CHAPTER 1

INTRODUCTION

*This chapter introduces the topics related to the present work. **Section 1.1-1.8** gives an overview of the topics, theories, and definitions relevant to the present work. **Section 1.9** provides the motivation of the work. **Section 1.10** presents the research objectives of the work and their significance, and **Section 1.11** deals with the structure of the thesis.*

1.1 Solar energy

Solar energy is generated by nuclear fusion in the sun. This energy source is known for its everlasting, renewable, clean, and equitable availability. About 1.8×10^{11} MW of solar energy gets intercepted by the earth, which is significantly more than the present total amount of power use [1].

The renewable energy sources came to focus in 1970s due to oil crises. During that period the energy insecurity increased significantly mainly the fossil fuel leading to the various governments including the developed countries to initiate programs in search of renewable energy sources. Other factors that supported its importance and growth are concerns related to emission of greenhouse and global warming, uneven distribution of fossil fuel and oil fields, greater financial risk and uncertainty [1]. The global oil and natural gas hike in late 2020 due to the relaxation of COVID-19 restrictions and the Russian-Ukraine war has raised concerns about obtaining net zero emissions through enhanced technological support and progress. Thus, this has declined the cost of photovoltaic, wind energy storage systems, and other renewable energy. Total amount of electricity generated from fossil fuels has dropped from 65% to 62% in 2018-2021, the reason being the growth in the contribution of photovoltaic and wind in electricity production. The total contribution of renewable in electricity generation has increased from 500 TWh in 2020 to 8000 TWh in 2021, especially due to generations from solar photovoltaic and wind as reported by International Energy Agency (IEA) in World Energy Outlook, 2022 [2]. Figure 1.1 depicts the share of renewable energy in the capacity addition for various regions by stated policies scenario (STEPS) over 2022-2050. In India, energy demand and gross domestic product (GDP) are rising over 3% and 7% yearly in the STEPS from 2021 to 2031. Government initiative programs, including the Gati Shakti National Master Plan and the Self-Reliant India scheme, have raised the renewable and sale of electric vehicles in the STEPS. By 2030, 35% of the generation could be made by renewable and 15% of the generation solely by solar energy.

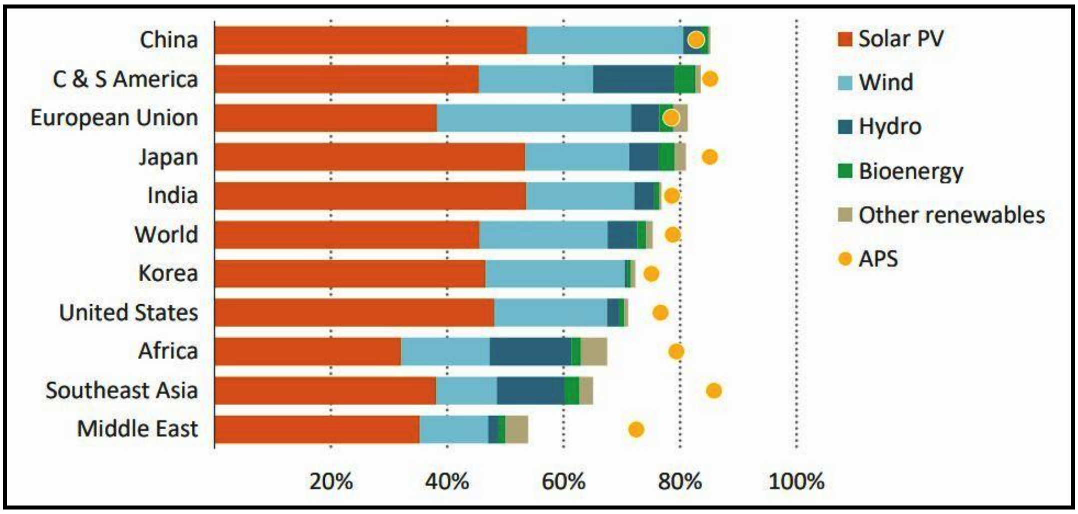

Figure 1.1 Renewable accounts for total power capacity addition in the stated policies scenario (STEPS) over the 2022-2050 outlook period. (C&S: Central and South, APS: Announced Pledges Scenario) [2].

