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Option : Renewable Energy and Environment

Chapter 1: Overview of Solar Resource

I.1 Introduction:

Solar energy is the most abundant renewable energy source available on Earth. Every day, the planet receives a considerable flow of energy in the form of electromagnetic radiation, a fraction of which can be converted into heat or electricity. However, efficient exploitation of this resource requires precise knowledge of its energy potential.

The assessment of solar resources is based on the study of radiation characteristics, atmospheric absorption and scattering phenomena, as well as on the consideration of climatic parameters such as cloudiness, humidity, and cloud cover. Several methods are available: direct measurements using specialized instruments (pyranometers, pyrheliometers), empirical methods based on meteorological correlations, analytical models derived from solar geometry, as well as satellite data and simulation software. These approaches make it possible to produce solar maps, establish indicators such as annual irradiation or the clearness index, and guide the sizing of solar systems (photovoltaic or thermal) in various fields, including electricity generation, heating, solar drying, and bioclimatic urban planning.

Thus, **the estimation of solar energy resources** is an essential step to ensure the **techno-economic** viability of **solar energy projects**.

I.2 Characteristics of Solar Radiation:

Solar radiation is the primary source of energy for the Earth. It drives natural processes (photosynthesis, the water cycle, and climate) as well as energy technologies (drying, photovoltaics, and solar thermal systems). Understanding solar radiation requires studying its physical, spectral, and geometrical characteristics.

I.2.1 The solar constant

By definition, the solar constant (Gsc) is the energy flux received outside the Earth's atmosphere, on a surface perpendicular to the solar rays, at the mean Earth–Sun distance. Its average value is estimated at **1367 W/m²**.

Currently, this variable solar value is more accurately referred to as the **Total Solar Irradiance (TSI)**, while the term *"solar constant"* should be used only to describe the long-term average of the TSI.

The annual variation of the solar constant is related to the **elliptical orbit of the Earth** (i.e., the day of the year). Since the distance between the Earth and the Sun changes throughout the year, a **minimum** occurs around **January 3**, known as the *Perihelion*, and a **maximum** around **July 5**, called the *Aphelion*.

The **extraterrestrial solar irradiance** on the n^{th} day of the year is expressed by the following equation (Eq. I.1):

$$G_{on} = G_{on} \times (1 + 0.033 \times \cos\left(\frac{365 \times n}{360}\right)) \qquad (I.1)$$

where n = Julian day number (for example, January 2 corresponds to $n = 2$, February 1 to $n = 32$, and so on).

I.2.2 Components of solar radiation at Earth's surface

In practice, the total radiation received on a surface—called **incident solar irradiation** (or **global solar irradiance**)—is defined as the sum of three components, as illustrated in Figure I.1:

- **Direct irradiation**, which comes directly from the Sun. This component becomes zero when the Sun is obscured by clouds or an obstacle.
- **Diffuse irradiation**, which corresponds to the radiation received from the sky dome, excluding direct sunlight. This energy, scattered by the atmosphere and directed toward the Earth's surface, can represent up to **50%** of the total global radiation when the Sun is low on the horizon, and up to **100%** under a completely overcast sky.
- **Reflected irradiation**, which corresponds to the radiation reflected by the surrounding environment, particularly the ground, whose reflection coefficient is called the **albedo**.

$$G = G_b + G_d \qquad (I.2)$$

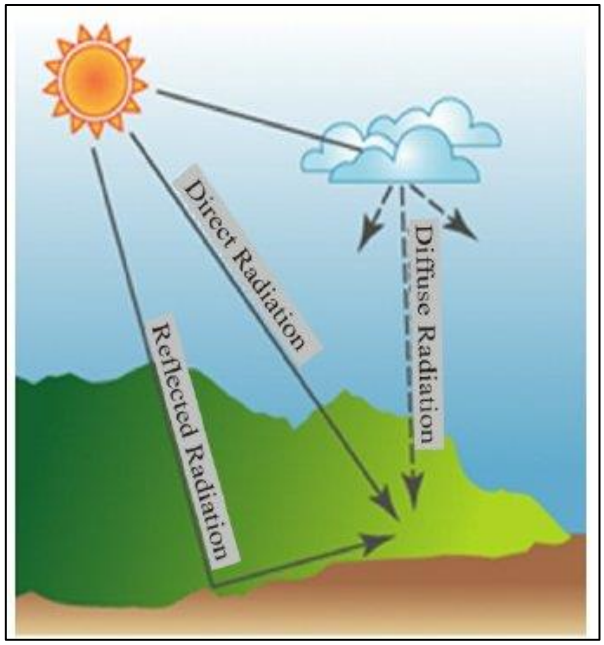

Figure I.1 : Component of Solar Radiation [Web1].

