scalable, ranging from residential setups to large utility-scale solar farms. This technology is universally accessible, infinitely renewable, and produces no operational emissions. Notably, solar radiation serves as the primary energy source for most Earth systems, either directly or through intermediary processes like wind and biomass (Green et al., 2021; Smith, 2022).

1.5.Solar Astronomie

1.5.1. Stellar Characteristics

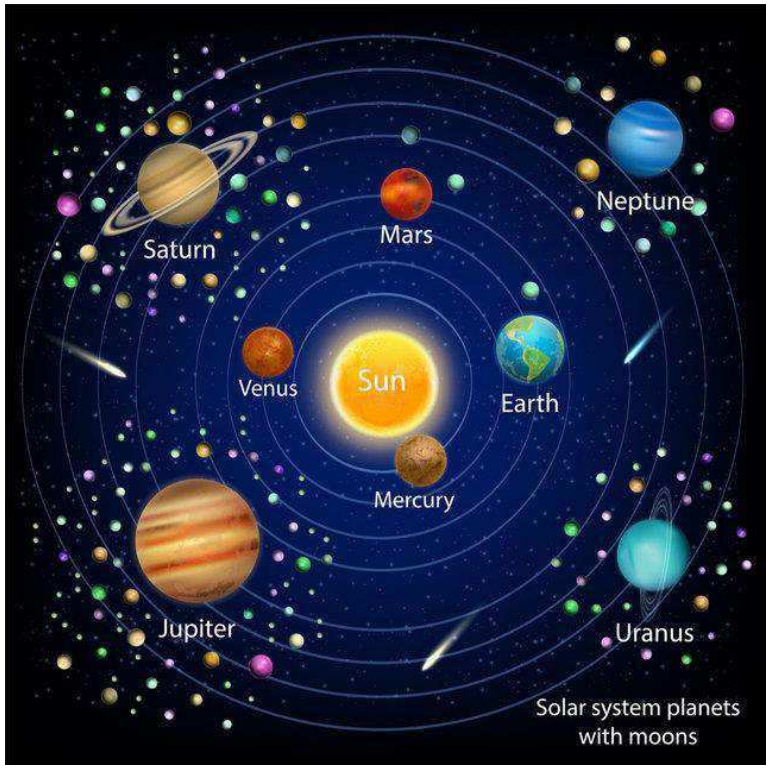

Figure 1.2 *Overview of the solar system (Zitouni et al, 2020)*

The Sun, classified as a G2V star, orbits at an average distance of 1 astronomical unit (149.6 million km) from Earth. Key physical parameters include:

- Diameter: 1.39 million km (equivalent to 109 Earth diameters)

- Mass: 1.99×10^{30} kg (around 333,000 times that of Earth)
- Composition: 73% hydrogen, 25% helium, and 2% heavier elements
- Gravitational influence: 99.86% of the solar system's mass

The Sun's gravitational reach extends roughly 2 light-years (200,000 AU), influencing the orbital mechanics of the entire solar system (Kitchin, 2009).

1.5.2. Atmospheric Dynamics

The Sun's gaseous outer layer exhibits differential rotation, with equatorial regions completing a rotation in 25 days, compared to 35 days at the poles, which confirms its plasma state. This ionized environment generates complex magnetic fields, observable through sunspots and coronal loops.

1.5.3. External structure

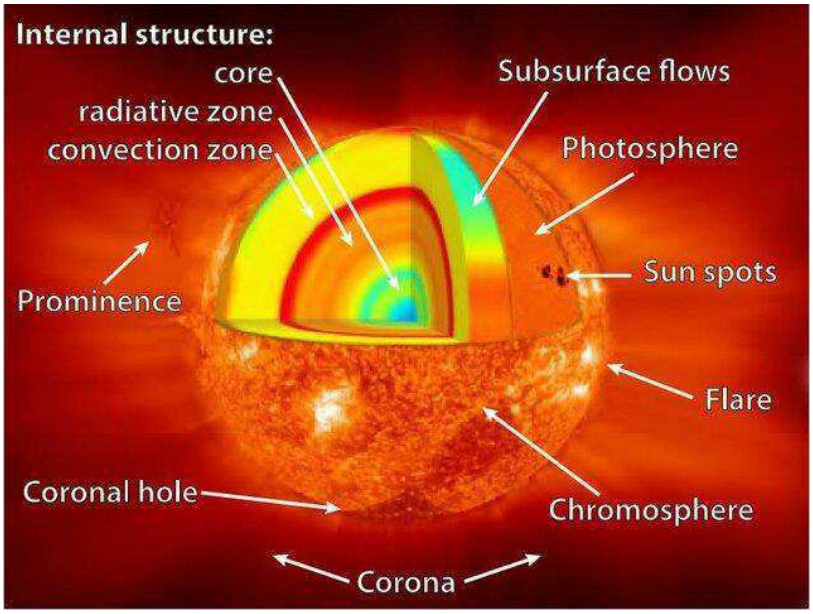

Figure 1.3 *The external structure of the sun (Zulfiqar, 2023)*

The solar atmosphere is divided into three distinct layers:

A. Photosphere (5,700 K):

Figure 1.4 *Photosphere pf the sun (Sundararaman, 2011)*

- The visible surface layer, approximately 300 km deep
- Exhibits a granulated texture due to convection cells
- Contains sunspot regions with temperatures around 4,500 K, indicating magnetic anomalies

B. Chromosphere (10,000 K):

- A transition layer of 2,000-3,000 km in thickness
- Characterized by Hα emission at 656 nm
- Features spicules that extend up to 10,000 km

C. Corona (1-3 million K):

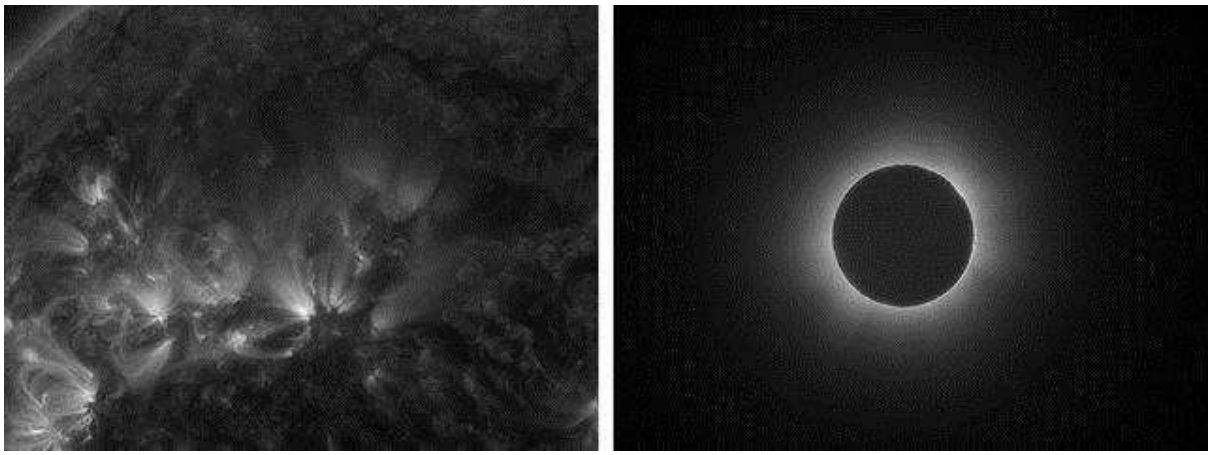

Figure 1.5 *Solar corona (Druckmüller and Druckmüllerová, 2014)*

- An expansive plasma envelope
- The primary source of X-ray emissions
- Visible during total solar eclipses

1.5.4. Internal structure

Models of the solar interior reveal three concentric zones:

i. Core (0-0.3 R⊙):

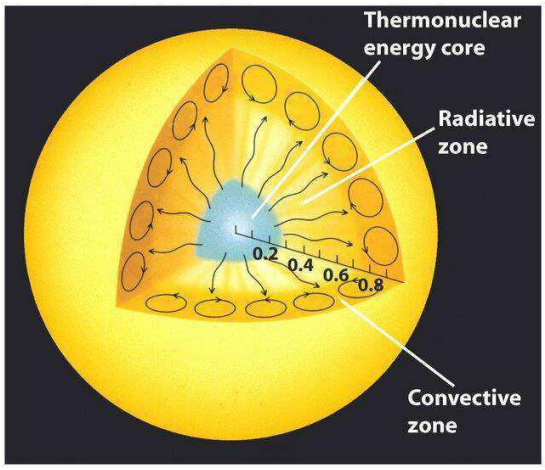

Figure 1.6 *The three inner layers of the sun (Whitbread, 2016)*

- A plasma region with temperatures reaching 15 million K
- Site of proton-proton chain fusion reactions

- Primary energy generation zone

ii. Radiative Zone (0.3-0.7 R⊙):

- Region where photon diffusion occurs
- Energy takes about 200,000 years to traverse this zone
- Temperature gradient from 7 million K to 1 million K

iii. Convective Zone (0.7-1 R⊙):

- Characterized by turbulent plasma circulation
- Energy is transported to the surface within about two months
- Responsible for the granulation seen in the photosphere

1.5.5. Solar energy

The solar constant, measuring 1,360 W/m² at 1 AU, results in:

- Total luminosity of 3.826×10^{26} W
- Annual energy output estimated at 1.2×10^{34} J

1.5.6. Magnetic Activity Cycle

The frequency of sunspots follows an 11-year cycle, reflecting reversals in magnetic polarity. This activity results from the distortion of internal magnetic fields due to differential rotation, with historical minima such as the Maunder Minimum indicating variability in these cycles (Kitchin, 2009).

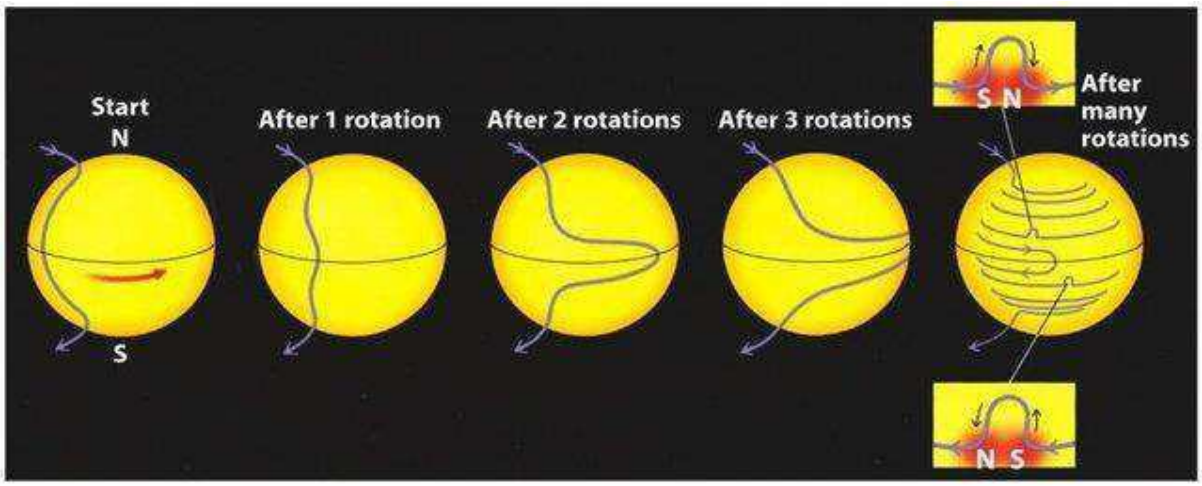

Figure 1.7 *The differential rotation of the Sun is responsible for the deformation of the magnetic field (Hamouda, 2018)*

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Chapter 2

Algerian Solar Potential

Chapter 2: Algerian Solar Potential

2.1.Introduction

Algeria is home to one of the most significant renewable energy potentials globally. While the country is rich in fossil fuels, boasting the tenth largest natural gas reserves and the third largest oil reserves in Africa, its energy future appears secure (British Petroleum [BP], 2022). The solar energy potential, characterized by its renewability, environmental cleanliness, and widespread availability, is particularly evident in the vast expanse of the Sahara, as illustrated in Figure 2.1 (D Mohamed Ali, 2012). The solar energy potential is influenced by various factors, including the criteria for equipment installation. Annually, Algeria enjoys some of the world's highest sunshine durations, often exceeding 2,000 hours and potentially reaching up to 3,900 hours in the Highlands and Sahara regions (National Renewable Energy Development Center [CDER], 2021). For instance, a photovoltaic system with a capacity of 5 kWp powers the reference measurement station of the Global Atmospheric Watch program at the Assekrem site in Tamanrasset province (World Meteorological Organization [WMO], 2019).

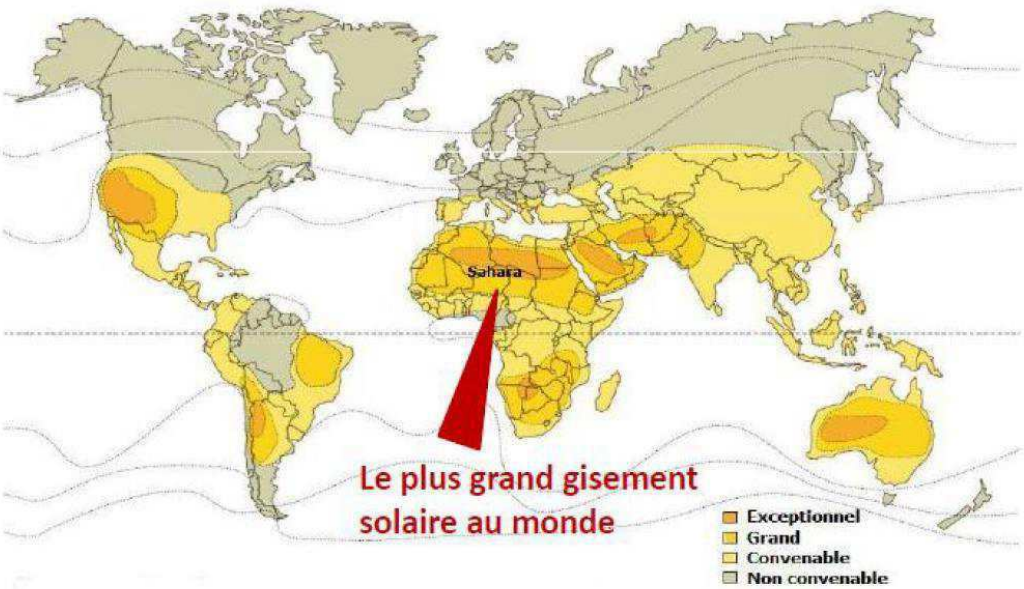

Figure 2.1. *Global solar potential (*D Mohamed Ali, 2012)

2.2.Solar Potential

2.2.1. Concept of Solar Potential

A defining feature of solar energy is its capacity for sustainable extraction. The sun continuously provides energy to Earth (Kalogirou, 2014). Consequently, solar potential is virtually limitless and remains consistent over specific periods and locations. However, solar energy potential can fluctuate based on geographical factors (land availability for solar installations), technological advancements (innovative conversion methods), economic conditions (cost fluctuations), and regulatory constraints (national energy policies) (International Energy Agency [IEA], 2021). Additionally, solar energy is

classified as an intermittent energy source due to its varied spatial and temporal distribution, unlike fossil fuels or freshwater reservoirs, which can more effectively balance supply and demand (Jacobson, 2009). Both solar and fossil fuel sources share a common limitation: not all available energy can be harvested or utilized. Solar potential can be categorized into three distinct values:

- **Potential Energy**: This reflects the raw energy from the solar source (e.g., solar irradiation at a specific location) (Duffie & Beckman, 2013).
- **Theoretical Energy**: This represents the portion of energy that can be captured by the conversion system (e.g., solar radiation absorbed by a defined area of solar panels) (Goswami et al., 2015).
- **Exploitable Energy**: This is the portion of energy that can be realistically utilized, factoring in legal, environmental, and economic considerations (IRENA, 2020).

The Sahara Desert accounts for approximately 87% of Algeria's land area, spanning latitudes 20° N to 34° N (National Office of Statistics [ONS], 2022). This geographical feature grants Algeria one of the highest solar potentials in the world, with annual sunlight hours exceeding 2,000 and potentially reaching 3,900. Daily solar energy received on a horizontal surface of 1 m² is roughly 5 kWh across much of the country, with about 1,700 kWh/m²/year recorded in the northern regions and approximately 2,263 kWh/m²/year in the south (CDER, 2021). Table 2.1 presents the distribution of solar potential across Algeria's climatic regions based on annual sunshine.

Areas	**Coastal Area**	**High Plains**	**Sahara**
Surface (%)	4	10	86
Area (km²)	95,270	238,174	2,048,297
Mean Daily Sunshine Duration (h)	7.26	8.22	9.59
Average Duration of Sunshine (h/year)	2,650	3,000	3,500
Received Average Energy (kWh/m²/year)	1,700	1,900	2,650
Solar Daily Energy Density (kWh/m²)	4.66	5.21	7.26
Potential Daily Energy (TWh)	443.96	1,240.89	14,870.63

Table 2.1 *Repartition of solar potential in Algeria (Chabani et al, 2021)*

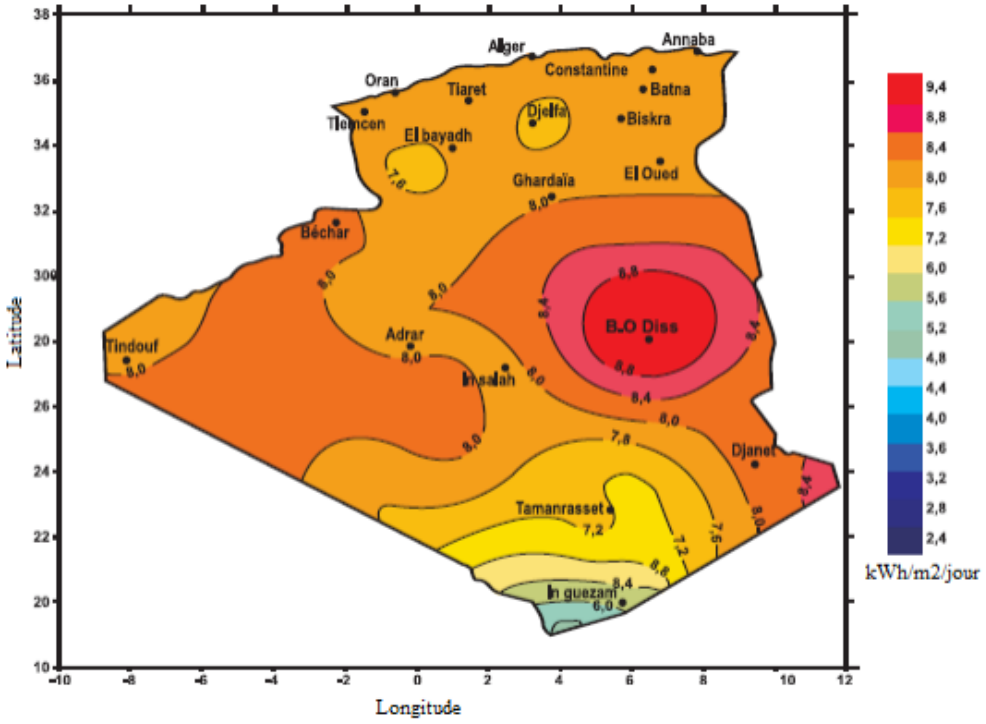

Figure 2.2 *Daily global irradiation that received from horizontal plan for month of December (Dahmani, 2015)*

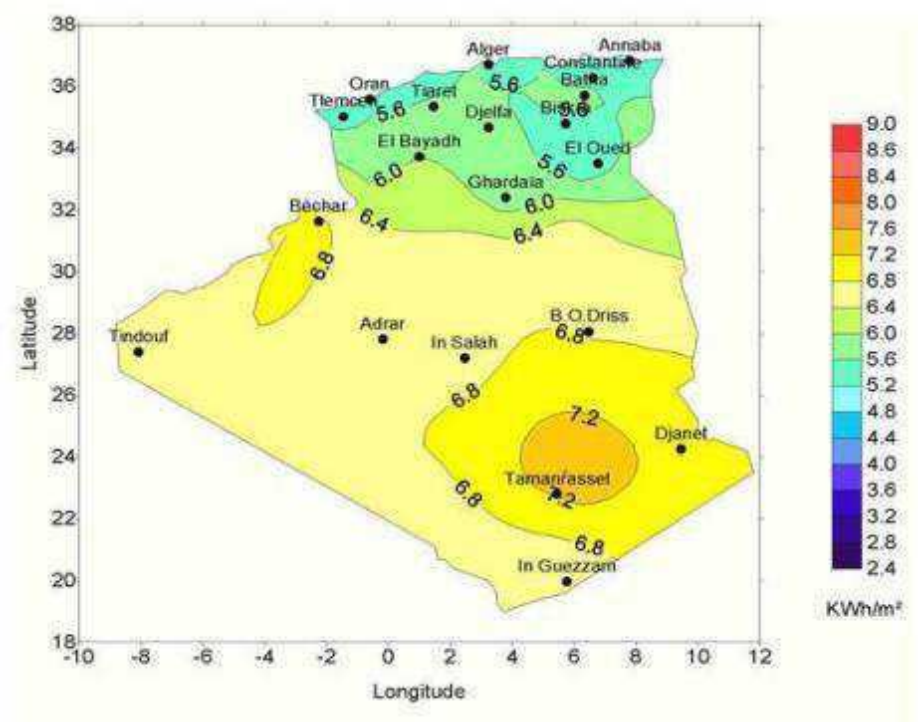

Figure 2.3 *Annual average of energy received in Algeria (Rahmane et al, 2019)*

2.2.2. Measurements of Solar Radiation in Algeria

2.3. Solar Radiation

Solar radiation, which is electromagnetic energy produced by thermonuclear reactions in the sun, closely resembles the energy emitted by a black body at slightly below 5800 Kelvin (Kalogirou, 2014). Despite the vast distance from the sun, this radiation significantly impacts Earth, with an estimated 178 x 10^15

watts of power intercepted by the illuminated half of the planet. However, this distribution is neither geographically nor temporally uniform (IEA, 2021).