1.2 Solar spectrum

The sun radiates electromagnetic waves from X-rays to the radio wave. However, 99 % of solar radiation energy is dominant in the visible, ultraviolet, and infrared regions of the spectrum (150 - 4000 nm), with the peak of the spectrum in the visible wavelength region. Variability in the solar spectrum received by the earth's atmosphere over a year changes around 6.6% due to changes in the earth-sun distance and changes around 1% due to solar activity [3]. The absorption and scattering phenomena alter the radiation in the atmosphere on its way to the earth surface. Figure 1.2 shows the absorption and scattering by various components in the atmosphere on a typical clear sky day at air mass one (AM1). Out of 100% solar radiation, 70% is received by the earth's surface directly, and 7% reaches after the scattering process in the atmosphere. In comparison, 3% and 18% of the solar radiation gets scattered back and absorbed, respectively [4]. AM is the path length the sun's ray passes through the atmosphere normalized to the path length at its minimum (sun positioned directly overhead). It quantifies the power loss of light due to its scattering and absorption by atmospheric air molecules and dust particles as it passes through the atmosphere [5]. The equation to express the air mass (AM) is as follows:

$$AM = \frac{1}{cos\theta} \qquad (1.1)$$

where θ is the zenith angle. Zenith angle is the angle between the sunbeam and the vertical. For instance, when $\theta = 0°$, AM value is equal to 1, and AM1 is the solar spectrum when the sun is directly overhead (at sea level). AM0 is the extraterrestrial solar spectrum on top of the atmosphere (close to the blackbody spectrum), emitted by the sun with the integrated spectral irradiance of 1366 W/m^2. The AM value increases as the zenith angle increases.

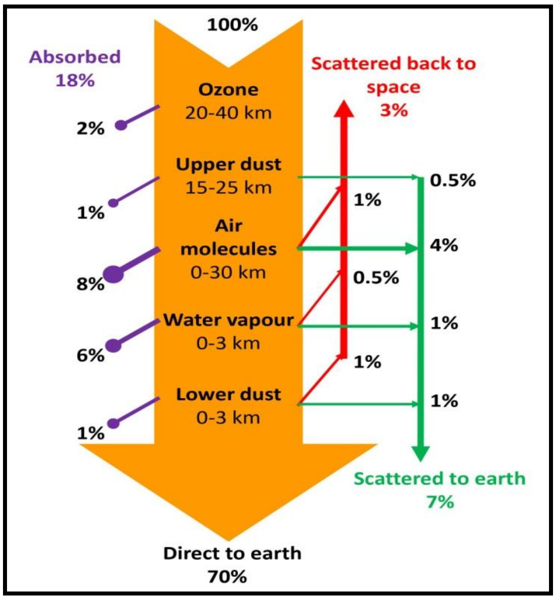

Figure 1.2 Typical absorption and scattering of incident sunlight at air mass one (AM1) under clear sky conditions [4].

Figure 1.3 illustrates the solar spectrum at the top of the atmosphere (AM0) at the ground for a range of wavelengths. The air molecules and particulates absorb solar radiation at a range of wavelengths. The ozone (O_3) and oxygen (O_2) absorb the ultraviolet (UV) irradiance at wavelength below 300 nm. The fraction of visible irradiance gets altered by the clouds and aerosol. The water vapor (H_2O), $O_{2,}$ and O_3 absorb infrared irradiance.

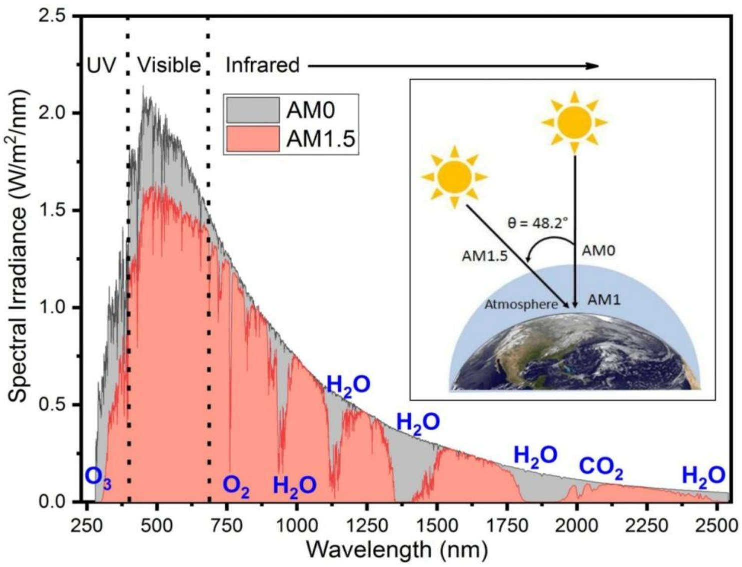

Figure 1.3 Solar spectrum for a range of wavelengths on the top of the atmosphere and the ground [6].