On a cloudy day, almost all the solar radiation reaching the Earth is **diffuse**; whereas on a clear day, about **15–20%** of the total solar radiation reaching the surface is diffuse. The importance of **direct radiation** depends on the **attenuation by the atmosphere**, which is caused by **scattering and absorption**. Under clear sky conditions, approximately **80%** of the solar radiation reaching the Earth's surface is **direct radiation**.

These distinctions are important for solar energy applications, since **concentrating solar collectors** use only **direct solar radiation**, while **flat-plate solar thermal collectors** can utilize **the entire solar radiation**. Clouds absorb very little solar radiation, which explains why they do not evaporate in sunlight. The effect of clouds on solar radiation is mainly due to **scattering and reflection**.

Atmospheric pollution—especially in urban areas—along with **smoke from forest fires** and **ash from volcanic activity**, reduces solar radiation by increasing both **scattering** and **absorption** of solar energy.

I.2.3 Solar Radiation Spectrum

The solar radiation received at the outer limit of the Earth's atmosphere is called **extraterrestrial solar radiation**. The **spectral distribution** of this radiation approximately follows that of a **black body** at a temperature of **5760 K**, whereas the **solar radiation spectrum**

at sea level always shows lower values due to the **influence of the Earth's atmosphere**, as illustrated in Figure I.2**.**

Extraterrestrial solar radiation is available everywhere on Earth, but only a fraction of it reaches the ground. This fraction varies according to atmospheric conditions—it can reach up to **85%** on a clear day, but may drop to **5%** on a very cloudy day.

The **reduction of solar radiation** during its passage through the Earth's atmosphere is influenced by the following phenomena: **absorption** by atmospheric constituents, **scattering** by air molecules and aerosol particles, and **reflection** by clouds, which is **independent of wavelength**.

The **energy distribution** of the radiation reaching the Earth's surface is shown in Figure I.3**,** and includes the following spectral ranges:

- **UV (200–400 nm):** ~8%
- **Visible (400–700 nm):** ~47%
- **Infrared (700–2500 nm):** ~45%.

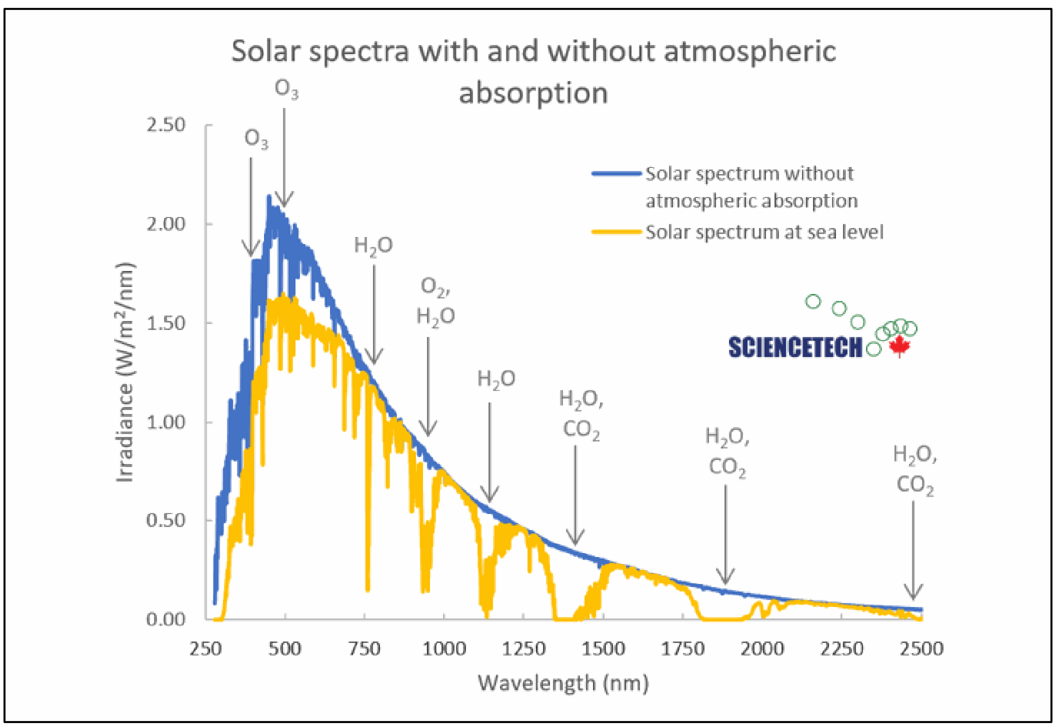

Figure I.2 : Spectral distribution of extraterrestrial and sea-level solar radiation.[Web2]