2.3.1. Components of Solar Radiation

The solar radiation that reaches us is emitted from the sun's outer layer, which is approximately 6000 K. At this temperature, around 40% of the energy falls within the visible spectrum, with wavelengths ranging from 0.3 µm (violet-blue) to 0.7 µm (red) (Duffie & Beckman, 2013). By directing a beam of light through a glass prism or diffraction grating, a spectrum of colors emerges, spanning from blue to red, including green and yellow. Each color corresponds to a specific wavelength. In the early 1800s, William Herschel discovered that the temperature behind the prism increased not only in the visible spectrum but also beyond the red, leading to the identification of infrared radiation, which constitutes about 50% of the sun's emitted energy. The remaining 10% is emitted as ultraviolet radiation, with wavelengths shorter than those of violet (Goswami et al., 2015).

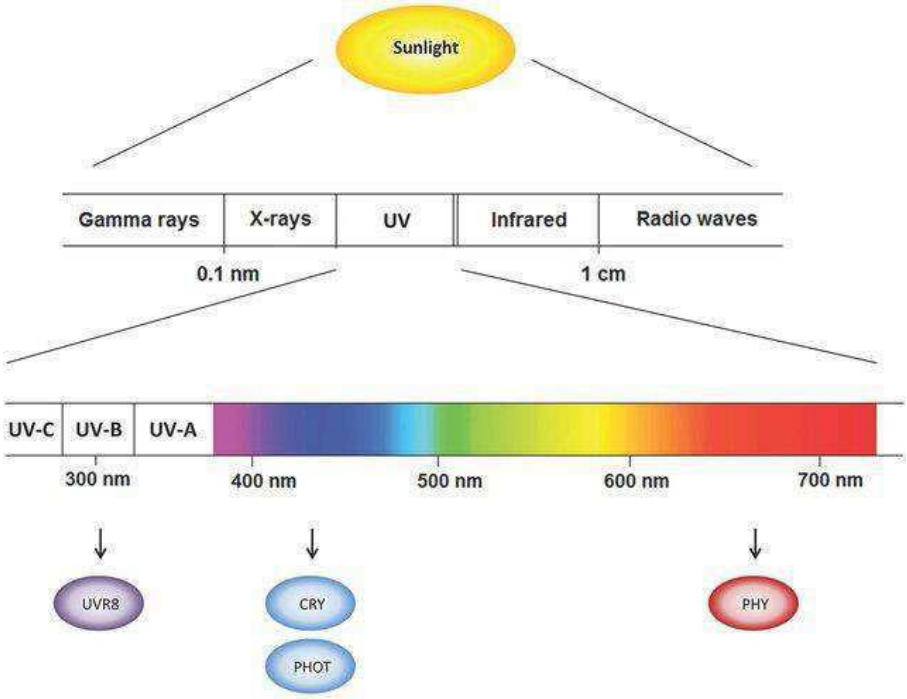

Figure 2.4 *Distribution of solar radiation (Zoratti et al, 2014)*

Solar energy comprises two components: extraterrestrial solar energy, which refers to energy outside the atmosphere, and global solar energy, which pertains to the energy available beneath the Earth's atmosphere. The latter includes a direct component, a diffuse component, and albedo (the reflection of rays by surfaces, including land and water), as illustrated in Figure 2.5. As solar radiation traverses the atmosphere, it is partially absorbed, scattered, and reflected by molecules, aerosols, water vapor, and clouds (diffused radiation). The energy that reaches the Earth's surface directly is termed direct solar radiation, while the total solar energy intercepted on the ground is referred to as global solar radiation (Kalogirou, 2014). Therefore:

- **Direct Radiation**: This is the unaltered radiation that passes through the atmosphere.

- **Diffuse Radiation**: This portion of solar radiation is scattered by atmospheric elements (air, aerosols).
- **Albedo Radiation**: This is the radiation reflected by the ground, which varies based on the site's environment and must be considered when assessing radiation on inclined surfaces. Thus, global radiation can be defined as follows:

$$P_{glo} = P_{dir} + P_{diffus} + P_{albedo} \quad \text{(eq. 2.1)}$$

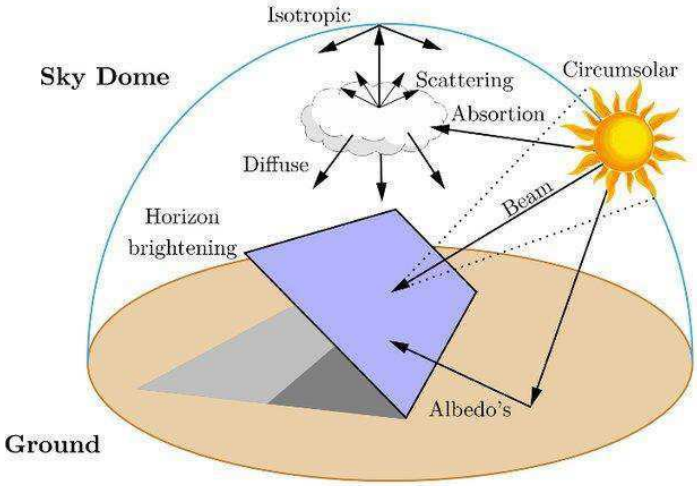

Figure 2.5 *The components of global solar radiation (de Simón-Martín et al, 2016)*

2.3.2. Instruments for Measuring Solar Radiation

To measure direct solar radiation, a pyrheliometer is utilized (Figure 2.6.d). The sensor's receiving surface must always face directly towards the sun, necessitating that the pyrheliometer is often mounted on a dual-axis sun-tracking system (Vignola et al., 2012). The pyrheliometer consists of a multi-junction thermopile located at the bottom of a collimation tube, with a black-painted detector that absorbs solar energy across wavelengths from 0.28 µm to 3 µm. An aperture ensures that only direct solar radiation is measured, typically within an angle of 2.5° to 5° around the sun, known as the circumsolar area (IEA, 2021).

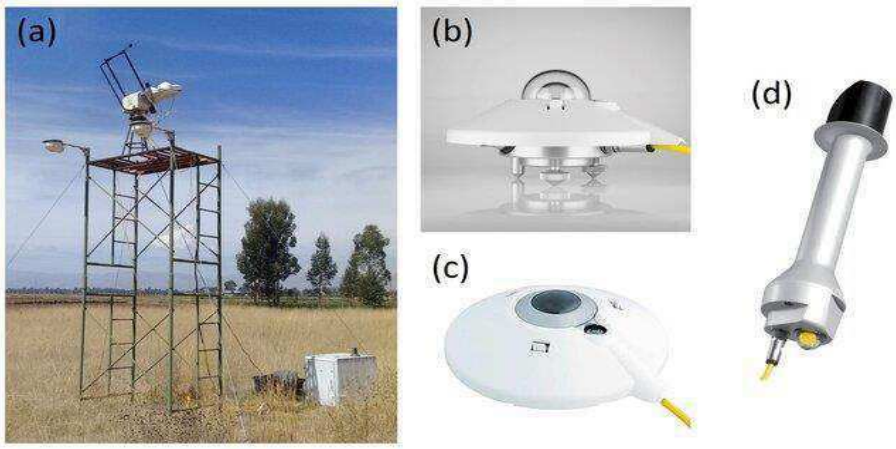

Figure 2.6 *Radiometric measuring instruments of pyrheliometer, pyranometer with shading (Flores-Rojas et al, 2019)*

To measure global solar radiation, a pyranometer is employed, which detects radiation across wavelengths ranging from 300 to 3000 nm. Its sensor comprises a horizontal radiation detector that collects solar energy from the entire sky (covering a solid angle of 2π sr) and converts this energy into heat. The measurement of this thermal energy allows for the calculation of global solar radiation. Pyranometers are equipped with a white disk to restrict the incidence angle to 360° and are protected by two transparent hemispherical glass covers to guard against thermal convection and external factors such as rain, wind, and dust. Modern pyranometers are typically thermopile types, sharing a similar structural design to thermoelectric pyrheliometers (Duffie & Beckman, 2013).

A pyranometer can also measure diffuse solar radiation by eliminating the direct component of solar flux. This can be achieved by placing a small shading disk on an automated sun-tracking system, ensuring the pyranometer remains shaded (Figure 2.6.b and c). Alternatively, a shading ring can be utilized to block the direct radiation throughout the day (Figure 2.6.a) (Vignola et al., 2012).

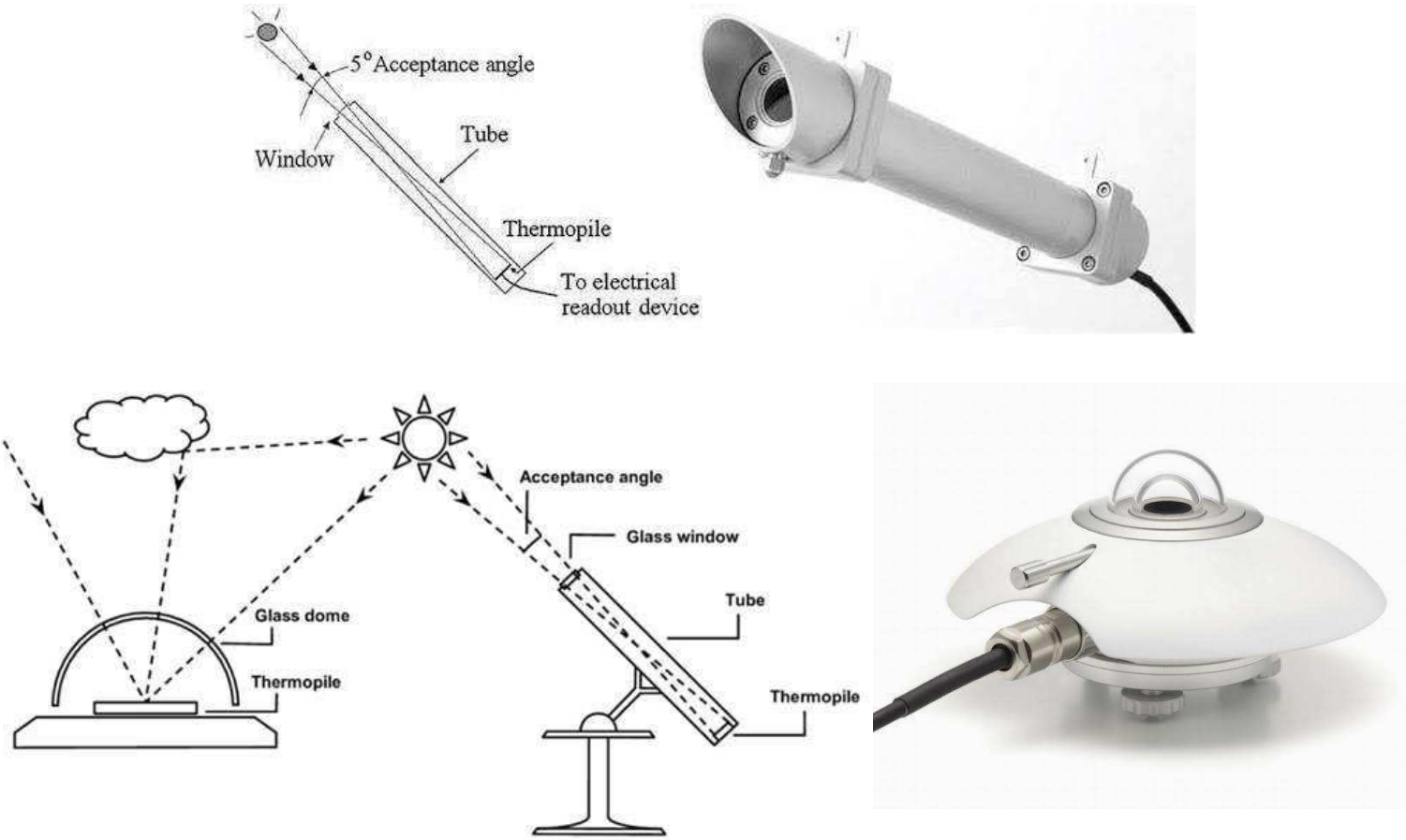

Figure 2.7 *Principe de captation des rayons solaire par pyrhéliomètre et pyranomètre (Widén, J. and Munkhammar, J., 2019)*

2.4.Climate Needs

In regions above the 39th latitude, air conditioning becomes less critical. Algeria, situated at a latitude of 36° N, experiences a predominantly hot climate for much of the year, oscillating between humid and dry conditions (National Meteorological Office [ONM], 2022). This climate presents challenges in maintaining indoor temperatures suitable for human activities. Consequently, air conditioning is recommended in areas where the average daily temperature surpasses comfort thresholds, which applies

to various climatic zones in Algeria. Figure 2.8 illustrates the four climatic zones and their sub-zones, including the Chlef region, where daily temperatures often exceed 30°C during hot periods. Table 2.2 provides baseline values that are useful for designing air conditioning systems.

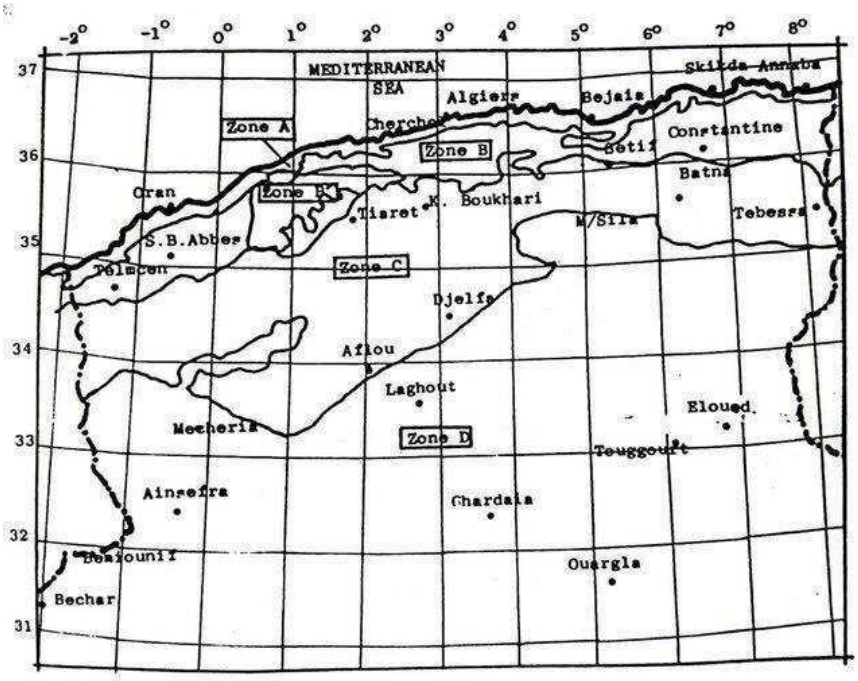

Figure 2.8 *The four climatic zones in Algeria (Abada et al, 2021)*

Climatic Zones	Base Conditions: Summer	Temperature t_B (°C)	Diurnal Variation (°C)	Relative Humidity Φ_B (%)
Zone A	<500 m	34	9	44
	500 m to 1000 m	33.5	10	40
	>1000 m	30.5	9	47
Zone B	<500 m	38	15	30
	500 m to 1000 m	37	15	28
	>1000 m	35	14	28
Sub-zone B'	Entirely >500 m	41	18	41
Zone C	500 m to 1000 m	39.5	20	22
	>1000 m	36	18	25
Zone D	<500 m	45	20	11
	500 m to 1000 m	42	18	13
	>1000 m	37.5	16	17

Table 2.2 *External basic conditions for calculating air conditioning installations in Algeria*

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Chapter 3

Thermal Conversion of Solar Energy

Chapter 3: Thermal Conversion of Solar Energy

3.1.Introduction

Active technologies transform solar energy into electrical or thermal forms that we can use directly. This includes photovoltaic cells that convert sunlight directly into electricity, solar collectors that heat water for homes, solar heating and cooling systems, solar concentrators that use mirrors to focus sunlight and generate intense heat turning water into steam to produce electricity and even solar ovens. Passive technologies involve properly orienting buildings to the sun or using special materials and architectural designs to effectively harness solar energy (Li et al., 2019).

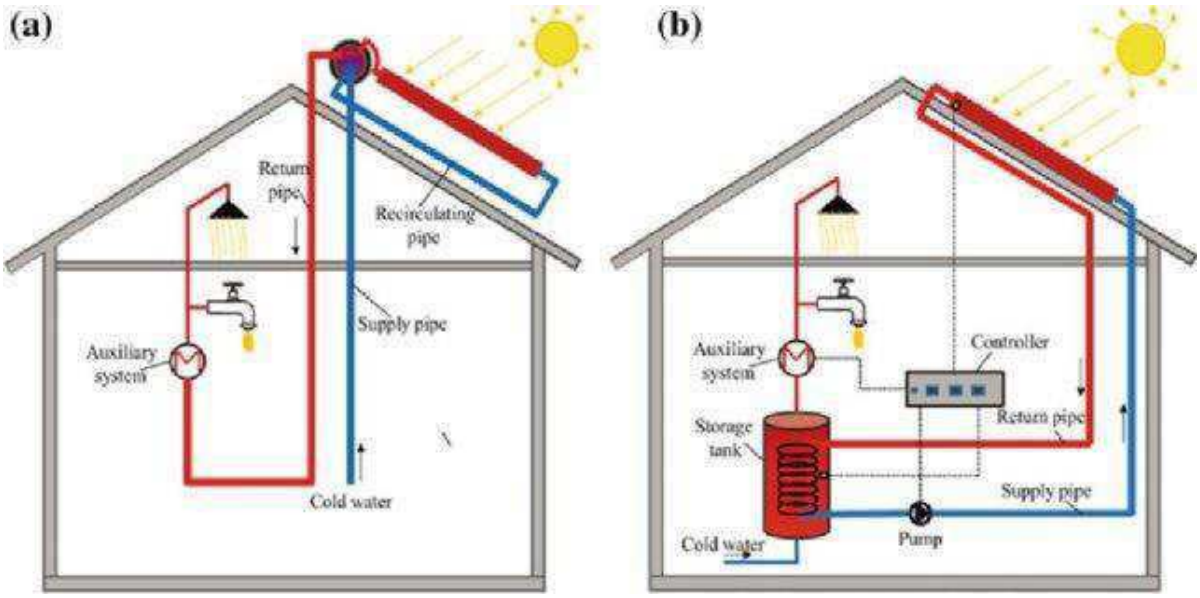


Figure 3.1 *Passive (a) and active (b) technologies of solar thermal energy (*Li, B., Chen et al, 2029)

3.2.Thermal Conversion

Solar thermal energy is a process that transforms solar energy into a thermal form that can be utilized in two ways (Kunelbayev et al., 2024):

- Direct heat usage: solar water heaters, solar heating systems, solar cookers, and solar dryers.
- Indirect usage: where heat serves another purpose, such as in solar thermodynamic power plants and solar cooling.

3.3.Solar Collectors

Solar thermal collectors are devices that capture and absorb solar radiation, transforming it into heat, which is then transmitted to a heat transfer fluid (water, air or oil) circulating within these devices (Ndiaye, 2018). The thermal energy can be stored or used directly. Solar thermal collectors are classified based on several criteria, such as the type of heat transfer fluid used and its temperature.

3.3.1. Flat Plate Collectors

Flat plate collectors consist of an insulated box with a glass or plastic cover (Kunelbayev et al., 2024). Inside, a black metal sheet absorbs the sun's heat trapped within the box. This heat is transmitted to air, water, or any other non-freezing heat transfer fluid. The fluid circulates freely or through pipes to the point of use. The temperature rise compared to ambient air can reach +70 °C.

There are two types of flat plate collectors based on the transfer medium: liquid (water or oil mixture) or air (mainly for space heating or drying).

3.3.1.1.Glazed Flat Plate Collector

A glazed flat plate collector typically consists of absorbing material plates and flat glazing. Inside the absorber, tubes or passages allow the fluid to circulate, carrying heat away from the absorber.