1.3 Photovoltaic technology

The conversion of solar energy directly to electrical energy is termed as Photovoltaics (PV). The photoelectric effect is the process through which electricity is generated from solar cells when exposed to sunlight. In 1839, Edmund Becquerel discovered this effect while experimenting with wet cells to observe the rise in voltage when its silver plates were under sunlight exposure. This process primarily results due to the intrinsic properties of the semiconductor materials like silicon and germanium. These semiconductor materials are doped with pentavalent and trivalent element to produce n-type and p-type semiconductor, respectively, and eventually to form p-n junction. When sunlight is incident on these materials, electrons are excited by the incident photon energy, and current is generated due to the movement of electrons and holes. The first silicon solar cell was manufactured by Chapmin in 1954. The PV technology found its first applications in space missions and remote Electricity stations. Although photovoltaics have been around since 1950's the terrestrial applications were heightened during the oil embargo period of the 1970s. The solar industry has never looked back since and has been widely developed across the globe.

The solar cell is essentially a p-n junction which is formed by coupling the n and p-type materials. The n-type materials have excessive electrons, and the p-type materials have excessive holes. Due to the higher gradient the electrons diffuse from n-type to p-type, leaving behind a positive (+ve) charge. In a similar way, the holes diffuse from p-type to the n-type, leaving negative (-ve) charge, generating an electric field at the interface [7]. The basic working principle of the solar cell is shown in Figure 1.4.

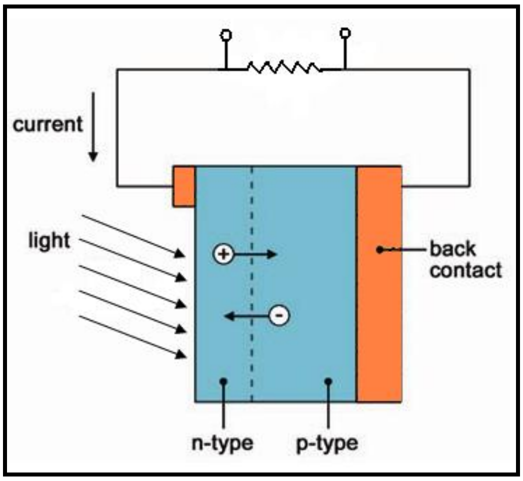

Figure 1.4 Circuit diagram of solar cell highlighting the components [8].

The sunlight, when incident on the solar cell, excites an electron on the n-type material and moves it across the junction towards the p-type material, hence creating an electron-hole pair movement along the junction, which leads to the production of current [9-11].

Types of solar cells: Photovoltaic technology in a solar cell can be divided into four basic categories, namely

a) Crystalline silicon solar cells such as monocrystalline silicon (m-Si) and polycrystalline silicon (p-Si)
b) Thin film solar cells such as cadmium telluride (CdTe), copper indium gallium selenide (CIGS), and amorphous silicon (a-Si)
c) Concentrating PV included single-crystalline silicon and III-V multijunction cells

d) New materials such as organic photovoltaic (OPV), dye-sensitized solar cells (DSSC), quantum dot solar cells (QDSC), and perovskite solar cells.