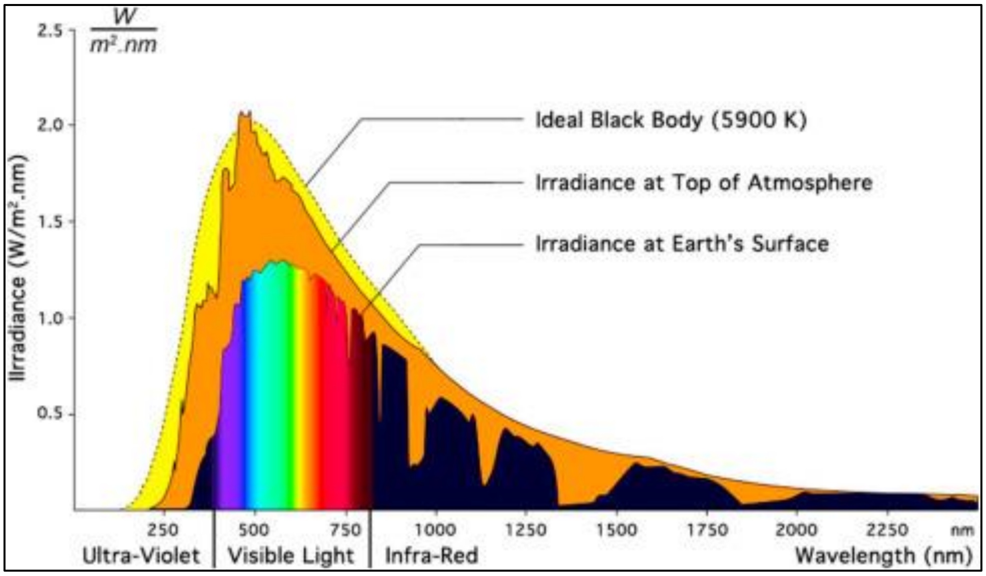

Figure I.3: Solar radiation spectrum [Web 3].

I.3 Measurement of solar radiation :

The measurement of solar radiation is essential for evaluating the available energy resources, sizing photovoltaic and thermal systems, and analyzing the performance of processes such as solar drying. Several instruments have been developed to measure the different components of radiation (global, diffuse, direct, and infrared).

The measurement of solar radiation relies on specific instruments adapted to each component. The **pyranometer** is the most commonly used device; it measures the **global radiation** (direct + diffuse) received on a horizontal or inclined surface. The **pyrheliometer** measures the **Direct Normal Irradiance (DNI)** using a collimating tube pointed toward the Sun, often with the help of a **heliostat**. The **heliograph** records the **sunshine duration**, while the **pyrgeometer** is designed to measure **infrared radiation** emitted by the Earth and the atmosphere. These instruments require regular maintenance (such as dome cleaning and calibration) to ensure accurate measurements.

When pyranometers or pyrheliometers are not available, **solar radiation can be estimated** from simple meteorological parameters such as **sunshine duration, cloudiness, air temperature,** and **relative humidity**. These methods are based on **empirical or semi-empirical correlations** that have been validated for a specific region.

The symbols generally used for **solar radiation** are as follows: **G** is used for **instantaneous values**, **I** for **hourly values**, and **H** for **daily, weekly, monthly, or annual values**. These symbols are sometimes accompanied by subscripts: **b** for **beam (direct) radiation**, **d** for **diffuse radiation**, **0** for **extraterrestrial radiation**, **T** for **radiation on a tilted surface**, and **n** for **radiation on a plane normal to the direction of propagation**.

The most commonly used **methods for measuring global solar radiation** are listed below.

I.3.1 Methods Based on Sunshine Duration

a. Ångström–Prescott Relationship

It is the **most widely used method** to estimate **daily global irradiation** on a horizontal surface. It is simple and reliable if **sunshine duration data** are available, but it requires **local calibration**. This method is expressed by the following formula:

$$\frac{H}{H_0} = a + b \times \frac{n}{N} \qquad \text{(I.3)}$$

Where:

H: daily global irradiation on a horizontal surface

H_0: daily extraterrestrial irradiation

n: actual sunshine duration

N: maximum possible day length

a, b: empirical coefficients, depending on the local climate

b. Improved variants

In an alternative formula, a **quadratic term** can be introduced, and the equation is expressed as follows:

$$\frac{H}{H_0} = a + b \times \frac{n}{N} + c \times \left(\frac{n}{N}\right)^2 \qquad \text{(I.4)}$$

Additional parameters such as **average cloudiness** or **relative humidity** can also be included.