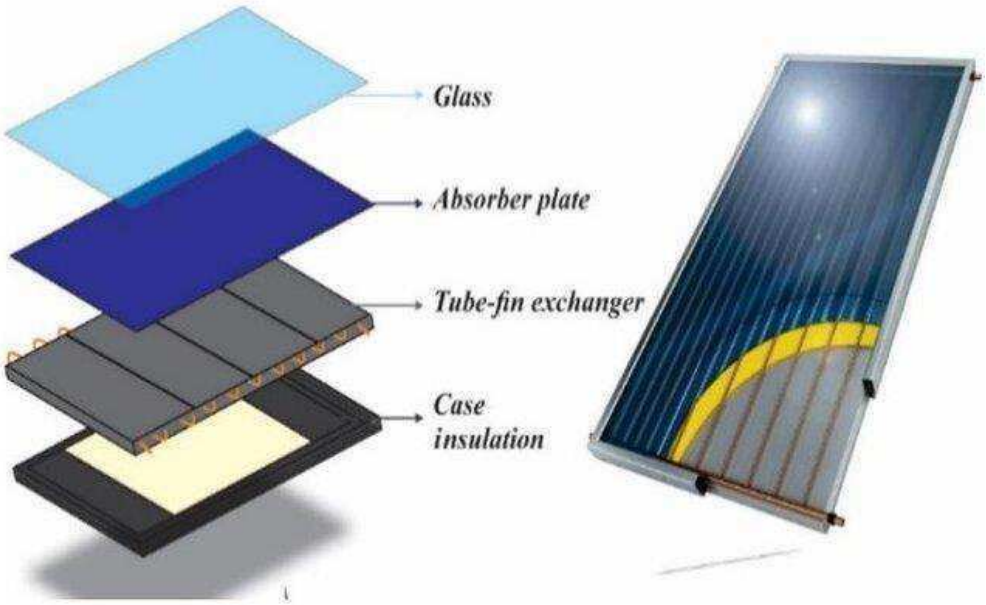


Figure 3.2 *Composition and operation of the flat-glazed solar collector (Kunelbayev et al, 2024)*

These collectors are recommended for service temperature ranges of 30 to 80 °C (Kunelbayev et al., 2024). The heat transfer fluid, often a mixture of water and food-grade antifreeze (such as propylene glycol), flows through a coil attached to the underside of an absorbing sheet, all placed behind a glass cover in an insulated box made of mineral wool or polyurethane foam. The glass is transparent to sunlight but opaque to infrared radiation from inside, trapping heat.

The popularity of these collectors stems from their:

- Robustness and simple structure.
- Technical sophistication (quality of glass, insulation).
- Unmatched cost-performance ratio.
- Easy integration due to their flat surface.
- Discreet appearance when mounted on roofs.

Components of the Glazed Flat Plate Collector:

a. The Absorber

The part of the collector that receives solar radiation is called the absorber. It is usually dark-colored, often black. This black metal sheet captures solar heat, ensuring two functions: absorbing the maximum possible solar radiation and transmitting the produced heat to the heat transfer fluid with minimal losses. The absorber must have the following characteristics: a good absorption coefficient, good thermal conductivity, and good corrosion resistance. The choice of material and construction method greatly influences the quality of the collector. Due to their high conductivities, absorbers are typically made of copper, steel, or aluminum (Kunelbayev et al., 2024).

Material	Conductivity (W/m °C)	Expansion Coefficient
Aluminium	230	2.38
Copper	380	1.65
Zinc	112	2.9
Steel	52	1.15
Stainless Steel	52	1.15
Plastic	0.2–0.4	7–20

Table 3.1 *Characteristics of Materials Used as Absorbers*

To reduce losses due to radiation, absorbers are often coated with a selective layer. For most collectors, the selective coating is made from nickel and chrome. The most common coating methods are shown in Table 3.2.

Coating	Absorption	Emission
Black paint	0.92–0.97	0.95
Black chrome on copper (selective)	0.95	0.14
Black chrome on steel (selective)	0.91	0.07
Tinox (selective)	0.95	0.05

Table 3.2 *Absorber Surface Coatings*

b. Glazing (The Transparent Cover)

This cover is primarily made of tempered glass with high light transmission and resistance to mechanical shocks (hail, snow) and thermal shocks (sudden cooling during storms). This glass is preferably low in iron oxide, making it very transparent to incoming solar radiation.

c. Thermal Insulation (Back and Side)

Insulating materials used in collector construction are either mineral wools or synthetic materials. The insulation must be decay-resistant and able to withstand high temperatures inside the collector. The properties of the most commonly used insulators are listed in Table 3.3.

Insulation Material	Thermal Conductivity at 500 W/m °C max	Maximum Temperature (°C)
Glass wool	0.041	150
Rock wool	0.05	150
Polyurethane	0.027	110
Polystyrene	0.039	85
Expanded cork	0.042	110

Table 3.3 *Properties of the Most Commonly Used Insulators*

d. The Frame (Collector Box)

The frame must withstand external conditions, internal stresses, and potential impacts during transport and installation. Therefore, it must be sturdy yet as lightweight as possible. The collector frame is made from aluminum or steel.

e. Heat Transfer Fluid Entry

The cold heat transfer fluid flows through the circulation tubes to absorb the solar energy trapped in the collector.

f. Heat Transfer Fluid Exit

The heat transfer fluid exits the collector at a high temperature (up to about 80 °C) and is either stored or used immediately (Kunelbayev et al., 2024).

3.3.1.2.Unglazed Flat Plate Collector

Unglazed flat plate collectors are typically made from black plastic that has been stabilized to resist ultraviolet rays. Since these collectors lack glazing, a significant portion of the solar energy is absorbed. However, because they are not insulated, much of the absorbed heat is lost when wind blows or when the outside temperature is not sufficiently warm (Ndiaye, 2018).

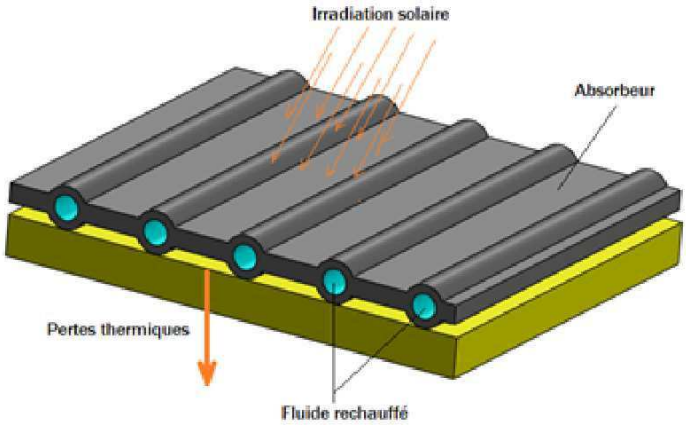


Figure 3.3 *Composition and operation of the unglazed flat panel collector (Ndiaye, 2018)*

Components of the Unglazed Flat Plate Collector

These collectors consist of a bare, uninsulated, and unglazed absorber. Commonly used materials include synthetic materials like high-density polyethylene. These plastics allow for direct water circulation from pools through the collectors. The collector operates at temperatures close to ambient temperature. Stainless steel absorbers with selective coatings are also used today for heating water and preheating domestic hot water.

3.3.2. Vacuum Tube Collector

Also known as vacuum tube collectors, these are glazed collectors containing rows of glass tubes connected to a collector tube. Each tube contains an absorber, usually made from a thin strip of metal or glass covered with a selective coating. The characteristics of these collectors provide good performance at high temperatures (above 70 °C), making them suitable for applications requiring high operating temperatures, such as industrial hot water production (Bist & Sircar, 2021).

The heat transfer fluid circulates inside a simple or double vacuum tube. The vacuum improves insulation against convection losses compared to the previous collector type. Two principles are encountered: the first is the same as for glazed flat plate collectors, where the heat transfer fluid travels back and forth through the tube to collect heat; the second, more technologically advanced, employs a heat pipe using a second heat transfer fluid remaining in the tube. Flat plate collectors are effective in well-sunlit regions, while vacuum tube technology is recommended for cold countries with low sunlight during winter (Alghoul et al., 2005).

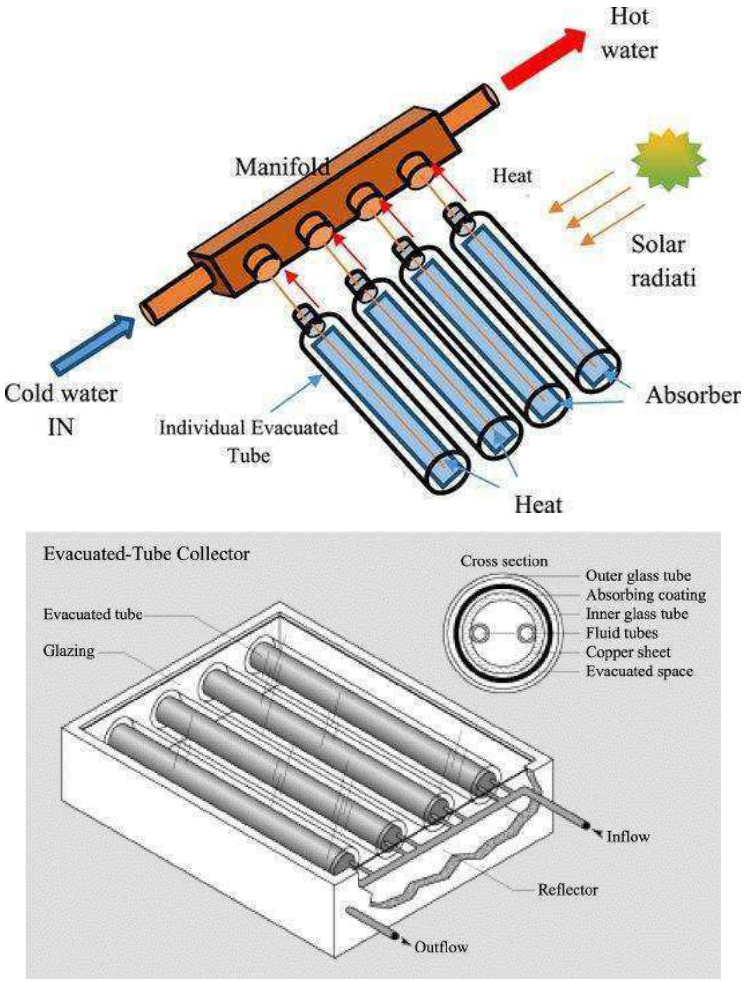


Figure 3.4 *Evacuated Tube Collector (Bist, N. and Sircar, A., 2021)*

Components of the Vacuum Tube Collector

These collectors consist of several glass tubes containing the absorbers, which are then connected in series The air vacuum in the tubes reduces losses due to convection and conduction. Otherwise, such a collector functions like a flat plate collector (Supankanok et al., 2021).

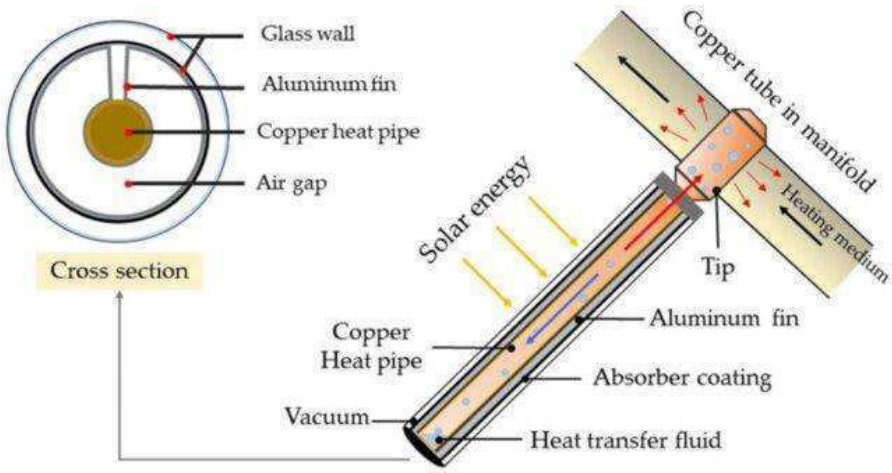


Figure 3.5 *Components and working principle of the solar vacuum tube (Supankanok et al, 2021)*

3.3.3. Thermal efficiency

a. Useful Flow Calculation

The useful energy extracted from the collector by the heat transfer fluid is calculated as follows:

$$Q_u = Q_{ab} - (Q_c + Q_r + Q_d) \quad \text{(eq. 3.1)}$$

- Q_u: Represents the actually usable energy.
- Q_{ab}: The energy absorbed by the absorber [W/m²].
- Q_c: The energy lost by convection between the absorber and the air in the collector [W/m²].
- Q_d: The energy lost by conduction through the insulation [W/m²].
- Q_r: The energy lost by radiation between the absorber and the glass [W/m²].

b. Evaluation of the Water Outlet Temperature Ts

For a flat plate collector, the outlet temperature of the water can be calculated by:

$$T_s = T_e + \left(\frac{Q_u}{\dot{m} * C_p}\right) \quad \text{(eq. 3.2)}$$

$$Q_u = \dot{m} * C_p * (T_s - T_s) = Q_{ab} - (Q_c + Q_r + Q_d) \quad \text{(eq. 3.3)}$$

- Te: Outlet water temperature [°C].
- ṁ: Water flow rate [kg/s].
- Cp: Specific heat of water [J/kg·°C].

c. Calculation of Instantaneous Efficiency η

The efficiency of a solar collector, denoted by η, is the ratio of the heat stored by the heat transfer fluid to the incident power received from solar radiation G (i, y):

$$\eta = \frac{\mathrm{Qu_u}}{G_{(i,y)}} \quad \text{(eq. 3.4)}$$

The radiation from a collector decreases throughout the day because its losses depend on the temperature difference between the ambient air and the absorber; the greater this temperature difference, the lower the efficiency of the collector.

Thus:

$$\eta = \frac{m^* * C_p * (T_s - T_e)}{G_{(i,\gamma)}} \quad \text{(eq. 3.5)}$$

Where G (i, y) is the global incident irradiance on the collector [W/m²].

3.4. Solar Concentration

The phenomenon of solar concentration depends on collecting solar rays at a point, line, or miniature surface compared to the reflective surface (Thakkar et al., 2015).

3.4.1. Parabola

A parabola is defined as a flat curve where each point is equidistant from a fixed point (the focus F) and a fixed line (the directrix D). Notably, FR equals RD. The line perpendicular to the directrix and

passing through the focus F is called the axis of the parabola. The vertex of the parabola, located on the axis, is midway between the focus F and the directrix D.

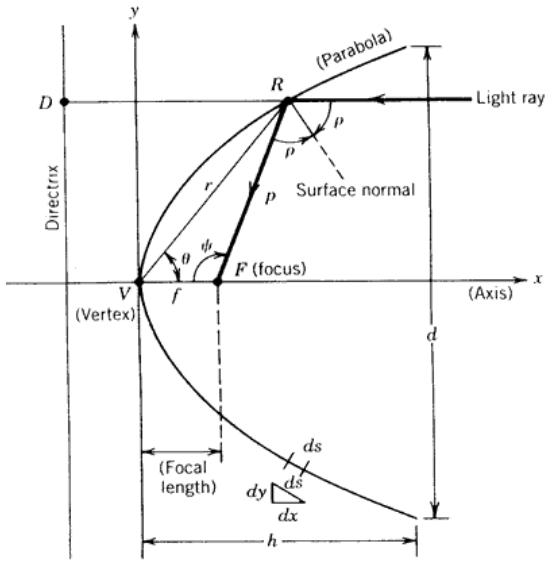


Figure 3.6 *Descriptive Diagram of Parabolic Physics (Thakkar et al, 2015)*

When the origin of the coordinate system coincides with the vertex of the parabola and (x'x) is the axis of the parabola, the equation of the parabola in Cartesian coordinates is:

$$y^2 = 4fx \qquad \text{(eq. 3.6)}$$

Focal distance f = VF.

In polar coordinates, where r is the radius, the vertex of the parabola coincides with the origin and is symmetric about the axis (x'x):

$$\frac{\sin^2\theta}{\cos\theta} = \frac{4f}{r} \qquad \text{(eq. 3.7)}$$

In practice, the parabola is studied in polar coordinates by choosing the origin at the focus F and measuring an angle Ψ between the line (VF) and the radius p of the parabola:

$$p = \frac{2f}{\cos\psi} \qquad \text{(eq. 3.8)}$$

Often used as a concentrator, the parabola has the property of converging all rays parallel to the focus. It can be shown that:

$$\psi = 2\rho \qquad \text{(eq. 3.9)}$$

In solar energy, the parabola used has limitations; thus, it can be described in terms of the "rim angle" and the ratio of the focal distance to the opening diameter (f/d).

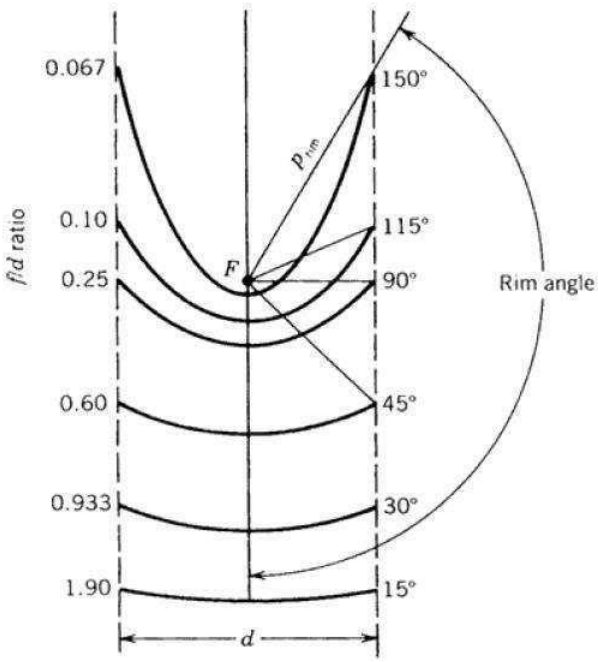


Figure 3.7 *Parabolic Segments with Identical Focal Points and Aperture Diameters (Thakkar et al, 2015)*

The height h can be defined as the maximum distance from the vertex of the parabola to a line drawn through the opening:

$$h = \frac{d^2}{16f} \qquad \text{(eq. 3.10)}$$

The opening angle can be determined from the dimensions of the parabola:

$$\tan \Psi_{\text{rim}} = \frac{1}{\left(\frac{d}{ah}\right) - \left(\frac{2h}{d}\right)} \qquad \text{(eq. 3. 11)}$$

The length of the arc s of the parabola can be determined for the specific case defined by x = h and y = d/2 by integrating the equation:

$$s = \left[\frac{d}{2}\sqrt{\left(\frac{4h}{d}\right)^2 + 1}\right] + 2f\ln\left[\frac{4h}{d} + \sqrt{\left(\frac{4h}{d}\right)^2 + 1}\right] \qquad \text{(eq. 3.12)}$$

Where d is the opening diameter of the parabola and h is the distance from the vertex to the opening.

3.4.2. Cylindrical Parabolic Surface

Cylindrical parabolic surfaces concentrate radiation along a line when the plane containing the axes of the parabola is aligned parallel to the rays of the sun. For a cylindrical parabolic surface of length l with cross-sectional dimensions represented in Figure 3.8, the opening area is:

$$A_a = ld \qquad \text{(eq. 3.13)}$$

The reflective surface is determined using the arc length developed in equation (11):

$$A_{sa} = ls \qquad \text{(eq. 3.14)}$$

The focal distance f and the opening angle Ψ of a cylindrical parabolic surface are determined from equations (09) and (10) (Olia et al., 2019).

3.4.3. Paraboloid

a. Definition

A paraboloid is the surface obtained by rotating a parabola around its axis. Concentrators with this surface are called "dish" parabolic concentrators.

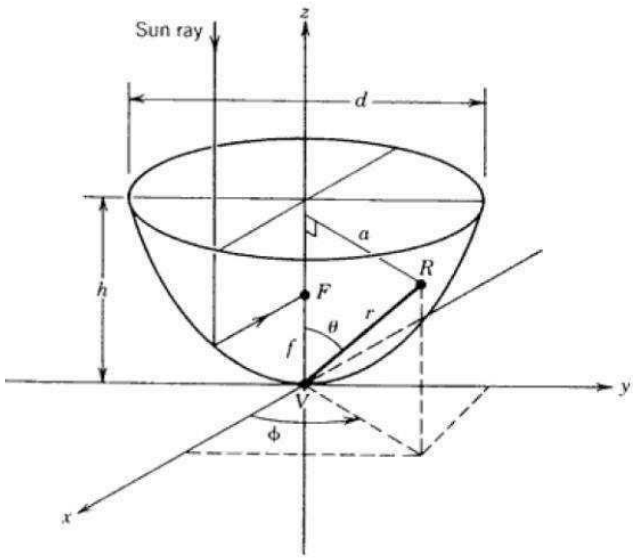


Figure 3.8 *Paraboloid*

b. Equation of the Paraboloid

The equation of a paraboloid with a symmetry axis z in Cartesian coordinates is:

$$x^2 + y^2 = 4fz \qquad \text{(eq. 3.15)}$$

Focal distance f = VF.

In cylindrical coordinates, the equation of the paraboloid is :

$$z = \frac{a^2}{4f} \qquad \text{(eq. 3.16)}$$

a: distance to the axis.