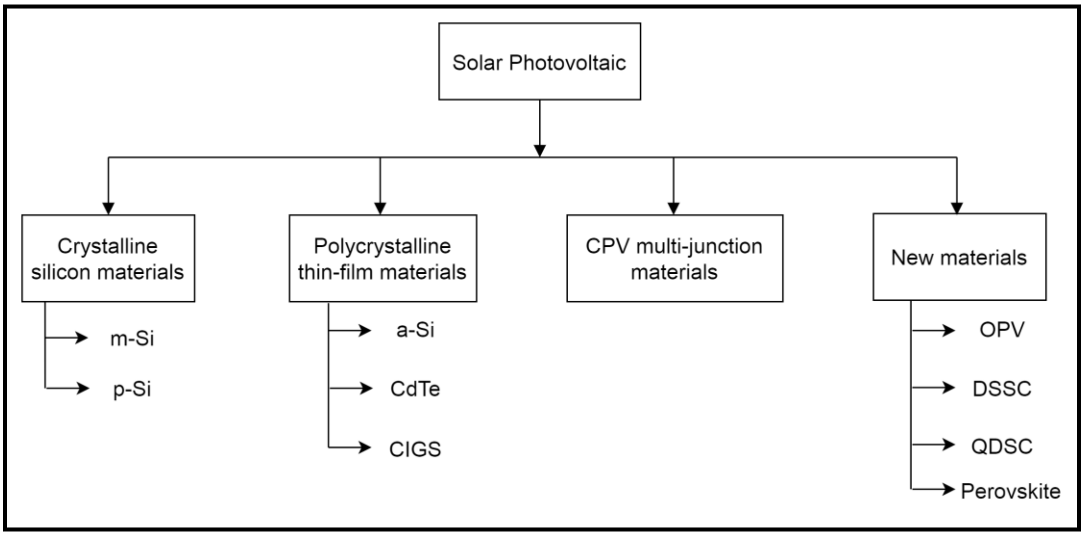

Figure 1.5 Different type of photovoltaic technologies [8].

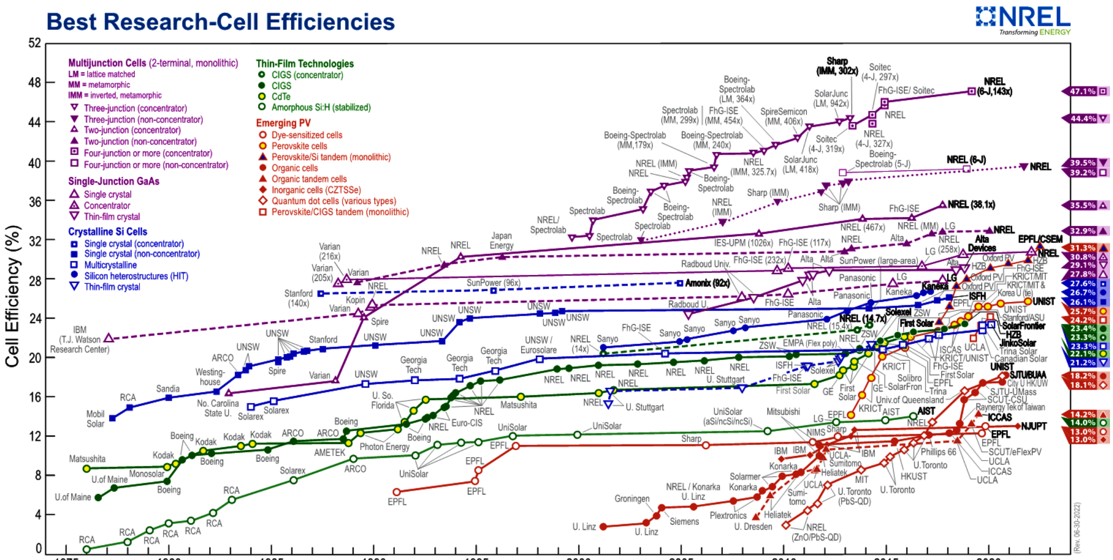

Figure 1.6 Efficiency of different types of solar cells over the year [12].

The photovoltaic technologies are grouped and sub-grouped, as given in Figure 1.5. The efficiency of different types of the PV cell technologies measured by different institutes and laboratory is shown in Figure 1.6. The reported efficiency of the m-Si is 26.1% and for p-Si is 23.3%. The highest cell efficiency is obtained for four-junction or more concentrator solar cell of 47.1% [12]. In 2021, out of total market for photovoltaic, crystalline silicon cell exceeds 95%, of which monocrystalline silicon cell contributes 84%. The 5% of the market is covered by the thin-film [13].

Crystalline silicon materials**:** The performance of Si-based photovoltaics has greatly improved in the last decades in terms of stability and reliability [14]. Crystalline silicon solar cells (monocrystalline/polycrystalline) dominated the PV market manufactured worldwide. The wafer is manufactured using two processes namely, inner diameter saw and multiwire saw. The later is newer process and has advantages over the former process, as it is cost-effective, reduces the sawing loss to 30% comparatively, reduces crystal defect on silicon surface, and enhances cell efficiency [15].