I.3.2 Methods Based on Cloudiness and Cloud Cover

Cloudiness represents the fraction of the sky covered by clouds, and **cloud cover** strongly influences the amount of solar radiation reaching the ground. Since direct instrumental measurements are not always available, several **empirical methods** have been developed to estimate solar irradiation from these data.

The **cloudiness index (in oktas)** is defined as the fraction of the sky covered by clouds, expressed between **0** (clear sky) and **1** (completely overcast sky). **Statistical relationships** establish a correlation between the cloudiness index and the **daily global radiation**. As cloud cover increases, **H** decreases, and the **diffuse fraction** becomes more significant.
For example; simple linear form (very common)

$$\frac{H}{H_0} = a + b \times (1 - C) \qquad \text{(I.5)}$$

Where;

H = daily global irradiation on a horizontal surface

H_0= daily extraterrestrial irradiation

C = cloud fraction (0 = clear, 1 = overcast)

a,b = empirical coefficients (local calibration required)

I.3.3 Methods Based on Air Temperature

Some correlations relate the daily global irradiation to the daily temperature range:

$$H=a+b(Tmax-Tmin) \qquad \text{(I.6)}$$

A high level of sunshine results in a large difference between maximum and minimum temperature. This method is used in regions where only temperature data are available.

I.3.4 Combined Methods

It is possible to combine several meteorological variables — such as sunshine duration, temperature, relative humidity, and precipitation — to estimate the daily global irradiation. Alternatively, statistical models or **Artificial Neural Networks (ANN)** can be used to improve the accuracy of the estimation.

I.3.5 Estimation Using Atmospheric Models and Databases

When local data are scarce, one can rely on data obtained from:

- **Satellites:** sources such as NASA-POWER, Meteosat, PVGIS, and SolarGIS.
- **Interpolated databases:** Meteonorm combines ground measurements with satellite data.

• **Physical models:** simulate the transmission of solar radiation through the atmosphere, taking into account absorption and scattering (e.g., MODTRAN, SMARTS).

I.4 Estimation of Solar Energy Resources:

The estimation of solar resources involves quantifying the amount of energy available at a given site. This allows for the **design of solar installations** (photovoltaic, thermal, dryers), **regional energy planning**, and **comparison between different locations**.

To evaluate the solar potential, several indicators are used:

- **Irradiance (W/m^2):** instantaneous power received per unit area.
- **Irradiation (Wh/m^2 or kWh/m^2):** energy received over a given period (day, month, year).
- **Sunshine duration (h/day or h/year).**
- **Clearness index (K_t):** ratio between the received global radiation and the extraterrestrial radiation.

To estimate solar resources, the following information is required:

• The site's **latitude and longitude**.

• **Meteorological data:** sunshine duration, cloudiness, temperature, humidity, wind.

• **Instrumental measurements** (pyranometer, pyrheliometer).

• **Satellite databases.**

I.4.1 Methods for Estimating Solar Energy Resources:

a. Empirical Methods

Empirical methods are based on statistical correlations established between available meteorological data (sunshine duration, cloudiness, temperature) and solar radiation. For example, the **Angström–Prescott correlation** links sunshine duration to the received global solar radiation. It can be applied with limited data, but its validity is often local and depends on the climatic conditions of the studied region.

b. Satellite Measurements

Meteorological satellites provide estimates of solar radiation using images of cloud cover, Earth's albedo, and atmospheric humidity.

• **Advantage:** global coverage and long time series (several decades).

• **Example:** NASA SSE, Meteosat, HelioClim databases.

• **Limitation:** spatial resolution may be insufficient for small local installations.

c. Analytical Methods

Several software tools combine meteorological data, physical models, and satellite databases to provide reliable estimates.

• **PVGIS (Photovoltaic Geographical Information System):** free tool developed by the European Commission.

• **HOMER, RETScreen, SAM (NREL):** tools for simulation and sizing of solar systems.

• These also integrate performance models for photovoltaic panels and solar thermal systems.

I.4.2 Solar maps

Solar maps illustrate the **geographical distribution of solar potential**. They are used to **select suitable locations** for the installation of **solar thermal and photovoltaic power plants**. These maps provide the **annual average solar irradiation** expressed in **kWh/m²/year**. An example is shown in Figure 4.