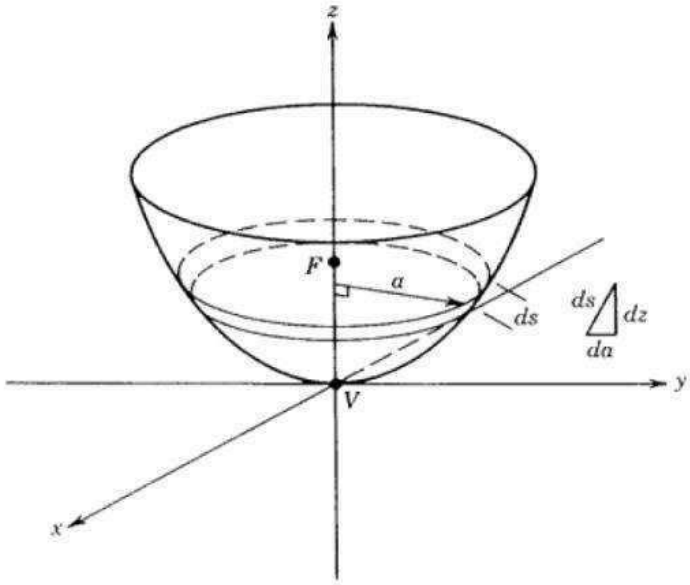


Figure 3.9 *Surface Element of a Paraboloid*

In spherical coordinates, where the origin of the coordinate system coincides with the vertex of the paraboloid, the equation is :

$$\frac{\sin^2\theta}{\cos\theta} = \frac{4f}{r} \qquad \text{(eq. 3.17)}$$

Each point of the paraboloid is identified by the coordinates (r, θ, Φ).

3.4.3.1.Surfaces of the Paraboloid

The total surface area of the paraboloid can be determined by integrating equation (16) (Kumar et al., 2022). We define an elemental surface ds as follows:

$$dA_s = 2\pi a\sqrt{dz^2 + da^2} \qquad \text{(eq. 3.18)}$$

By replacing dz, we have:

$$dA_s = 2\pi a\sqrt{\left(\frac{a}{2f}\right)^2 + 1}da$$

The total surface area of the paraboloid with focal distance f and opening diameter d is obtained by integrating equation (17) :

$$A_s = \int_0^{\frac{d}{2}} A_s = \frac{8\pi f^2}{3}\left\{\left[\left(\frac{d}{4f}\right)^2 + 1\right]^{\frac{3}{2}} - 1\right\} \qquad \text{(eq. 3.19)}$$

The opening area is the circular zone supported by the opening diameter d:

$$A_a = \frac{\pi d^2}{4} \qquad \text{(eq. 3.20)}$$

The opening area can be expressed in terms of the focal distance f and the opening angle Ψ (Kumar et al., 2022). Using equation (08), we have :

$$A_a = \frac{\pi}{4}\left(2p\sin\Psi_{\text{rim}}\right)^2 = 4\pi f^2 \frac{\sin^2\Psi_{\text{rim}}}{\left(1+\cos\Psi_{\text{rim}}\right)^2} \quad \text{(eq. 3.21)}$$

3.4.4. Concentration

This section discusses the opening of the concentrator, geometric concentration, and the limits of concentration.

3.4.4.1. Opening of the Concentrator

The concentrator is the optical device that focuses radiation onto the absorber. The opening of the concentrator is the flat surface that supports its edges and through which the incident radiation passes. For a cylindrical concentrator, the opening is characterized by its width, while for a parabola, it is characterized by its opening diameter.

3.4.4.2. Geometric Concentration C

Geometric concentration is the ratio of the opening area Aa to that of the absorber Ar:

$$C = \frac{A_a}{A_r} \quad \text{(eq. 3.22)}$$

3.4.4.3. Limits of Concentration

Concentration cannot exceed a limit value called ideal concentration. This concept was introduced by Winston and later expanded by Rabl The limit concentration varies depending on whether the system is two-dimensional (linear concentrators) or three-dimensional (paraboloid). The limit concentration is based on the second principle applied to radiative exchange between the sun and a receiver. Consider a three-dimensional system with an opening area Aa and a receiver Ar facing the sun of radius r at distance R (Colomer et al., 2014).

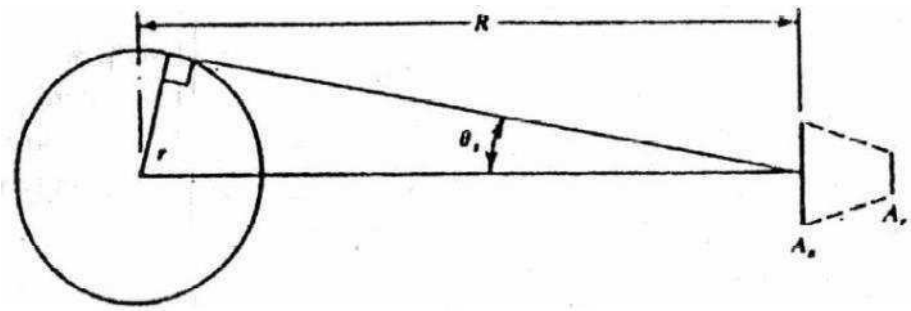


Figure 3.10 *Schematic of the Sun at Temperature Ts Located at Distance R from a Concentrating Collector with Aperture Area A_a and Receiver Area A_r*

The radiant flux from the sun intercepted by the opening area Aa is :

$$Q_{S\to r} = A_a \frac{r^2}{R^2}\sigma T_s^2 \quad \text{(eq. 3.23)}$$

A perfect receiver, considered a black body, radiates energy equal to ArTr2 and a fraction fr→s reaches the sun:

$$Q_{s\to r} = f_{r\to s} A_r \sigma T_r^2 \quad \text{(eq. 3.24)}$$

According to the second law of thermodynamics, there can be no energy exchange between two bodies at the same temperature. Therefore, if:

$$T_S = T_r \quad \text{(eq. 3.25)}$$

This leads to:

$$\frac{A_a}{A_r} = f_{r\to s}\frac{r^2}{R^2} \quad \text{(eq. 3.26)}$$

When fr→s approaches 1, the maximum concentration is:

$$C_{\text{ideal},3d} = \frac{r^2}{R^2} \quad \text{(eq. 3.27)}$$

A similar reasoning for two-dimensional systems (linear concentrators) leads to:

$$C_{\text{ideal},2d} = \frac{r}{R} \quad \text{(eq. 3.28)}$$

The apparent diameter of the sun: Θs = 16'.

3.5. Solar Concentrators

Solar concentrators, like all thermal collectors, are devices designed to absorb solar radiation and transfer the heat generated to a heat transfer fluid (Scalco et al., 2021). In these concentrating systems, solar radiation is received by an opening surface and directed towards a smaller absorber surface through one or more reflections or refractions. Compared to flat plate collectors, concentrating collectors offer several advantages :

- High operational temperatures (from 100 °C to 2000 °C).
- Higher efficiencies.
- Reduced absorber surface area limits convection losses.

However, they also have disadvantages:

- These collectors only concentrate direct radiation.
- They require a tracking system.

3.5.1. Classification of Concentrating Collectors

There are several types of concentrators, and they continue to attract researchers' interest (Sadhu et al., 2015). Various criteria can be used to distinguish different concentrators:

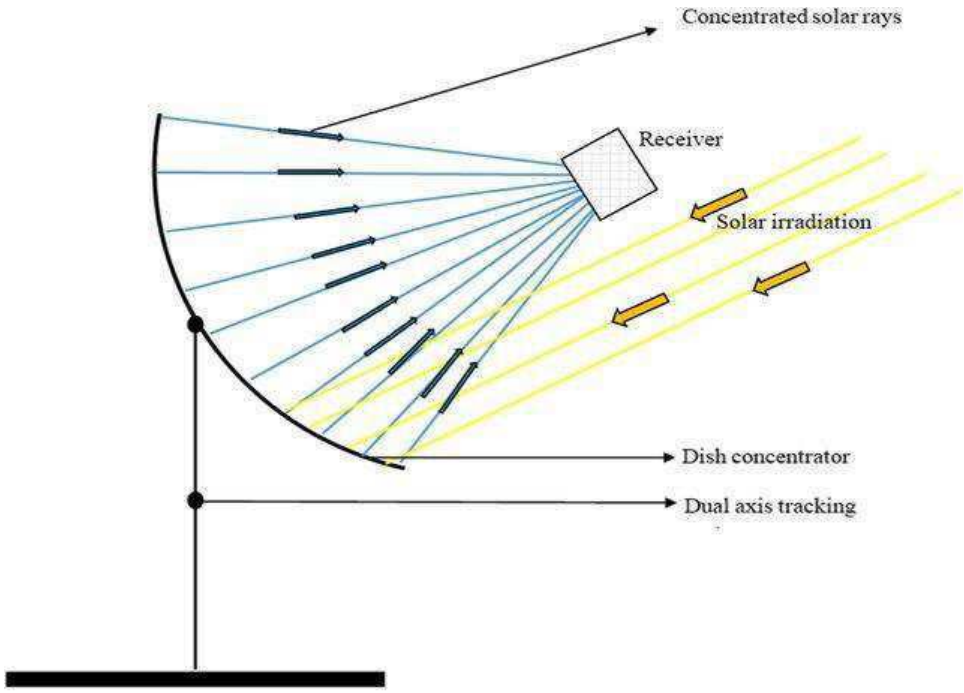
- Optical characteristics allow differentiation between imaging and non-imaging systems. Imaging concentrators can be linear or point-focused.
- Concentration ratio C determines operational temperatures. We can distinguish:
  - Low concentrations (1 < C < 10, T ~ 150 °C).
  - Medium concentrations (10 < C < 100, T ~ 300 °C).
  - High concentrations (C > 100; T > 500 °C).

- Geometric characteristics distinguish:
  - Two-dimensional systems.
  - Three-dimensional systems.
- Tracking modes: Concentrators can be:
  - Fixed or periodically oriented.
  - Mobile around one axis.
  - Mobile around two axes.
- Relative positions of the absorber and the concentrator, depending on whether one is mobile relative to the other or if both are fixed together.

They are categorized into cylindrical parabolic concentrators, linear Fresnel reflectors (LFR), parabolic concentrators, and heliostats.

3.5.1.1. Parabolic Concentrator

Parabolic concentrators are point-focused devices with parabolic symmetry. The solar rays reflected by the parabola converge at the focus (see Figure 3.11). They are oriented using mobile mounts around two axes (altazimuthal mount and equatorial mount). The necessity to move the parabola along two axes to track the sun is the main limitation of this type of system. The parabolic concentrator coupled with a Stirling engine (Dish-Stirling) is the most widely used technology for low-power electricity generation through thermodynamic solar conversion (Kumar et al., 2022). The efficiencies of these collectors are around 75%, and the installation powers range from 1 to 100 kWth, with concentration ratios from 6000 to 10000 allowing for working temperatures between 600 °C and 1200 °C. The instantaneous efficiency for solar energy to electricity conversion exceeds 22% (29% for the 25 kW module from the American manufacturer SES (Stirling Energy Systems)), but operational and maintenance costs remain high.



(a)

(b)

Figure 3.11 *(a) Parabolic dish solar concentrator model. (b) Euro dish stirling parabolic dish collector (Kumar et al, 2022)*

3.5.1.2. Cylindrical Parabolic Concentrator

The reflective surface of the concentrator is a cylinder with a parabolic cross-section. When they are well oriented towards the sun, they concentrate direct radiation onto a focal line where the receiver is located (see Figure 3.12). The sun tracking mechanism operates along a single axis. Cylindrical parabolic concentrators can be oriented along the East-West axis or the North-South axis. Concentrators

oriented along the North-South axis can collect more energy during the summer. The East-West orientation generally allows for greater energy collection. Operating temperatures range from 270 °C to 450 °C, and the conversion efficiencies of these collectors are around 70% under nominal conditions. In practice, opening angles are typically less than 20-30°. This technology is commonly used in thermodynamic power plants (Olia et al., 2019).

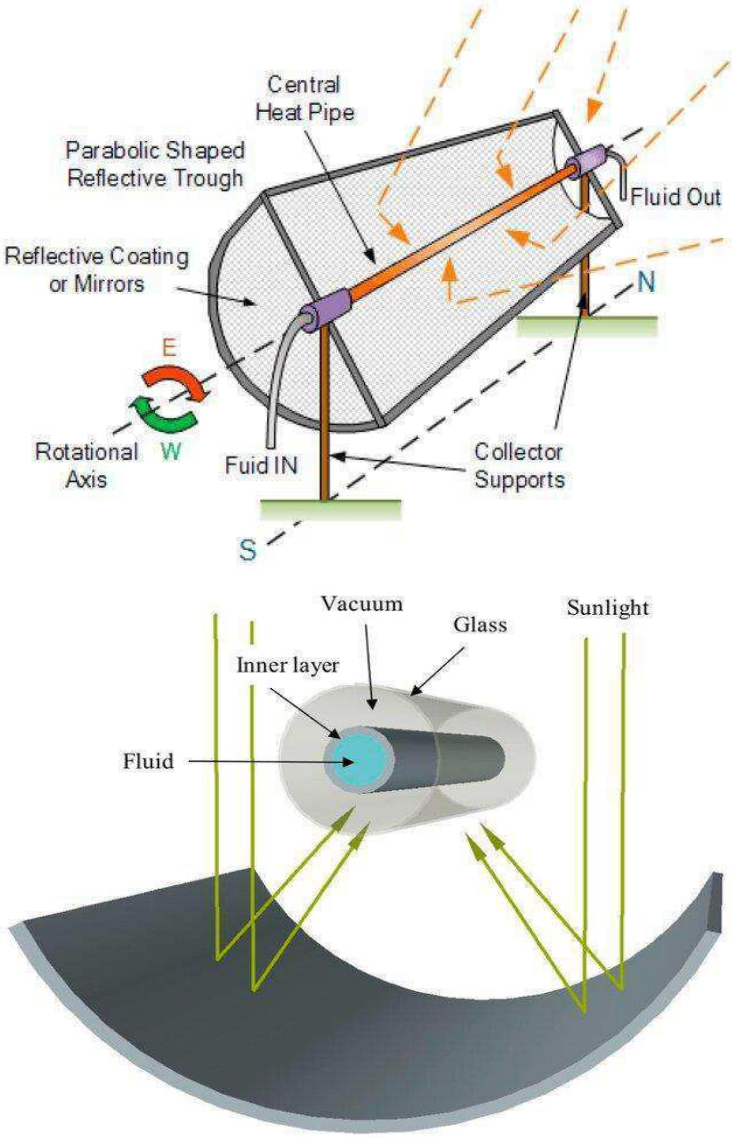


Figure 3.12 *Parabolic Trough Concentrator (Olia, H et al, 2019)*

3.5.1.3. Heliostat Concentrator

Heliostats consist of one or more flat or slightly concave reflective mirrors with surfaces ranging from 50 m² to 150 m². They are used in solar tower technology. The mirrors are mounted on a mechanical structure that tracks the sun's trajectory. The most commonly used mount is the altazimuthal mount, but also noteworthy is the elevation rotation mount (Non-Focusing Imaging Heliostat) developed by Malaysian researchers, which remains in prototype form (Colomer et al., 2014).

a. Reflection of a Heliostat Towards a Fixed Point

The rays reflected by a field of heliostats must be directed towards the receiver (central tower). The tracking and incidence angles of the heliostat can be determined using vector methods. The Cartesian coordinate system is based on the directions Zenith, East, and North, with the origin O at the base of the receiver (O, z, e, n), as seen in Figure 3.13. The position of the heliostat B is identified by its coordinates z1, e1, and n1. The receiver is located at a height z0 from the origin.

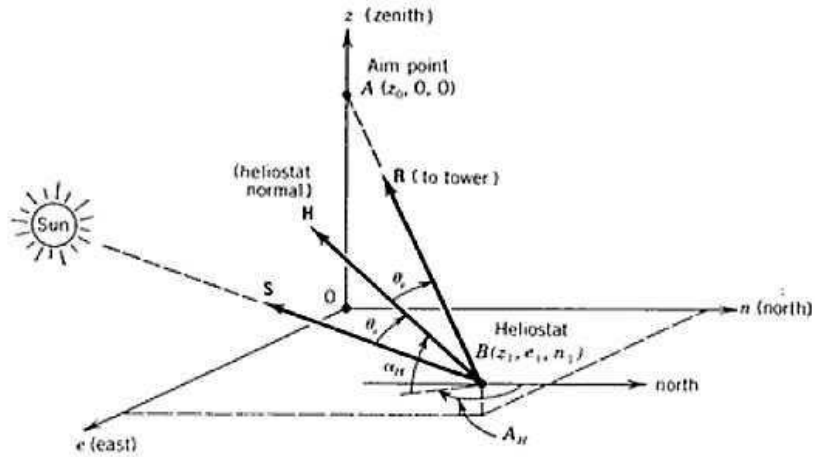


Figure 3.13 *Coordinates showing the reflection of a solar ray by a heliostat towards a fixed point.*

To determine the height αH and azimuth AH of the heliostat, we use three vectors:

- S: unit vector indicating the direction of the sun.
- N: unit vector normal to the surface of the heliostat.
- R: unit vector directed towards the target point of the receiver, defined by:

$$\vec{R} = \frac{(z_0 - z_1)\vec{\imath} - e_1\vec{\jmath} - n_1\vec{k}}{\sqrt{(z_0 - z_1)^2 + e_1^2 + n_1^2}} \qquad \text{(eq. 3.29)}$$

Where i, j, k are unit vectors in the directions z, e, n.

From this, we have:

$$\vec{R} = R_z\vec{\imath} + R_e\vec{\jmath} + R_n\vec{k} \qquad \text{(eq. 3.30)}$$

The normal vector H to the surface is defined by [Colomer et al., 2014]:

$$\vec{H} = H_z\vec{\imath} + H_e\vec{\jmath} + H_n\vec{k} \qquad \text{(eq. 3.31)}$$

According to the laws of Descartes, the angle of incidence equals the angle of reflection. The angle of incidence can be described by the vectors S and N as follows:

$$\cos 2\theta_i = \vec{S}\vec{R} \qquad \text{(eq. 3.32)}$$

By combining equations (07) and (32), we have:

$$\cos 2\theta_i = R_z \sin\alpha + R_e \cos\alpha \sin A + R_n \cos\alpha \cos A \quad \text{(eq.3.33)}$$

The normal vector N is the sum of the vectors S and R, divided by their dot product:

$$\vec{H} = \frac{\vec{s}+\vec{R}}{\cos 2\theta_i} = \frac{(R_z+S_z)\vec{i}+(R_e+S_e)\vec{j}+(R_n+S_n)\vec{k}}{\cos 2\theta_i} \quad \text{(eq.3.34)}$$

Replacing equation (07) and describing the height αH and azimuth AH of the heliostat, we have:

$$\sin\alpha_H = \frac{R_z+\sin\alpha}{\cos\theta_i} \quad \text{(eq. 3.35)}$$

and:

$$\sin A_H = \frac{R_e+\cos\alpha\sin A}{2\cos\theta_i\cos\alpha_H} \quad \text{(eq. 3.36)}$$

The third expression is determined as a complement:

$$\cos A_H = \frac{R_n+\cos\alpha\cos A}{2\cos\theta_i\cos\alpha_H} \quad \text{(eq. 3.37)}$$

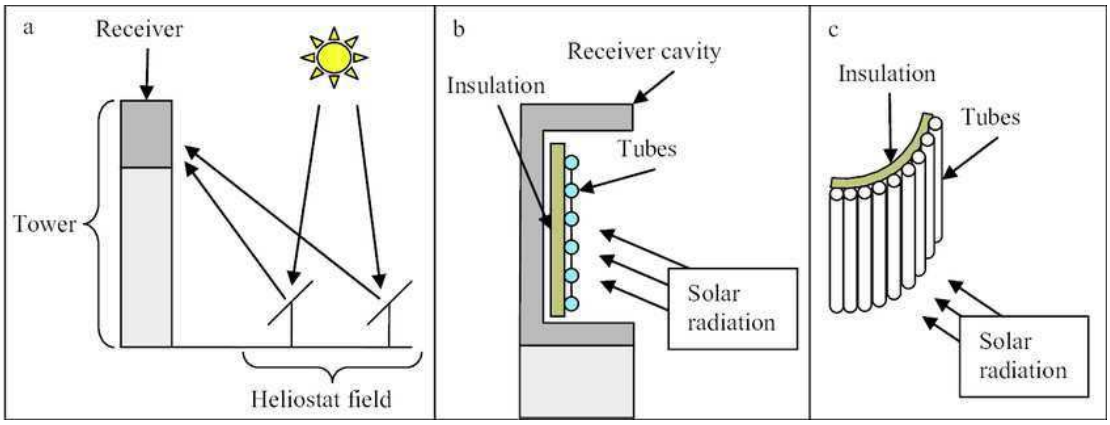


Figure 3.14 *Heliostat solar concentrator (Colomer et al, 2014)*

3.5.1.4. Fresnel Concentrator

Fresnel concentrators consist of flat or slightly parabolic mirrors arranged in parallel strips that can be tilted about an axis to reflect and concentrate light rays onto a line where the receiver is located (see Figure 3.15). Compared to parabolic trough collectors (PTC), linear Fresnel reflectors (LFR) are easier to manufacture, the tracking system uses smaller motors, the focal line is fixed, and the solar field is easier to mount and utilize (70% of the ground can be covered with mirrors). The optical performance of LFR is reduced by 30% to 40% compared to PTC (Scalco et al., 2021).