(a) Monocrystalline silicon (m-Si) solar cell: The terrestrial crystalline silicon cell with total area of 274.4 cm^2 efficiency under International Electrotechnical Commission IEC 60904-3:2008 or ASTM G-173-03 global is reported as 26.8±0.4% as tested by Institute of Solar Energy Research Hamelin (ISFH) [16]. Monocrystalline silicon are developed using single-crystal silicon using the Czochralski (CZ) process [17]. The initial set of the monocrystalline solar cell was cylindrical shape obtained from a silicon ingot. However, at present, they are shaped as semi-circle or squares in order to increase their density on the PV module's surface [18]. This type of PVs with the Back Contact-Back Junction (BC-BJ) and Heterojunction with Intrinsic Thin layer (HIT) are considered to have high efficiencies. However, due to time constraints and ungrown technical expertise, this cell structure has not reached the commercial level. One of the major drawbacks of this type of PVs is light-induced degradation (LID) effect is one of the negative effects on the monocrystalline cell, so LID effect free wafers such as n-type CZ-silicon wafers, boron-doped magnetic field CZ wafers, gallium-doped CZ wafers, phosphorous-doped n-type CZ wafers, and are used by the cell manufacturers [19].

(b) Polycrystalline silicon (p-Si) solar cell: in this type of solar cell, polycrystalline silicon high-purity silicon acts as a main component of solar cells. The chemical purification process is used for its processing. A polycrystalline silicon structure called a Ribbon structure is obtained from molten silicon with a flat thin-film [20]. In

2020, JinkoSolar reported efficiency of multicrystalline silicon solar cell to be 23.3% [12]. The efficiency of a polycrystalline silicon module for an aperture area of 14,818 cm^2 as measured by Fraunhofer Institute for Solar Energy Systems (FhG-ISE) is reported to be 20.4±0.3% [16]. Its contribution in the PV market increased from 30% to 48% from 1998 to 2010 [21, 22]. Typically, Si-wafer is developed by allowing silicon ingots with large columnar grains to grow from the bottom when solidifying molten silicon [21]. Several techniques have been reported for the manufacture and texturing of polycrystalline solar cells for efficiency enhancement [23-26]. The majority carrier recombination is the primary factor that restricts the performance of polycrystalline solar cells, attributed to the intragrain defects and dislocations formed during the manufacturing process. The material produces various defect structure based on the crystalline process, which determines and restrict their efficiency [27].

There exists different type of PV installations such as ground mounted, roof top, canal top, offshore, and floating. Out of all these installation type, floating PV is a novel concept that uses floating technology to place solar photovoltaic system over bodies of water such as oceans, lakes, lagoons, reservoir, irrigation ponds, waste water treatment plants, wineries, fish farms, dams and canals etc. This type of PV plant constitute of components including pontoon, floats, mooring system, solar PV module, and cables and connectors [28].

1.4 Electrical characteristics of photovoltaic module

The incident light on the current-voltage and power-voltage characteristics of the p-n junction (solar cell) is shown in Figure 1.7. The maximum power P_{max} is the multiplication of the maximum current, I_{mp}, and maximum voltage, V_{mp}.

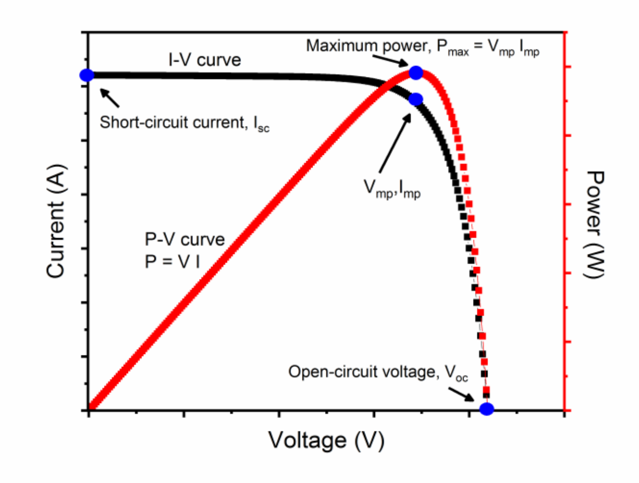

Figure 1.7 Current-voltage (I-V) and power-voltage (P-V) curves of a PV module [29].