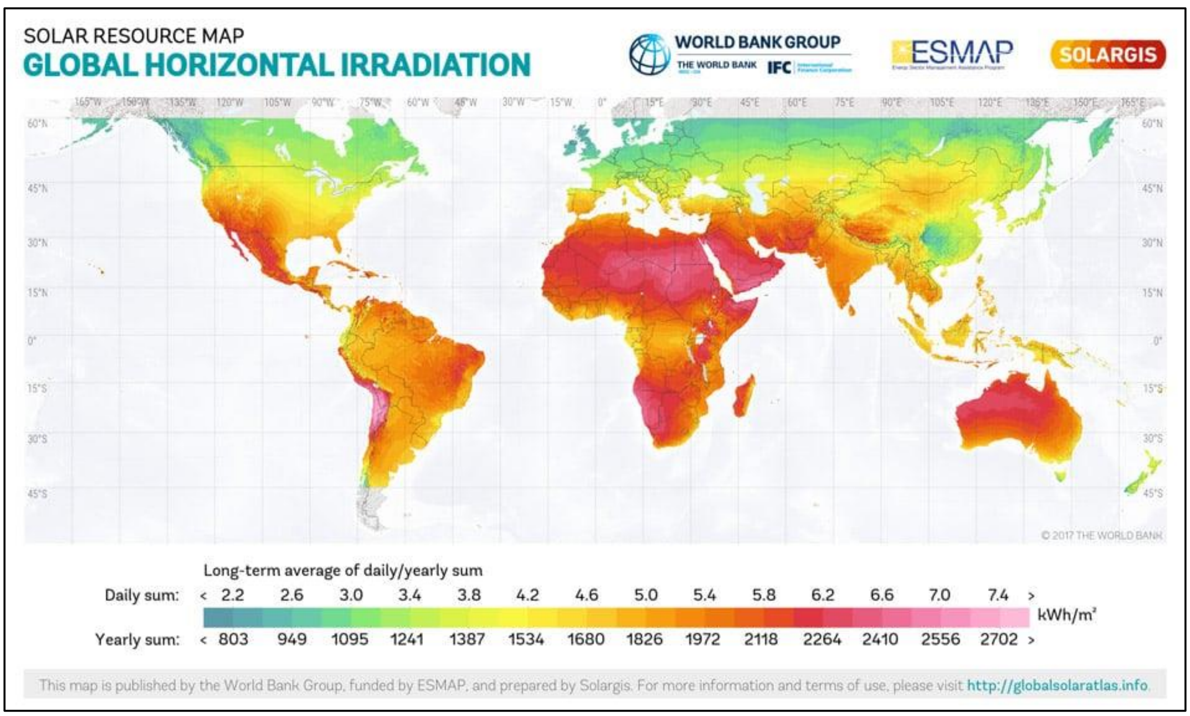

Figure I.4: Modeling of the Unequal Distribution of Solar Energy in the World: Here, the "GHI" (Global Horizontal Irradiation) is shown (source: Global Solar Atlas, World Bank) [Web 4].

I.4.3 Applications of Solar Resource Estimation

Accurate estimation of solar resources plays a key role in the development and planning of sustainable energy systems. It enables the assessment of solar energy availability and the optimization of its use across various sectors. The main applications include:

- **Sizing of photovoltaic systems:** Global solar irradiation data are used to calculate the expected annual energy production, optimize the installed panel surface, and evaluate the system's economic profitability.
- **Feasibility studies for solar thermal power plants:** Knowledge of the solar potential is essential for sizing thermal collectors, solar fields, and energy storage systems.
- **Electric grid management:** With the increasing share of renewable energy, solar radiation forecasting helps stabilize the grid, plan production schedules, and prevent energy imbalances.
- **Agriculture:** Solar energy is widely used for crop drying, soil sterilization, and greenhouse heating, promoting sustainable and energy-efficient agricultural practices.
- **Urban planning and bioclimatic architecture:** Solar potential assessment supports building orientation, façade design, and the integration of passive solar systems to reduce energy consumption and enhance thermal comfort.

Web1 :https://www.researchgate.net/publication/239847020_Assessment_of_the_Direct_SunLight_on_Rural_Road_Network_through_Solar_Radiation_Analysis_Using_GIS/figures?lo=1

Web2 : https://sciencetech-inc.com/blog/knowledge-centre-7/post/solar-simulators-overview-applications-and-types-24

Web 3: https://www.connaissancedesenergies.org/fiche-pedagogique/energie-solaire

Web 4: https://ar.m.wikipedia.org/wiki/%D9%85%D9%84%D9%81:World_GHI_Solar-resource-map_GlobalSolarAtlas_World-Bank-Esmap-Solargis.png