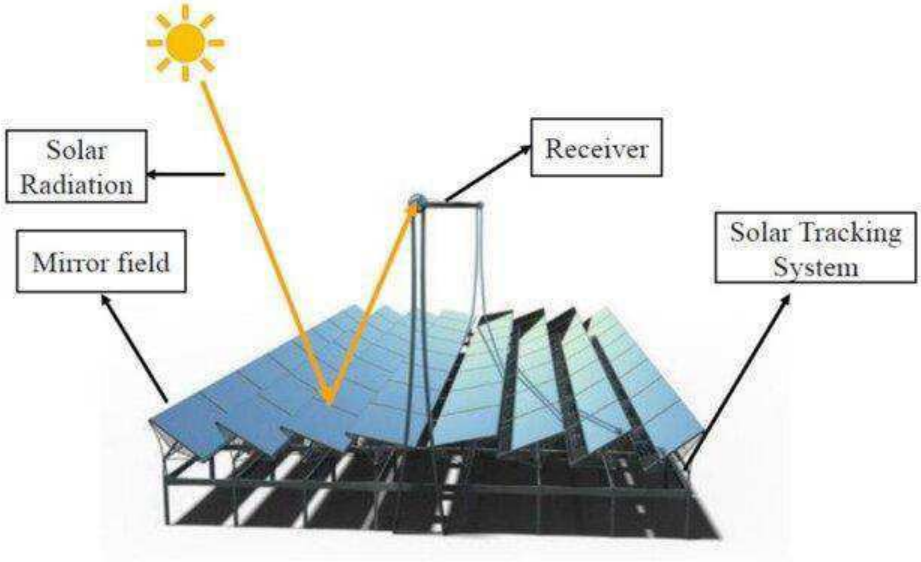


Figure 3.15 *Fresnel concentrator (Scalco et al, 2021)*

3.5.2. Applications of Solar Thermal Conversion

Solar concentrator technology has been widely applied in various fields, either directly for heating water, domestic cooling and air conditioning, food drying, and electricity generation, or indirectly for certain processes where the main energy source is electricity, such as water heating (Sadhu et al., 2015).

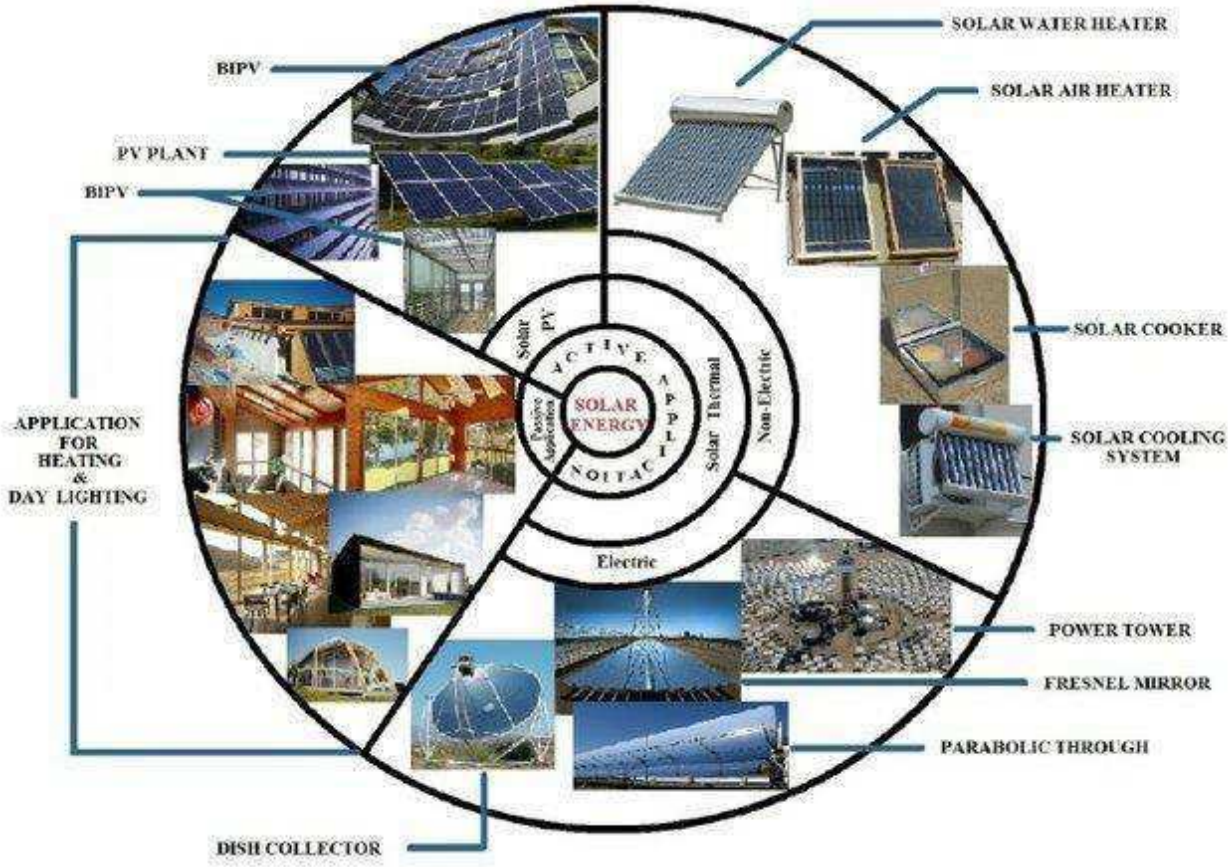


Figure 3.16 *Applications of solar thermal conversion (Sadhu et al, 2015)*

3.5.3. Efficiency of Concentrating Collectors

In general, the efficiency of a concentrating collector is given by:

$$\eta = \frac{\dot{m} c_p \left(T_{\text{out}} - T_{\text{in}} \right)}{I_{b,n} \cos \theta_i A_a} \quad \text{(eq. 3.38)}$$

Where:

- A_a: opening area of the collector.
- $I_{b,n}$: direct radiation.
- θ_i: angle of incidence.
- T_{out}: outlet temperature of the fluid.
- T_{in}: inlet temperature of the fluid.
- $\dot{m}$: mass flow rate of the fluid.

3.6. Solar Heat Storage

Currently, heat storage is rarely used . With the development of solar thermal power plants, its use is expected to increase (Dincer & Rosen, 2011).

3.6.1. Latent Heat Storage

This storage method is based on the energy involved when a material changes state (for example, solid to liquid). The reverse transformation allows for the release of accumulated energy as heat or cold, with an efficiency of around 60%. This technique can be applied in buildings through Phase Change Materials (PCM). Incorporated into walls, they serve as thermal regulators depending on the heat provided by the sun (Dincer & Rosen, 2011).

3.6.2. Thermochemical Storage

The term thermochemical storage encompasses two phenomena: sorption and chemical reaction. Sorption heat storage is interesting for low-temperature storage (T ≈ 80 °C), while for concentrated solar applications (T ≈ 200 to 1000 °C), chemical synthesis reactions seem to be the most suitable. In this system, a large amount of chemical energy is generated during the breaking and rearranging of molecular bonds in a reversible chemical reaction, resulting in a high heat storage capacity (Dincer & Rosen, 2011).

3.6.3. Sensible Heat Storage

The increase in temperature of a material allows for energy storage. This principle is exemplified by solar water heaters: they capture heat during the day for later use, achieving an average efficiency of around 40% for the most recent systems. Preferred materials include water, synthetic oil, rock, or concrete. For large volumes, heat from solar collectors or industrial waste can be stored underground. Geological storage, which can be coupled with geothermal operations, is still relatively uncommon (Dincer & Rosen, 2011).

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Chapter 4

Photovoltaic Conversion

Chapter 4: Photovoltaic Conversion

4.1.Introduction

The process of converting solar energy involves transforming the energy emitted by photons from the sun, which manifests as electromagnetic waves, into electrical energy. This transformation is facilitated by specialized optoelectronic devices known as "solar cells" or "photovoltaic cells" (Rau, 2008). Photovoltaic conversion operates on the principle of directly converting light energy into electrical energy, a function that solar cells are specifically designed to perform. The first silicon homojunction solar cell was developed in 1954 at Bell Labs, achieving an efficiency of approximately 4.5% (Chapin et al., 1954). By 1960, this efficiency had risen to over 10% for monocrystalline silicon cells (Green et al., 2010). Numerous studies have since been conducted to enhance this conversion efficiency. Until 1972, solar cells were primarily utilized in space applications due to their high costs and relatively low efficiencies (Moussa et al., 2019). Nevertheless, improving efficiency has been prioritized over reducing costs, as any enhancement in performance directly affects the cost of the produced energy.

4.2.Photovoltaic Conversion

To understand the materials used in the transition to electrical energy, we can categorize them into two main types:

- **Conductive Materials**: These include conductors like copper, known for their excellent electrical conductivity.
- **Semiconductor Materials**: These materials, such as silicon, fall between conductors and insulators, facilitating controlled electrical conductivity.

4.2.1. Physics of Photovoltaic Cells

As mentioned earlier, the materials utilized for energy conversion primarily consist of semiconductors, particularly those suitable for photovoltaic applications, such as solar panels. Silicon (Si) is the most prevalent material in the photovoltaic phenomenon. The photovoltaic effect was first observed by Antoine Becquerel in 1839, who found that certain materials could generate a small electric current when exposed to light (Becquerel, 1839). Albert Einstein later elucidated the photoelectric phenomenon in 1912, but it wasn't until the early 1950s that this knowledge was applied practically in the creation of silicon PV cells (Einstein, 1912). This effect enables the conversion of solar energy into electricity.

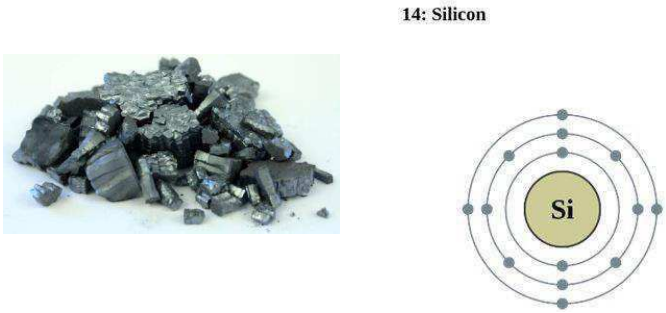

Figure 4.1 *Identification of silicon material (Filtvedt et al, 2013) (Yanlong et al, 2021)*

- **Silicon**: This material dominates the global photovoltaic panel market due to its abundance, stability, and non-toxicity (Green et al., 2010). The silicon sector is divided into various technologies based on the type of silicon used and the methods of production (Rau, 2008). The two primary technologies are monocrystalline and multicrystalline silicon. Over 90% of the photovoltaic industry relies on silicon as the foundational material (Moussa et al., 2019). Silicon offers several advantages:
  - It is widely available on Earth, easily extracted from sand, and is less toxic compared to other semiconductors.
  - It possesses a natural oxide (SiO_2) with excellent electronic properties and can be easily doped with elements like phosphorus or boron.
    Its main limitation is its indirect bandgap of 1.1 eV, which results in lower radiation absorption compared to materials with a direct bandgap. To absorb 90% of the solar spectrum, silicon requires a thickness of about 100 μm, while only 1 μm of gallium arsenide (GaAs) is necessary. Additionally, silicon's bandgap does not optimally capture the most effective part of the solar spectrum (between 1 and 1.7 eV); GaAs, with a bandgap of 1.38 eV, offers higher theoretical efficiencies. Despite these drawbacks, silicon remains the most widely utilized material in photovoltaics. It also benefits from a strong and enduring presence in the microelectronics industry, which uses highly pure monocrystalline silicon obtained through techniques such as the Czochralski process. Monocrystalline silicon modules generally demonstrate higher efficiencies than those made from multicrystalline silicon. Multicrystalline silicon, produced from less refined materials, accounted for 56.4% of modules manufactured in 2000 (Moussa et al., 2019). Silicon's atomic structure features four electrons in its outer shell, with each atom bonded to four neighboring atoms, resulting in all outer-shell electrons participating in these bonds. When a silicon atom is replaced by one with five outer-shell electrons (like phosphorus), one electron becomes free to move within the lattice, facilitating conduction and resulting in n-doping. Conversely, replacing a silicon atom with one that has only three outer-shell electrons (like boron) creates a vacancy, allowing an electron to occupy this gap, leading to conduction by a hole and p-doping (Moussa et al., 2019).

Doping can be categorized into two types based on the dopant materials:

- **N-Type**: This involves adding materials whose atoms have an extra electron, allowing free movement in the crystal. Phosphorus is a common n-type dopant (Green et al., 2010).
- **P-Type**: This involves adding materials whose atoms possess a positive charge. Boron is frequently used for p-type doping. The presence of both fixed positive and negative ions creates an electric field, allowing the electric charges generated by absorbed radiation to contribute to the current of the photovoltaic cell (Rau, 2008).

Enhancing the performance of silicon (Si) for efficient energy conversion during the photoelectric process relies on doping with small amounts of impurities like boron (B) and phosphorus (P) to modify conductivity characteristics. There are several methods for doping materials:

- Diffusion doping
- Ion implantation doping
- Nuclear transmutation doping
- Laser doping

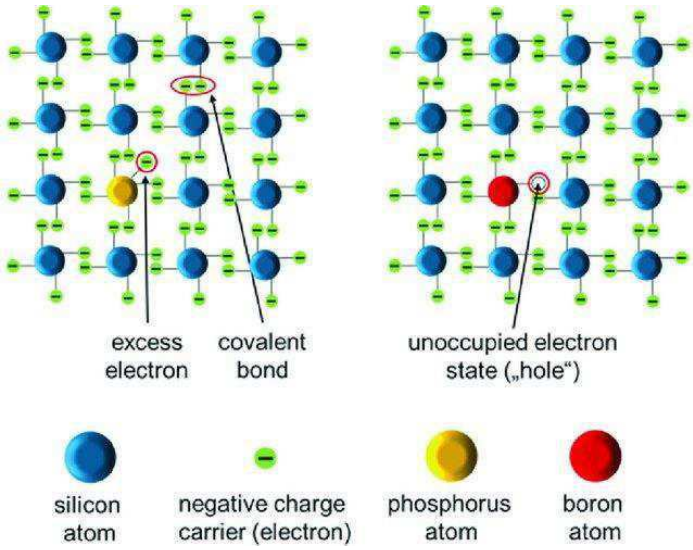

Figure 4.2 *Silicon/Phosphorus (Si/P) and Silicon/Boron (Si/B) Mixtures (Büttgenbach et al, 2020)*

4.2.2. Principle of Operation

When a photovoltaic cell is exposed to solar radiation, the photons in the absorbed light provide the energy necessary to free electrons from the semiconductor layer of the cell. The movement of these freed electrons generates electric current, a process referred to as the photovoltaic effect. Light, a form of energy, energizes the electrons in the semiconductor, prompting them to move. These electrons then flow freely within the semiconductor material, creating an electric potential difference that can be harnessed via conductive wires connected to the outside of the cell. To enhance the power output of photovoltaic cells, they can be connected in series to increase voltage and then in parallel to elevate current intensity, resulting in a photovoltaic solar panel. These panels can further be interconnected to create larger photovoltaic systems.

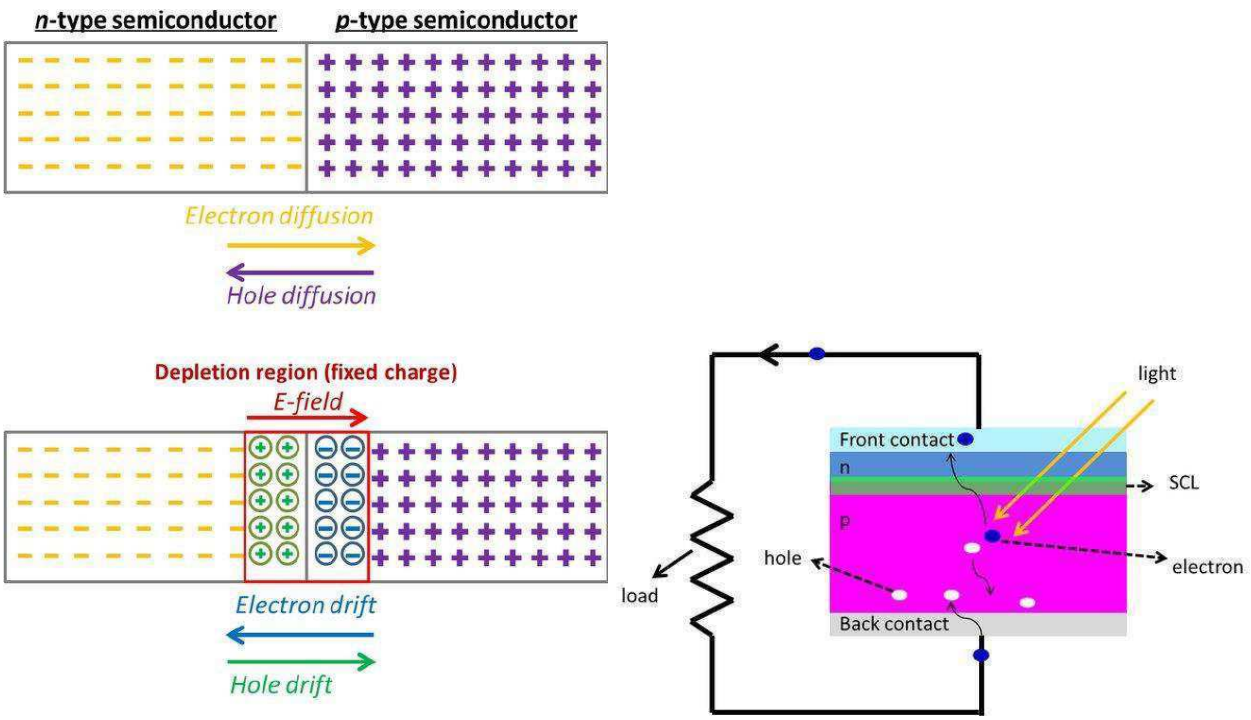

***Figure** 4.3 P-N Junction and Electricity Generation Process (Abass, 2014) (Berney, 2014)*

4.3.Different Types of Direct Conversion Solar Cells

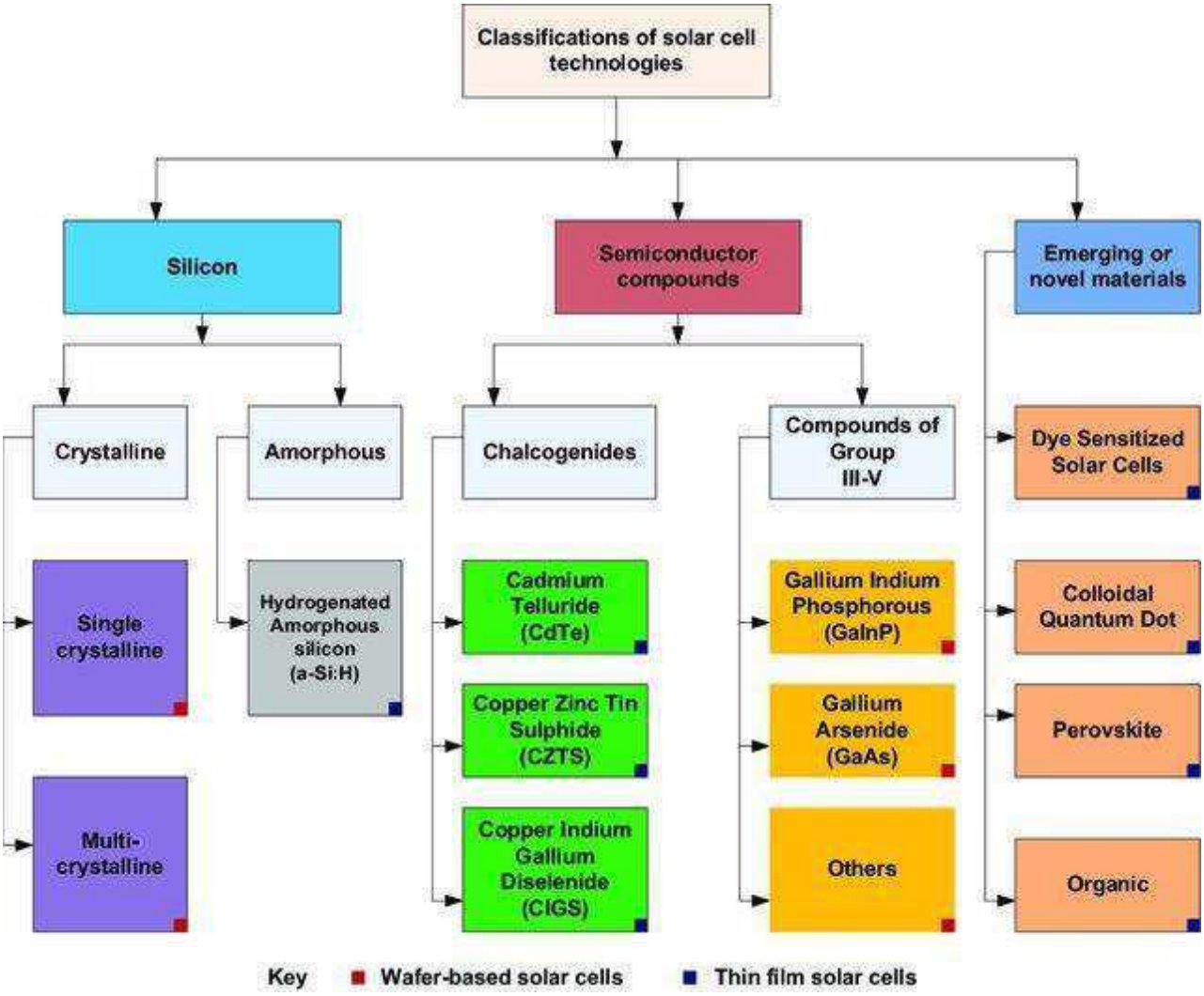

***Figure 4.4** The different types of solar cells (Ibn-Mohammed et al, 2017)*

Various types of solar cells exist, each with distinct efficiencies and costs. However, their efficiencies generally remain modest, ranging from 8% to 23% of the energy they receive (Green et al., 2010). Currently, three primary types of cells are prevalent:

4.3.1. Monocrystalline Cells

The production of numerous devices begins with high-purity monocrystalline materials (Rau, 2008). In particular, microelectronic chips require monocrystalline semiconductor substrates, such as silicon, germanium, or gallium arsenide. For silicon, two common methods for obtaining high-purity monocrystalline ingots are zone melting and crucible pulling (Czochralski method), producing ingots that can exceed several meters in length and up to 300 mm in diameter. These cells typically achieve photovoltaic efficiencies greater than 15% (Green et al., 2010).

4.3.2. Multicrystalline Cells

Multicrystalline cells are easier to manufacture and have lower production costs. Large single ingots can be produced by directional cooling of molten silicon, resulting in materials composed of multiple large crystals separated by grain boundaries. This heterogeneity leads to slightly lower commercial energy efficiency, around 13%, compared to monocrystalline silicon, but simplifies the manufacturing process (Moussa et al., 2019). These multicrystalline ingots are sliced into 200 to 400 mm thick wafers using a wire saw. Currently, multicrystalline silicon technology represents nearly 50% of the photovoltaic market.

4.3.3. Amorphous Cells

Amorphous cells exhibit lower efficiency (ranging from 8% to 10%, with laboratory efficiencies reaching 13%) but require very thin layers of silicon, making them more cost-effective. They are often employed in small consumer electronics, such as solar calculators and watches. Amorphous silicon features a disordered, non-crystalline atomic structure but has a light absorption coefficient that is about 1000 times higher than that of crystalline silicon A thickness of only about 0.3 mm is sufficient to absorb most of the visible spectrum. In this technology, silicon is deposited directly on glass substrates from silane gas (SiH_4). The process occurs in a heated vacuum chamber where silane is injected and decomposed via radio frequency discharge, resulting in silicon deposition on the glass. The presence of hydrogen is crucial for ensuring material quality. Dopants are introduced by adding gases such as PH_3 or BH_3 to the silane. This type of silicon is generally cheaper compared to other forms.

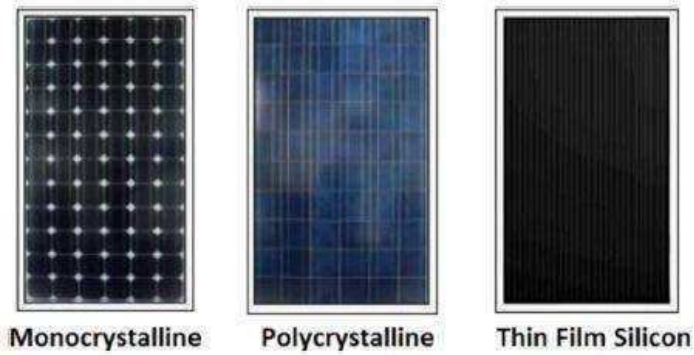

Figure 4.5 *Types of Silicon-Based Solar Cells (Nayan et al, 2016)*

Serial Number	Type of Solar PV Cell	Material of Fabrication / Architecture	Efficiency (%)
1	Single Crystalline	Titanium dioxide (TiO_2)	17
		Silicon solar cell, Pyramid Microstructure	20.19
		Lab efficiency	-
2	Polycrystalline	Gallium Arsenide (GaAs)	15.8
		Wafer based	19.9
3	Thin Film	Amorphous silicon	13.6
		Cadmium Telluride (CdTe)	18.6
		Copper indium gallium selenide (CIGS)	19.2
4	PERC (Passivated Emitter and Rear Cell)	Silicide on oxide-based, electrostatically doped (SILO-ED)	24.7
		Ion implanted	23.5
		N-type silicon, optimized poly-Si passivated contacts	22.52
5	Half Cut	Mono PERC	18.5–20
		Mono PERC Multi bus bar (MBB)	19–21
		MBB Heterojunction	20–22

Table 4.1 *Efficiency of Different Solar Cell Types (Shalwar et al., 2022)*

4.4.Thin Films

Despite recent price reductions, the high cost of kWc remains a significant barrier to large-scale photovoltaic development. The kilowatt peak (kWc) measures the power output of a photovoltaic generator under Standard Test Conditions (STC) (1000 W/m² and 25°C) (Green et al., 2010). A

substantial portion of the cost associated with photovoltaic generators stems from silicon and its purification processes. Several types of photovoltaic cells that aim to reduce material usage are currently under development and beginning to be industrialized. These technologies, known as thin films, utilize manufacturing processes designed to minimize cell thickness (Moussa et al., 2019). The most established thin-film technology is amorphous silicon (a-Si), which accounted for over 7% of the global market in 2008. This technique allows for the use of low-cost substrates. Silicon is deposited at low temperatures onto glass substrates, and flexible substrates can also be employed to create flexible solar cells. While their cost is lower than that of crystalline cells, the efficiency of a-Si cells is about 7%, which is less than that of crystalline cells. Implementing this type of cell requires galvanic isolation from the grid; without it, amorphous cells degrade rapidly (Rau, 2008). The precise reasons for this phenomenon are not fully understood. Amorphous cells excel at capturing diffuse radiation, making them less sensitive to fluctuations in direct sunlight. They represent a viable alternative to crystalline cells in areas prone to shading. Other materials used in thin-film technologies include Cadmium Telluride (CdTe), Copper Indium Selenide (CIS), and Copper Indium Gallium Selenide (CIGS) (Green et al., 2010). These technologies demonstrate good efficiencies, reaching up to 19% (Rau, 2008). However, concerns regarding environmental toxicity and raw material supply may limit their application to laboratory settings or very specific uses.

4.5.Organic and Plastic Cells

The photovoltaic effect in organic semiconductor materials has gained considerable traction over the past decade. Initially characterized by low conversion efficiencies, this field began to receive attention in 1986 when Tang's team demonstrated that efficiencies approaching 1% were attainable, aligning with Merritt's predictions from 1978. This bilayer cell, composed of vacuum-evaporated molecules, achieved a conversion efficiency of 0.95%. These cells can be categorized into two pathways: "wet" cells and organic polymer cells, commonly referred to as "plastic" cells. The advancements in these technologies have been rapid, with efficiency records frequently being surpassed, currently reaching around 6%. The primary challenge for these technologies lies in ensuring performance stability and longevity, which is currently about 1000 hours. The appeal of these cells also stems from their ability to be deposited over large areas at high speeds using conventional printing techniques, unlike traditional inorganic materials. This enables the development of lightweight, portable, and flexible applications. Furthermore, due to lower manufacturing and material costs, these organic cells are projected to be significantly cheaper than their inorganic counterparts.

4.6.Composition of a PV Solar Panel

A photovoltaic solar cell, or photopile, represents the smallest unit capable of directly converting light into electricity. It comprises semiconductor materials that convert light energy into electrical energy. Key components of photovoltaic cells include:

- A thin semiconductor layer that features a bandgap, serving as an energy barrier that electrons can only cross with external excitation, such as silicon, which exhibits relatively good electrical conductivity (Moussa et al., 2019).
- An anti-reflective layer designed to maximize solar ray penetration (Rau, 2008).
- A conductive grid on the top (cathode) and a conductive metal layer on the bottom (anode) (Green et al., 2010).
- Recent designs may incorporate reflective multilayers just below the semiconductor, allowing light to reflect longer within the cell to enhance efficiency.

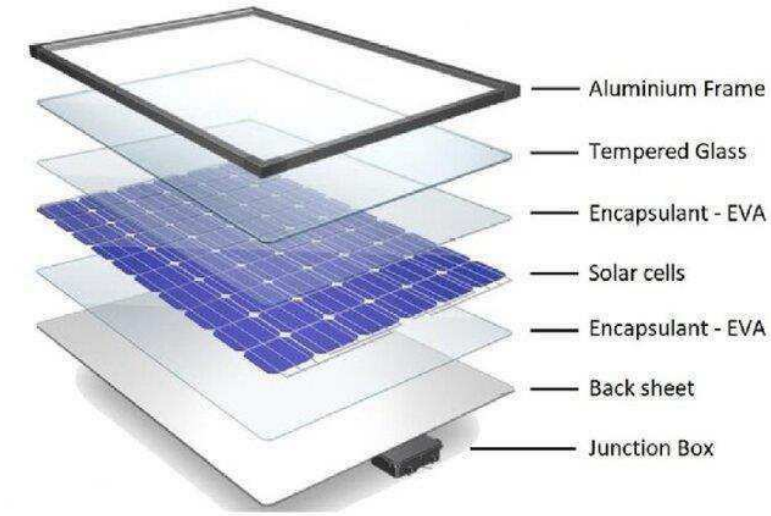

Figure *4.6 Construction of a photovoltaic panel (Kheirrouz et al, 2022)*

4.7.Applications of PV Solar Panels

Photovoltaic panels are widely recognized across various sectors that require electrical energy, and their advantages and disadvantages are summarized as follows:

***Figure** 4.7 Applications of PV solar panels (Thi , 2017)*

Advantages:

- They produce non-polluting electrical energy during operation, aligning with sustainable development principles.
- They represent a renewable energy source that is inexhaustible on a human scale.
- They are particularly useful in developing regions lacking extensive electrical infrastructure or in remote locations where connecting to the national grid is infeasible (Moussa et al., 2019).

Disadvantages:

- The high costs associated with photovoltaic technology are a significant barrier.
- The current efficiency of photovoltaic cells remains relatively low, averaging around 10% for consumer applications, limiting power output.
- The market for photovoltaics, while growing, remains limited.
- Electricity generation occurs only during daylight hours, while peak demand often falls at night.
- Current technologies face challenges in electricity storage, with batteries posing high ecological costs (Green et al., 2010).
- The lifespan of photovoltaic systems is typically 20 to 25 years, after which "crystallized" silicon renders the cells ineffective
- Environmental pollution during manufacturing is a concern, as some studies indicate that the energy expended in cell production is not fully recouped over the 20-year lifespan; even recycling initiatives present environmental challenges (Rau, 2008).

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Chapter 5

Wind Energy

Chapter 5: Wind Energy

5.1.Introduction

Wind energy is a renewable and economical resource that can be harnessed safely, producing minimal environmental impact. The global potential for wind energy is essentially limitless. Recent advancements in variable-speed wind turbines, power electronics, and electric machine control have made wind energy a competitive alternative to fossil fuels (Manwell et al., 2010).

The historical use of wind energy can be traced back to windmills, which first appeared around 600 AD in the East and later in Egypt (Spera, 2009). These early windmills were used to convert mechanical energy for tasks such as grain grinding and water pumping for irrigation.

Modern wind turbines capture wind energy to generate electricity. Positioned atop masts, these turbines optimize energy extraction by reaching heights of 30 meters or more, where wind speeds are higher and turbulence is reduced (Burton et al., 2011). They typically feature two to three blades that rotate around an axis and are classified into two main types: vertical-axis and horizontal-axis turbines.

Figure 5.1 *First wind turbine used in Egypt*

5.2.Wind Resource

Wind remains a renewable and cost-efficient energy source that is safe for exploitation and environmentally friendly. The availability of wind energy varies significantly across different geographic locations (Ackermann & Söder, 2002).

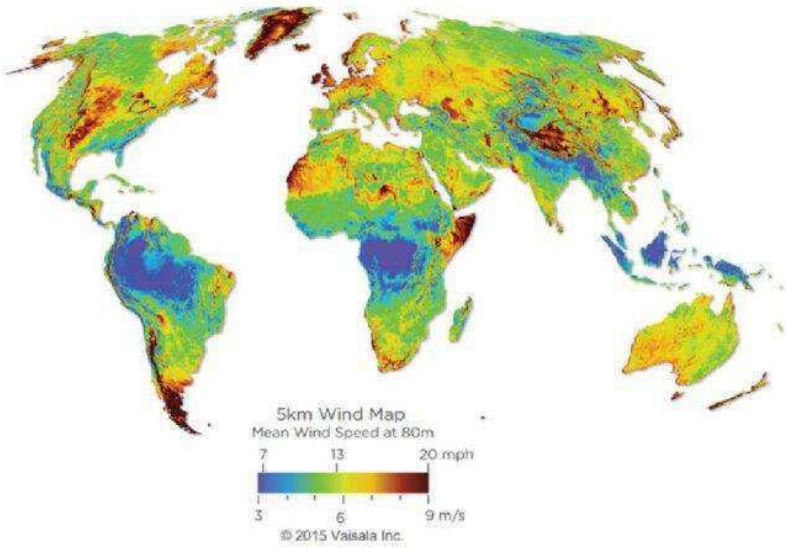

Figure 5.2 *World map of average wind speed distribution (Elsakka et al, 2022)*

In Algeria, the varied topography and climate lead to significant differences in wind resources. The southwestern regions, including Adrar, Timimoun, and Tindouf, experience the highest wind speeds. In contrast, northern areas generally have lower averages, though microclimates in coastal and high plateau regions can show notable variations. For instance, Tiaret's microclimate exhibits the highest recorded wind speeds (Kasbadji Merzouk, 2000).

Algeria possesses considerable wind potential, particularly in the southern regions, where higher wind speeds can be harnessed for electricity generation and water pumping, especially in the High Plateaus. The wind resource map of Algeria, estimated at a height of 10 meters, indicates that the Adrar region has the highest average wind speeds, exceeding 6 m/s (Dahmani et al., 2015).

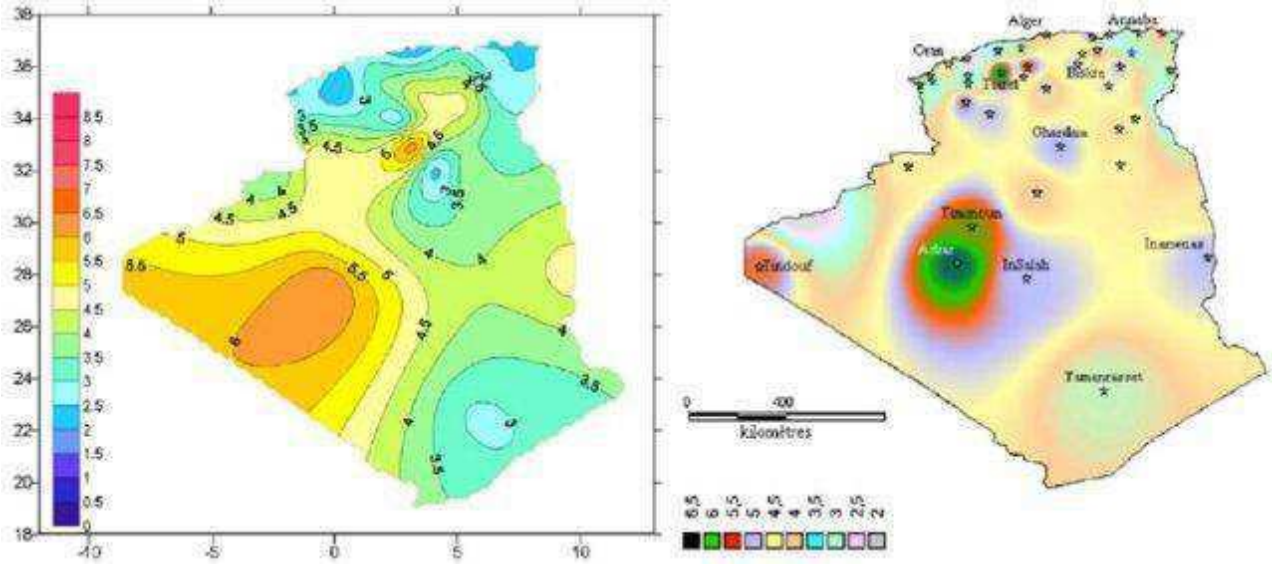

Figure 5.3 *Map of average wind speed distribution in Algeria (Laidi et al, 2012)*

5.3.Description of a Wind Turbine

Wind energy is derived from the kinetic energy of the wind, which is captured by devices known as wind turbines or wind generators, named after Aeolus, the ancient Greek god of the winds (Gasch & Twele, 2012).

A wind turbine transforms the kinetic energy of the wind into electrical energy. By 2012, wind electricity accounted for 2.4% of the total global electricity production (GWEC, 2013). Wind energy can be harnessed in three primary ways:

- As mechanical energy for various applications
- For electricity generation
- Through wind generators, which convert wind's kinetic energy into mechanical energy via a transmission shaft before converting it into electrical energy through a generator.

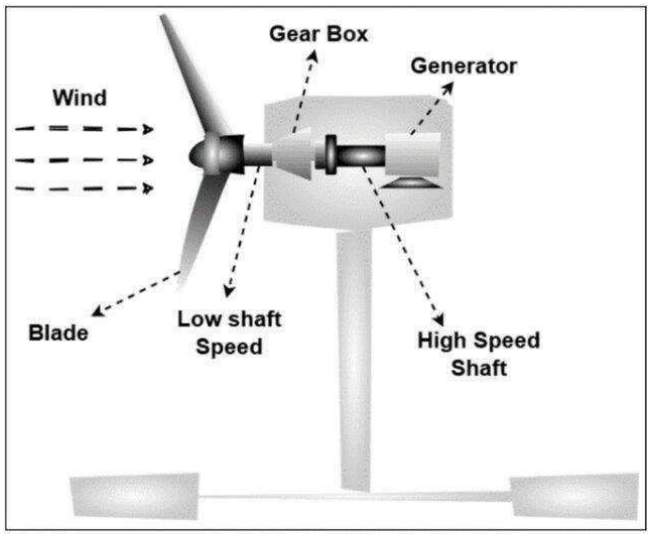

Figure 5.4 *A wind turbine (Irfan et al, 2025)*

5.4.Different Types of Wind Turbines

Wind turbines are classified based on the orientation of their blades' rotational axis into two main types (Mathew, 2006):

- Horizontal-axis wind turbines (HAWT)
- Vertical-axis wind turbines (VAWT)

5.4.1. Vertical-Axis Wind Turbines (VAWT)

VAWTs have a vertical rotational axis relative to the ground and perpendicular to the wind direction. This design simplifies maintenance by allowing the gearbox and generator to be positioned at ground level (Eriksson et al., 2008). However, because they operate closer to the ground, they typically face weaker winds due to terrain friction.

VAWTs can capture wind from any direction due to their symmetrical design, eliminating the need for rotor orientation. Nonetheless, they require manual initiation to start.

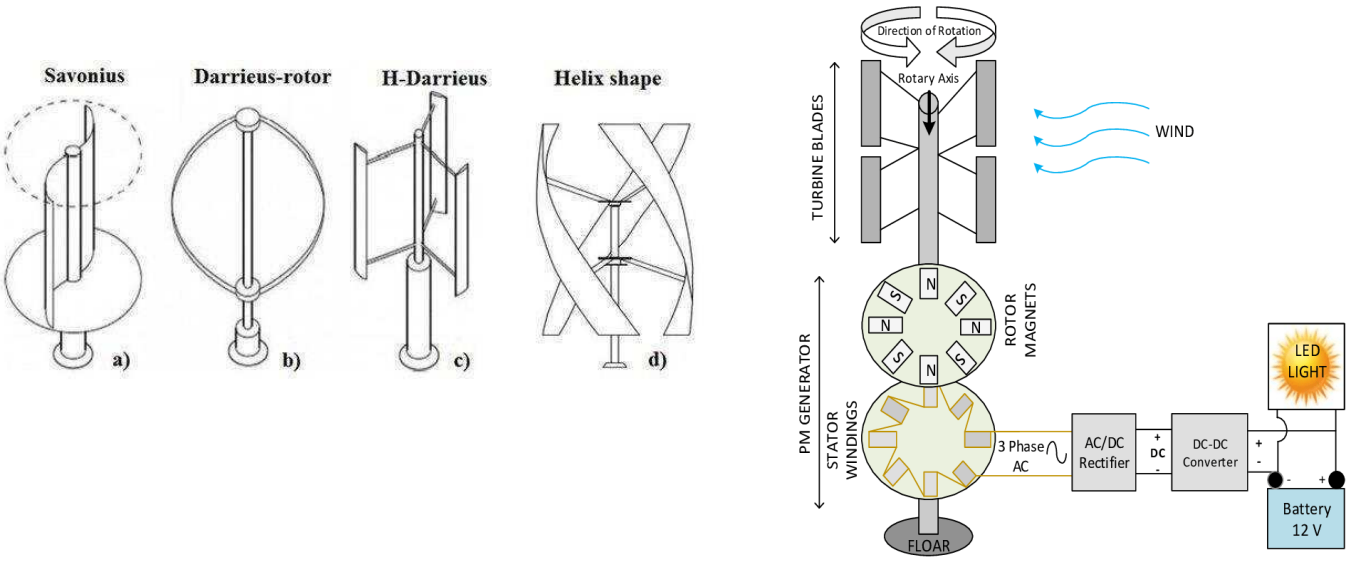

Figure 5.5 *Vertical axis turbines (Boztaş et al, 2021)(Castellani et al, 2019)*

These turbines generally have a larger footprint than horizontal-axis models since they are supported by guy cables, which can complicate installation, especially in agricultural areas. The combination of these drawbacks and lower energy conversion efficiency has limited the popularity of VAWTs compared to HAWTs (Mertens, 2006).

5.4.2. Horizontal-Axis Wind Turbines (HAWT)

HAWTs are based on traditional windmill technology and feature several aerodynamically designed blades similar to airplane wings. These turbines typically have one to three blades for electricity generation (Hansen, 2008).

The majority of existing wind installations utilize horizontal-axis turbines, which can be categorized into three types based on their power output and blade length, as shown in *Table 5.1* (Bianchi et al., 2007).

Scale	**Rotor Diameter**	**Delivered Power**
Small	Less than 12 m	Less than 40 kW
Medium	12 m to 45 m	40 kW to 1 MW
Large	46 m and above	1 MW and above

Table 5.1 *Classification of Wind Turbines*

The architecture of HAWTs includes:

- **Rotor**: Captures the wind's kinetic energy and typically consists of three blades connected to a main shaft via a central hub, rotating at speeds between 10 and 60 revolutions per minute (Hau, 2013).
- **Nacelle**: Houses the electrical generation equipment and connects to the tower through an orientation pivot.
- **Tower**: Supports the rotor and nacelle, elevating them to optimize performance by minimizing the impact of wind speed variations near the ground (Burton et al., 2011).

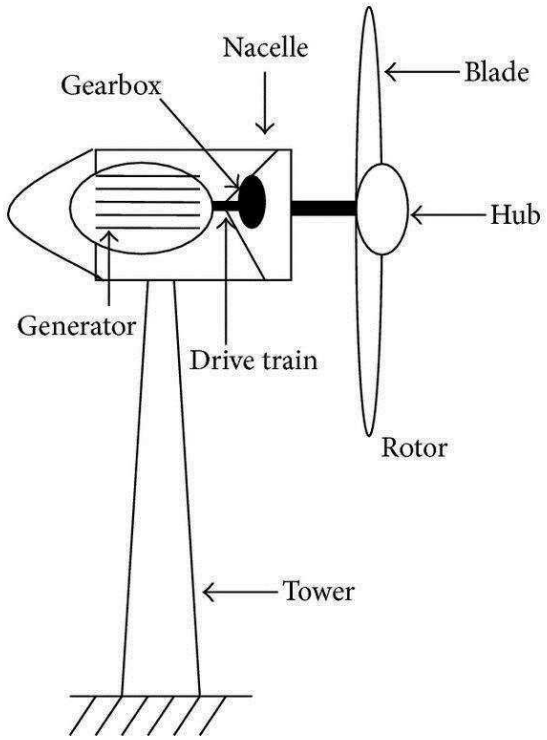

Figure 5.6 *Horizontal axis turbines (Arturo Soriano et al, 2013)*

5.5.Main Components of a Wind Turbine

- **Tower (Mast)**: Raises the rotor to access stronger winds and houses electrical components such as modulators and gearboxes.
- **Rotor**: Made of composite materials, the rotor captures wind energy
- **Nacelle**: Sits atop the tower and contains mechanical elements connecting the rotor to the electric generator
- **Electric Generator**: Converts mechanical energy into electrical energy
- **Orientation System**: Adjusts the turbine's position relative to wind direction

5.6.Operating Principle of the Wind Turbine

A wind turbine blade operates similarly to an airplane wing. As wind flows over the blade, a pressure difference is created, generating lift that pulls the blade in the direction of the wind (Hau, 2013).

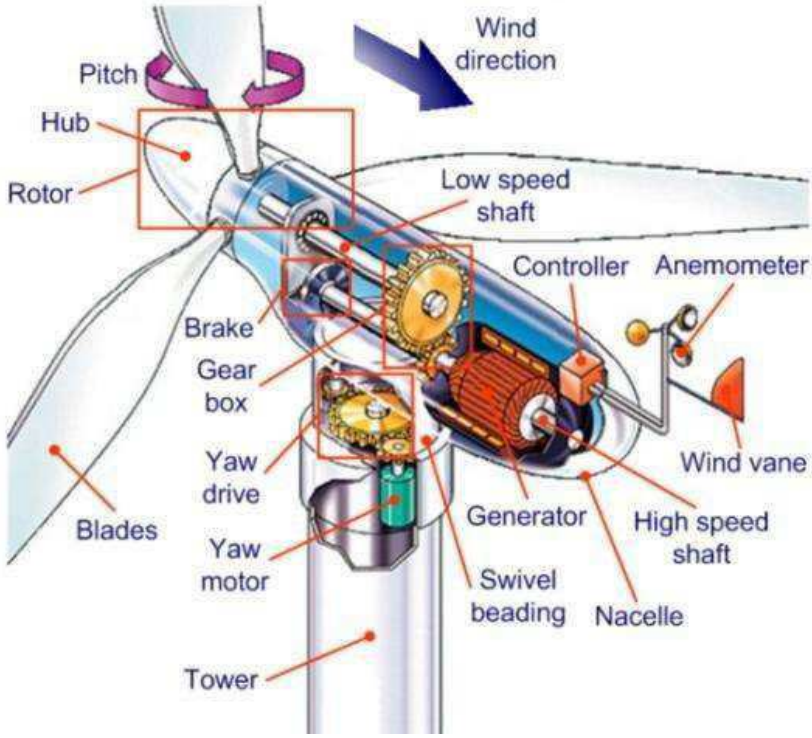

Figure 5.7 *Detailed view of a wind turbine (Christ and Abeykoon, 2015)*

Advantages and Disadvantages of Wind Turbines

Advantages:

- Wind energy is renewable and non-polluting (Ackermann & Söder, 2002).
- The modular design allows adaptability to various wind conditions and energy requirements (GWEC, 2013).
- Offshore wind farms can provide competitive output compared to nuclear energy.

Disadvantages:

- The intermittent nature of wind energy requires energy storage solutions
- Visual and noise impacts on the landscape must be considered

5.7.Regulation and Protection System of the Wind Turbine

A comprehensive regulation and protection system is essential to prevent damage to wind turbines during high winds (Bianchi et al., 2007).

5.7.1. Manual Braking System

This straightforward approach involves an operator immobilizing the wind turbine when wind speeds exceed safe thresholds (Hansen, 2008).

5.7.2. Automatic Braking System

- Variable Pitch: Adjusts blade angles to optimize energy capture and protect the turbine (Gasch & Twele, 2012).
- Fixed Pitch: Utilizes blade design to prevent excessive acceleration (Hau, 2013).

5.7.3. Variable Speed Wind Turbines

- Fixed-Speed Wind Turbine: Operates at a constant speed with slight variations (Bianchi et al., 2007).

- **Variable-Speed Wind Turbine**: Utilizes power converters to allow flexible operation (Manwell et al., 2010).

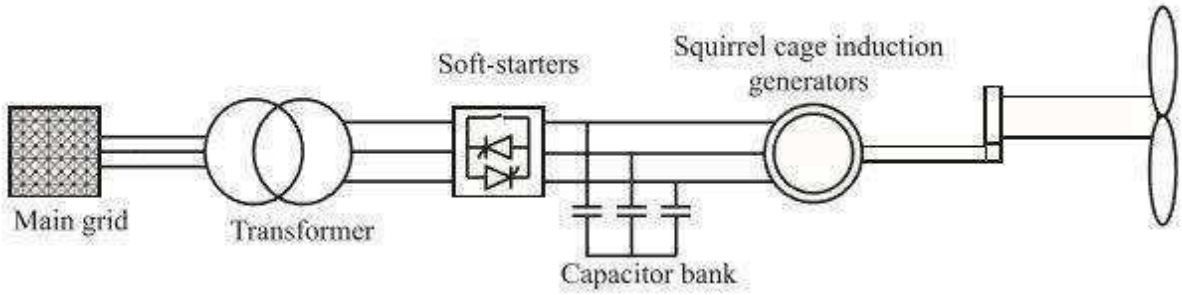

Figure 5.8 *Fixed speed wind turbine (Garba et al, 2015)*

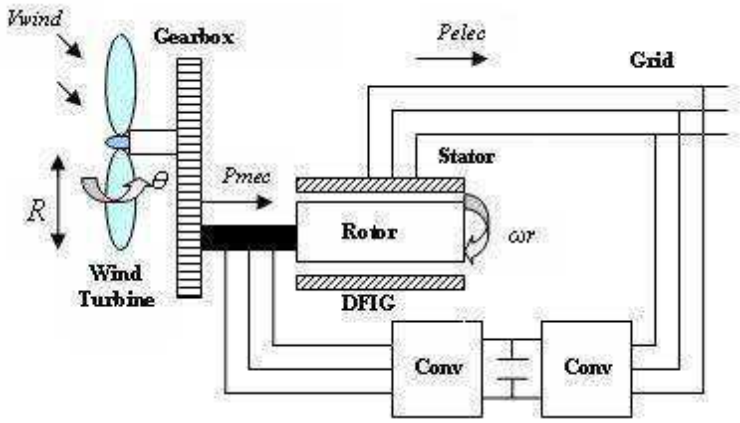

Figure 5.9 *Variable speed wind turbine (Aouani et al, 2009)*

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Chapter 6

Geothermal Energy

Chapter 6: Geothermal Energy

6.1.Introduction

Geothermal energy, derived from the Greek words "geo" (earth) and "thermos" (heat), encompasses both the scientific study of the Earth's internal thermal phenomena and the technologies developed to harness this energy (Dickson & Fanelli, 2003). This energy, emanating from the Earth's heat, can be converted into various usable forms, such as electricity and direct heating. Globally, geothermal resources are essentially limitless and can be found in numerous geographical locations, making it a vital component of the renewable energy landscape (Fridleifsson et al., 2008).

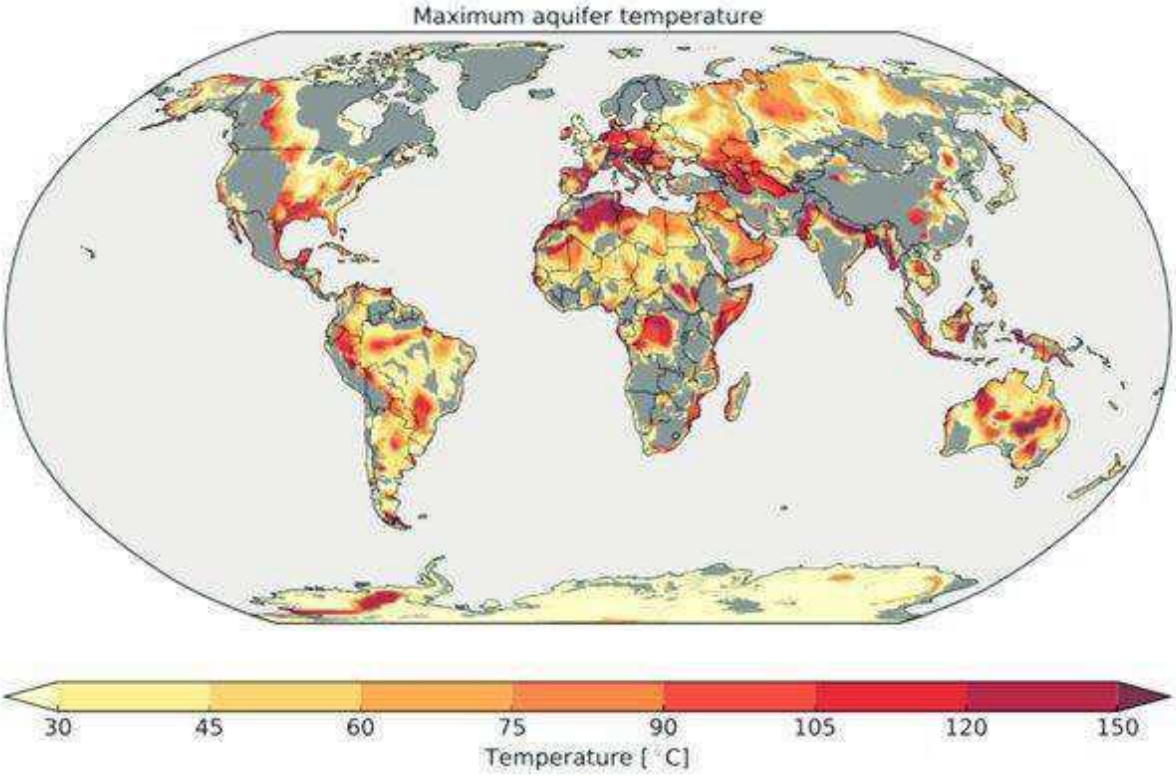

Figure 6.1 *World map of geothermal distribution (Kurek, 2021)*

6.2.Geothermal Resources

Algeria possesses significant and diverse geothermal resources. The Jurassic limestone formations in northern Algeria create essential geothermal reservoirs, resulting in over 200 thermal springs mainly located in the northeastern and northwestern regions (Saibi, 2009). Many of these springs exhibit temperatures exceeding 40°C, with Hammam Meskhoutine reaching a remarkable 98°C.

In the southern region, the Albien aquifer, part of the intercalary continental formation, constitutes a vast geothermal reservoir spanning thousands of square kilometers (Bouchareb-Haouchine, 2012). The average temperature of the water in this aquifer is around 60°C, and collectively, the Albien aquifer and thermal springs yield a combined power output exceeding 900 MW (Saibi et al., 2012). This substantial geothermal potential positions Algeria favorably in the global landscape for renewable energy sources.

6.3.Classification and Principle of Geothermal Energy

Geothermal energy can be classified based on its operational principles into two main types: shallow geothermal energy and deep geothermal energy (Rybach, 2003).

- **Shallow geothermal energy** involves the recovery of heat from the Earth's surface layer, which provides warmth in winter and coolness in summer. This type of energy effectively meets thermal needs by utilizing the thermal inertia of the ground as a sustainable resource (Sanner, 2001). For example, ground-source heat pumps can be used in residential heating and cooling systems, taking advantage of stable temperatures just below the surface.
- **Deep geothermal energy** captures heat from the Earth's crust by retrieving water that circulates through geological layers extending several kilometers deep (Barbier, 2002). This method is particularly effective in areas with volcanic activity, where the temperature gradients are higher.

6.4.Thermal Capture in Geothermal Energy

The extraction of geothermal energy is categorized into four temperature levels: high temperature, medium temperature, low temperature, and very low temperature (Fridleifsson, 2001). High- and medium-temperature sites are capable of producing electricity, while low-temperature sites utilize hot underground water, and very low-temperature sites employ heat pumps for heating purposes (Lund, 2007).

6.4.1. Horizontal Collector

Horizontal collectors differ significantly from vertical ones and are subject to building permit requirements in compliance with local regulations (Banks, 2012). Technically, these collectors must be buried at depths ranging from 0.6 to 1.8 meters, recovering an average power of 35 W per square meter of land (Sanner et al., 2003).

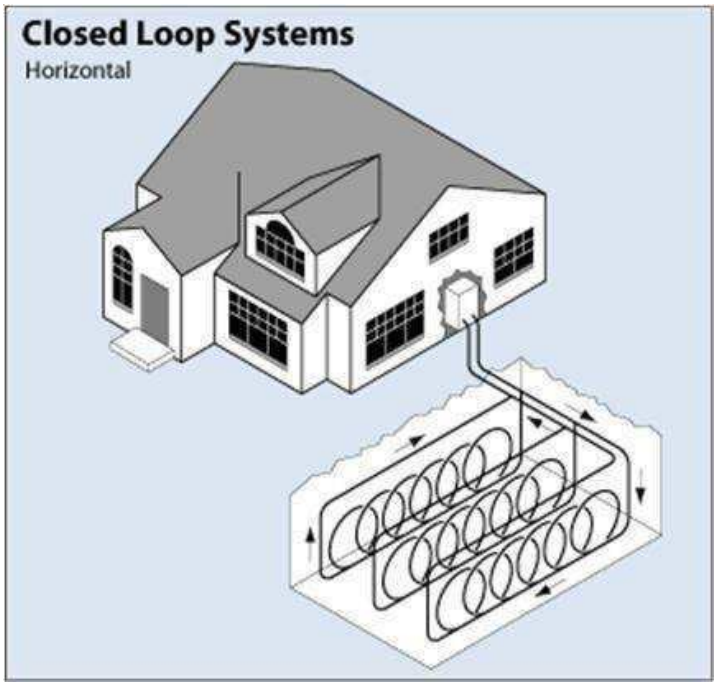

Figure 6.2 *Description of a horizontal geothermal capture (Magdy, 2024)*

Advantages:

- The depth is optimal for harnessing solar heat effectively (Rybach, 2003).
- This system contributes to reducing annual heating costs (Lund, 2007).

Disadvantages:

- Horizontal systems are generally less efficient than vertical ones due to the influence of surface temperatures at such depths
- They require a substantial land area to achieve the desired energy output

6.4.2. Vertical Collector

Vertical collectors are advantageous in that they do not require extensive land areas, although they need suitable drilling that can extend to depths of up to 100 meters (Fridleifsson et al., 2008). These systems can recover approximately 40 W per square meter, making them more efficient than horizontal collectors (Lund & Boyd, 2015).

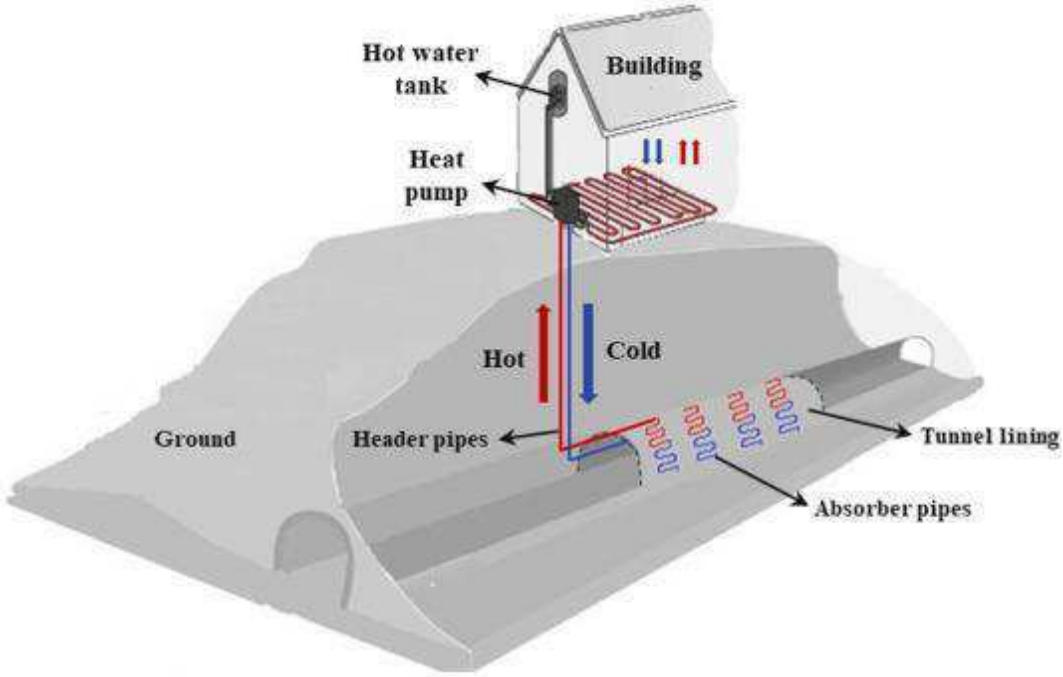

Figure 6.3 *Description of a vertical geothermal capture (Bianchini et al, 2027)*

Advantages:

- Vertical boreholes occupy significantly less land than horizontal systems (Rybach, 2003).
- They easily adapt to urban environments, making them suitable for densely populated areas (Lund et al., 2004).

Disadvantage:

- Installation costs for vertical systems can be higher than for horizontal systems, although the long-term return on investment can be favorable (Banks, 2012).

6.5.Application Areas

a. High Temperature

High-temperature geothermal resources (≥150°C) are primarily used for electricity generation. These resources can be tapped by accessing underground sources of extremely hot water, typically found in volcanically active regions (Fridleifsson, 2001).

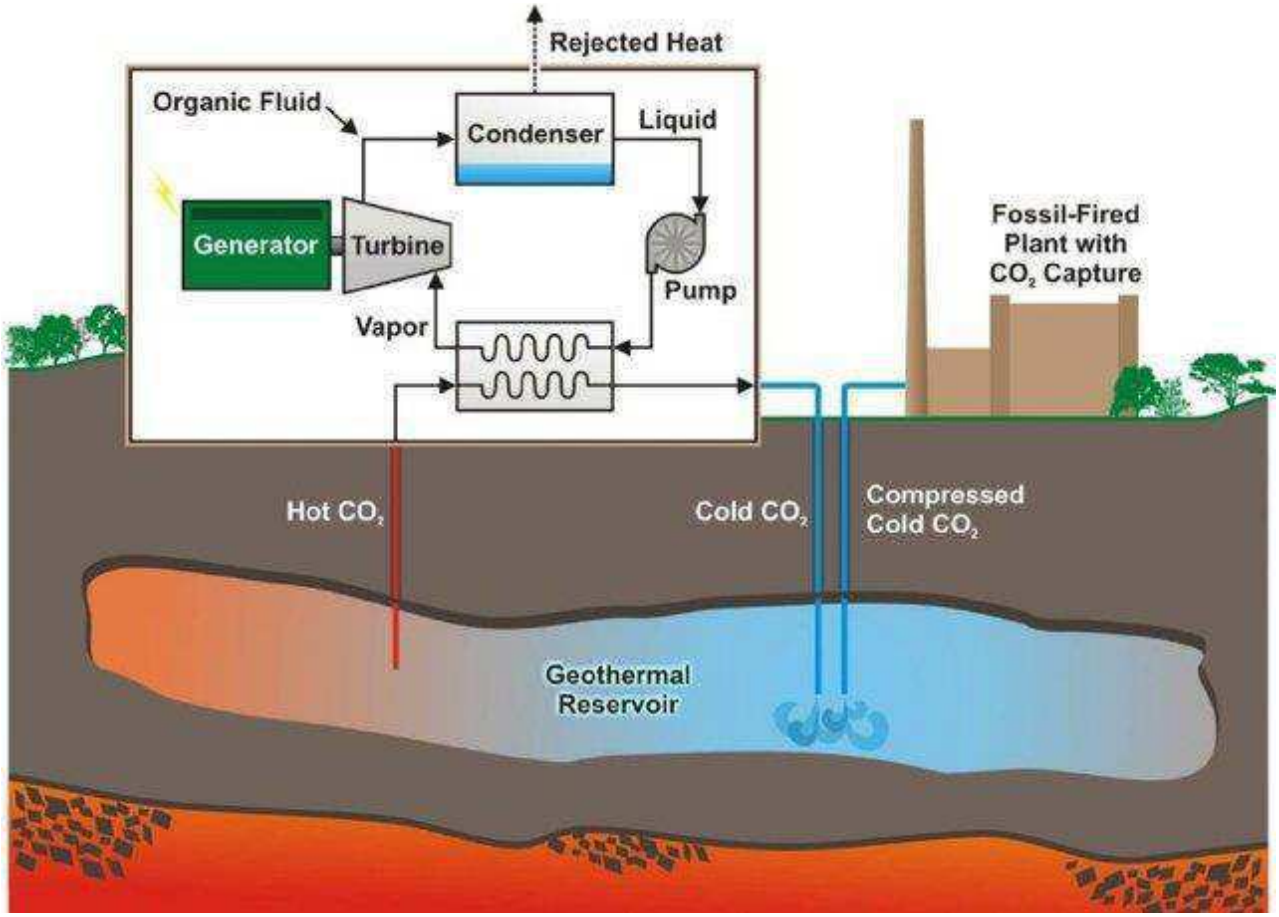

Figure 6.4 *High temperature geothermal heat capture system (Romero et al, 2016)*

b. Medium Temperature

Medium-temperature geothermal applications include:

- **Direct Use:** Heating and cooling buildings using ground-source heat pumps that exploit stable shallow surface temperatures (Lund, 2007).
- **Industrial Processes:** Applications such as food processing, laundry, and textiles that operate at temperatures between 60-140°C (Barbier, 2002).

c. Low Temperature

Low-temperature geothermal energy can be utilized in various ways:

- **Residential Heating:** Suitable for temperatures below 30°C, making it ideal for heating single-family homes and apartment buildings (Sanner, 2001).
- **Hybrid Energy Systems:** These systems can combine low-temperature geothermal resources with other clean technologies to enhance efficiency and reliability (Rybach, 2003).

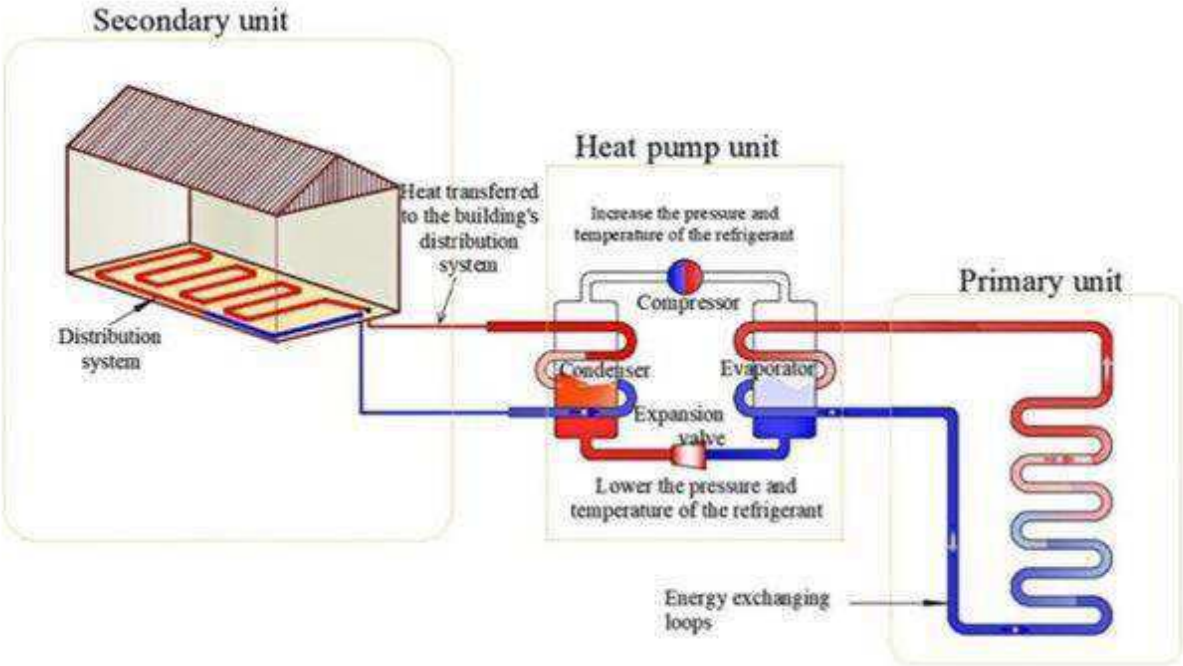

Figure 6.5 *Medium temperature geothermal heat capture system (Assad et al, 2022)*

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Chapter 7

Biomass

Chapter 7: Biomass

5.8.Introduction

Biomass refers to all organic matter derived from plant or animal sources, including wood, agricultural residues, and animal waste. This material can be converted into energy through various processes, primarily combustion (McKendry, 2002). Biomass stands out as one of the leading sources of renewable energy in Europe, surpassing hydropower, wind power, and geothermal energy in terms of production (Eurostat, 2021). The energy generated from biomass can be harnessed for electricity production through the heat released from combustion or from biogas produced by the fermentation of these materials in biomass power plants (Demirbas, 2008). Although biomass combustion does release greenhouse gases, the carbon emitted is partially offset by the carbon dioxide absorbed by the plants during their growth (Cherubini et al., 2009). Additionally, biomass can be one of the most cost-effective and localized energy sources available in the market (IEA, 2020).

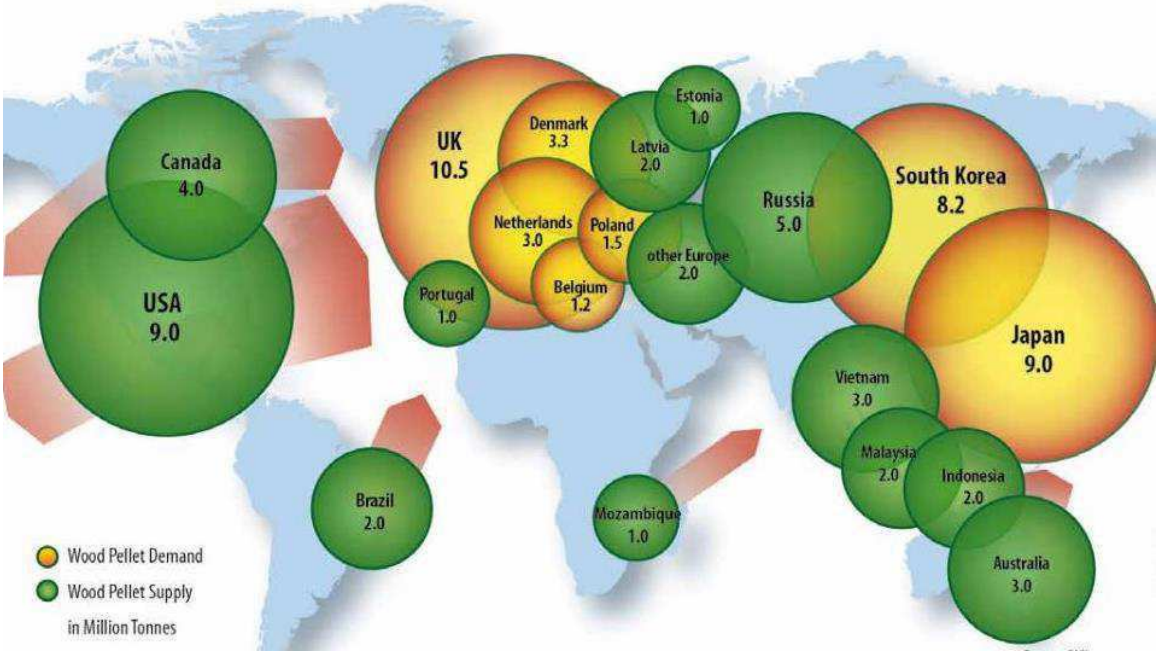

Figure 7.1 *Demand and Supply of Wooden Industrial Pallets in 2027*

5.9.Biomass Resources

Algeria's biomass potential is significant, primarily consisting of forest resources, urban waste, and agricultural residues. However, the exploitation of this biomass potential remains limited, currently occurring mainly at the laboratory and small scales (Mekhilef et al., 2011).

a. Forest Potential

The forest biomass potential in Algeria is estimated to be around 37 million tons of oil equivalent (TEP) (Boukelia et al., 2015). Of this, the recoverable potential is approximately 3.7 million TEP, with a current recovery rate of only about 10% (Saheb-Koussa et al., 2015). This underutilization indicates a significant opportunity for growth in the biomass sector, particularly if strategies for sustainable harvesting and processing are developed.

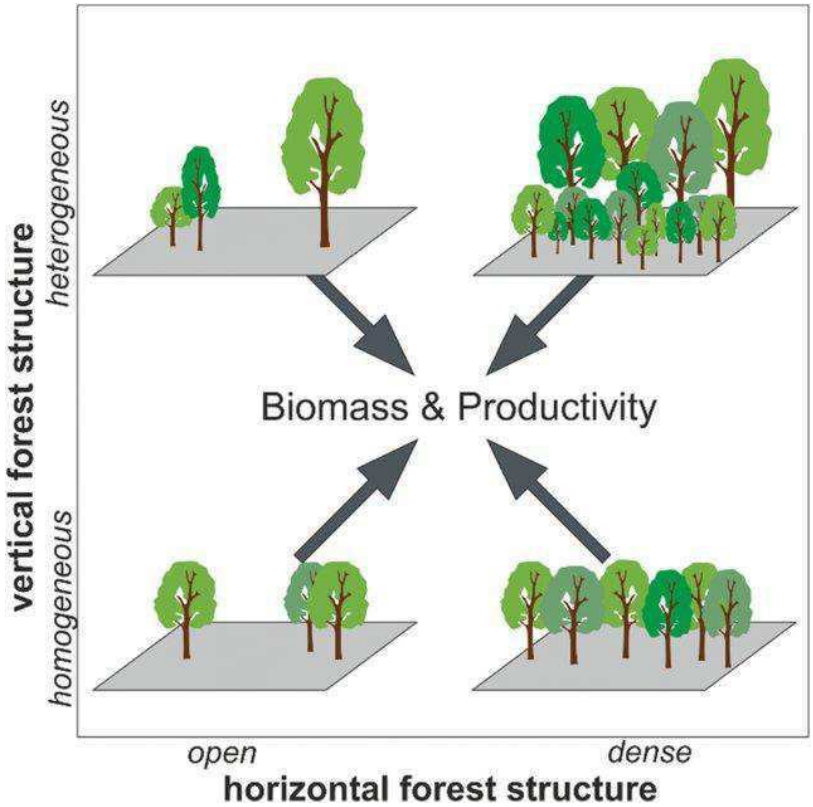

Figure 7.2 *Potential of forest biomass deposits (Fischer et al, 2019)*

b. Energy Potential of Urban and Agricultural Waste

Algeria generates approximately five million tons of urban and agricultural waste annually, much of which is not recycled (Boukelia et al., 2017). This waste represents a biomass resource of around 1.33 million TEP per year, highlighting a substantial opportunity for energy recovery from waste materials. Properly managed, this biomass could contribute significantly to the country's renewable energy portfolio.

Figure 7.3 *Potential of Biomass from Urban and Agricultural Waste Sources*

5.10. Classification and Principle of Biomass

Biomass is classified into two main categories: biomass energy and ecological biomass (McKendry, 2002).

- **Biomass energy** refers to organic materials used as a source of energy, commonly known as bioenergy (Demirbas, 2008). This includes fuels derived from biomass such as wood pellets, biofuels, and biogas.
- **Ecological biomass** is defined as the total organic matter present in a specific area at a given time, encompassing both terrestrial and aquatic biomass (Chapin et al., 2011). This classification emphasizes the importance of biomass in maintaining ecological balance and supporting biodiversity.

Biomass can be further classified into three types (McKendry, 2002):

- **Solid Biomass**: This includes wood, agricultural residues, and organic waste. Solid biomass is commonly used for direct combustion to produce heat and power (Van Loo & Koppejan, 2008).
- **Liquid Biomass**: This category comprises vegetable oils, bioalcohols (such as ethanol), and sewage sludge. Liquid biomass can be converted into biodiesel or used directly in engines (Naik et al., 2010).
- **Gaseous Biomass**: This includes biogas, which is produced through anaerobic digestion, as well as natural gas and other gaseous fuels (Weiland, 2010).

The principle of biomass energy centers on recovering energy from organic materials to produce:

1. **Heat**: This can be achieved through individual wood stoves or district heating networks (Verma et al., 2017).
2. **Electricity**: This occurs in cogeneration systems, boiler rooms, or dedicated power plants (Bauen et al., 2009).
3. **Biofuels**: Examples include ethanol, biodiesel, and other bio-based fuels (Naik et al., 2010).

Direct Combustion

The most ancient use of biomass energy dates back to the discovery of fire in prehistory, which allowed humanity to harness wood as a fuel source (Pyne, 2001). Today, the combustion of wood continues to provide heat and cooking fuel for a significant portion of the global population, particularly in developing regions (Bailis et al., 2015).

Methanization

Methanization involves the fermentation of organic materials, resulting in the production of gaseous effluents, including methane—a highly flammable gas (Weiland, 2010). By capturing and burning this gas, methanization units can generate heat or electricity, showcasing a versatile method of energy recovery (Bauer et al., 2013).

Biofuels

Biofuels, often referred to as agrofuels, are derived from agricultural or forestry products. They can exist in solid, liquid, or gaseous forms (Demirbas, 2008). The versatility of biofuels allows them to be used in various applications, including transportation, heating, and electricity generation.

Utilizing biomass energy not only decreases dependence on fossil fuels but also promotes energy independence by diversifying energy sources (IEA, 2020). The availability of a wide range of organic materials enhances the practicality of biomass as an energy source (Van Loo & Koppejan, 2008).

5.11. Advantages and Disadvantages of Biomass

Advantages of Biomass

Biomass offers several compelling benefits (Cherubini et al., 2009; IEA, 2020):

- **Renewable Resource**: Biomass is a sustainable energy source that can be replenished through careful management of biological resources.
- **Economic Potential**: Biomass can provide low-cost energy, particularly in rural areas where waste materials are abundant and can be converted into energy locally.
- **Greenhouse Gas Reduction**: Biomass use can help mitigate greenhouse gas emissions, as the carbon dioxide released during combustion is offset by what the plants absorbed during their growth cycle.
- **Energy Security**: Increased use of biomass reduces reliance on imported fossil fuels, contributing to national energy security.

Disadvantages of Biomass

Despite its advantages, biomass energy also presents challenges (Haberl et al., 2012; Searchinger et al., 2008):

- **Resource Management Risks**: Unsustainable practices in biomass harvesting can lead to deforestation, soil degradation, and loss of biodiversity.
- **Environmental Impact**: The use of biomass can result in air pollution and other environmental impacts, particularly if not managed properly.
- **Market Volatility**: As demand for biomass energy grows, prices for raw materials may increase, potentially making it less economically viable.
- **Land Use Competition**: Biomass production can compete with food production, leading to potential conflicts over land use.

5.12. Areas of Application

Biomass energy has diverse applications across various sectors (Bauen et al., 2009; McKendry, 2002):

- **Electricity Generation**: Biomass can be converted into electricity in dedicated power plants, contributing to the energy mix (Demirbas, 2008).
- **Heating and Cooling**: Biomass systems can provide space heating for residential and commercial buildings (Verma et al., 2017).
- **Combined Heat and Power (CHP)**: CHP systems utilize biomass to produce both heat and electricity, offering higher efficiency compared to separate systems (Bauen et al., 2009).
- **Transport Fuels**: Biomass can be converted into liquid fuels suitable for transportation, such as biodiesel and ethanol (Naik et al., 2010).

- **Waste Management**: Biomass energy systems can help manage waste by converting organic waste into energy, thereby reducing landfill burden (Kothari et al., 2010).
- **Industrial Applications**: Biomass can be used in various industrial processes, providing hot water or steam (Van Loo & Koppejan, 2008).
- **Gas Production**: Biomass can be processed through anaerobic digestion and gasification to produce biogas, a valuable renewable energy source (Weiland, 2010).

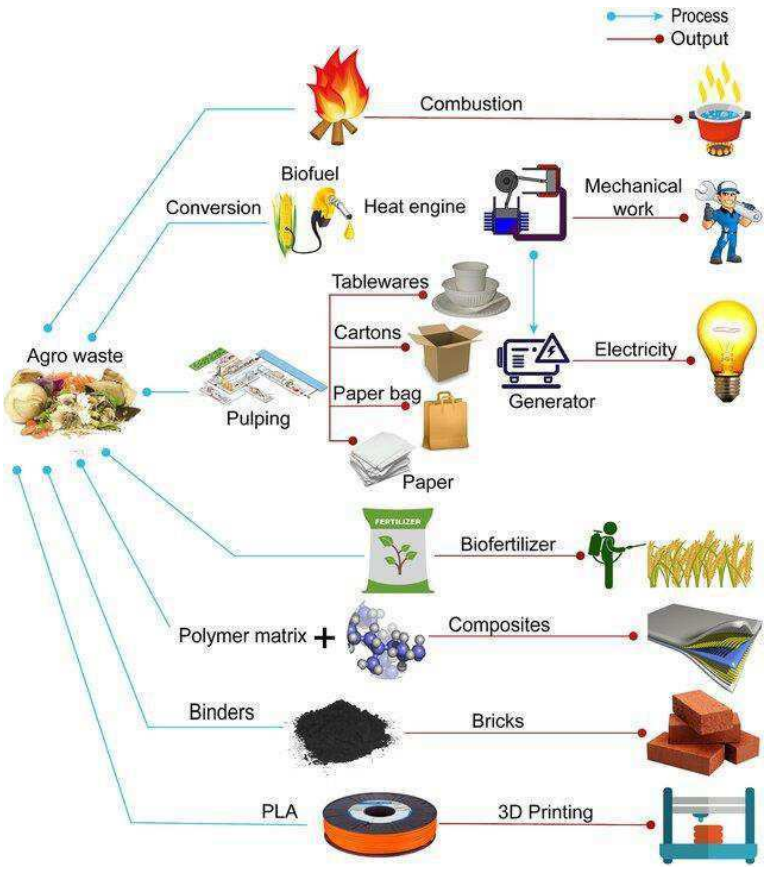

Figure 7.4 *Biomass utilization for various end-use applications (Gupta et al, 2022)*

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Conclusion

Conclusion

The transition to renewable energy represents a fundamental shift in how societies generate, distribute, and consume power. As the global community confronts the dual challenges of finite fossil fuel resources and the urgent need to mitigate climate change, renewable energy technologies offer a viable and sustainable pathway forward. Their capacity to provide clean, abundant, and increasingly cost-effective energy is critical to achieving environmental sustainability, energy security, and economic development. This course has equipped students with a comprehensive understanding of the scientific principles, technological advancements, and policy considerations underpinning renewable energy systems. By integrating knowledge of solar, wind, geothermal, biomass, and other renewable sources, learners are prepared to analyze, design, and implement solutions that contribute to the decarbonization of the global energy sector.

Ultimately, the successful adoption and expansion of renewable energy depend on continued innovation, interdisciplinary collaboration, and informed decision-making. Graduates of this course will be well-positioned to play an active role in shaping a resilient and sustainable energy future that balances ecological stewardship with societal needs.

Renewable technologies not only reduce greenhouse gas emissions but also improve energy security and create economic opportunities. Wind power, for example, is increasingly cost-competitive with fossil fuels when accounting for environmental externalities, and energy storage solutions are evolving to address intermittency challenges. Furthermore, community-based renewable energy initiatives are emerging, enhancing local energy autonomy and reducing costs

In summary, renewable energy is a cornerstone of the clean energy transition, offering scalable, sustainable solutions to meet growing energy demands while mitigating climate change. Continued innovation, policy support, and investment are critical to accelerating deployment and integrating diverse renewable sources into global energy systems