The basic parameters PV module is defined as follows [1]:

Maximum power, P_{max}: The operating current and voltage reach a point to the maximum power point (MPP), and the power achieved at that point is the maximum power.

Maximum current, I_{mp}: The operating current value corresponding to MPP.

Maximum voltage, V_{mp}: The operating voltage value corresponding to MPP.

Short-circuit current, I_{sc}: The maximum current value obtained when the PV terminals are connected without any load and the voltage is zero.

Open-circuit voltage, V_{oc}: The maximum voltage value obtained when the PV terminals are not connected to any load and the current is zero.

Fill factor, FF: The ratio of the P_{max} to the product of J_{sc} and V_{oc} from the PV is defined as the fill factor. It signifies the squareness of the I-V curve.

$$FF = \frac{P_{\max}}{V_{oc}\, I_{sc}} = \frac{V_{mp}\, I_{mp}}{V_{oc}\, I_{sc}} \quad (1.2)$$

where P_{max} is the maximum power (W), I_{mp} and I_{sc} are the current at maximum power point (A) and short-circuit condition (A), respectively. V_{mp} is the voltage at maximum power point (V), and V_{oc} is the open-circuit voltage (V).

Efficiency, η: The fraction of incident solar power which is converted to electricity is defined as the efficiency of the PV module.

$$\eta = \frac{P_{mp}}{P_{incident}} = \frac{P_{mp}}{G \times A} \tag{1.3}$$

where G is the incident solar spectral irradiance (W/m^2), and A is the active area (m^2). $P_{incident}$ is the incident power, which is the product of the G and A.

1.5 Spectral response and importance of spectral variations

The actual energy output of the PV module differs from the standard test conditions (STC), where solar irradiance of 1000 W/m^2, AM value of 1.5, cell temperature of 25°C, and wind speed of 1 m/s. This is due to the difference in the latitudes of the location and the variations in the solar spectral distribution as one of the significant factors in addition to irradiance and cell temperature. It is reported that error due to ignorance of influence of solar spectral variations on energy output estimations of PV plants can lead to profit or loss of billons of euros in long run of its operation [30].

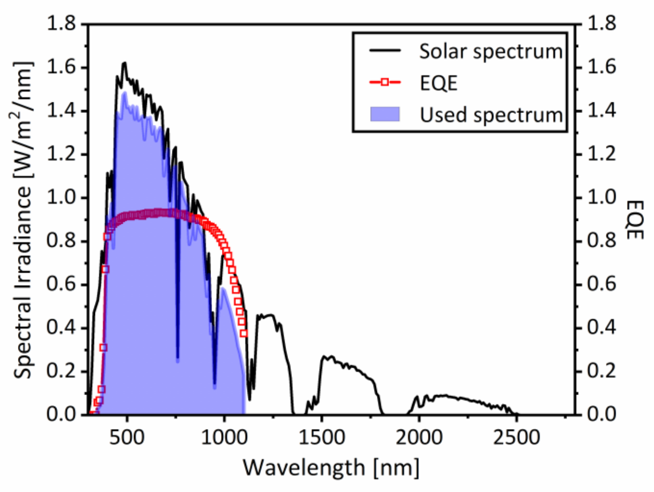

Figure 1.8 Solar spectrum and external quantum efficiency (EQE) of the PV module [31, 32].

The solar spectrum incident on the surface of the PV module does not get fully used in electricity generation. Only the part of solar spectrum which has the same wavelength range as that of the spectral response (device-dependent) of the PV cell takes part in electricity generation. For instance, for the monocrystalline PV module as shown in Figure 1.8, the area filled with blue is the area that is used in generation of the electricity. This area is obtained by multiplication of the solar spectrum and external quantum efficiency (EQE) of the solar cell. Spectral response refers to the current generation by the solar cell to the incident power, and quantum efficiency is the ratio of the number of electrons counted by the solar cell to the incident photons. The correlation between the spectral response (*SR*) and *EQE* is as follows [33]:

$$SR = \frac{q\lambda}{hc} EQE \tag{1.4}$$

where q is the electronic charge (1.602×10^{-19} C), λ is wavelength in nm, h is Planck's constant (6.626×10^{-34} J.s), and c is the speed of light (3×10^{8} m/s).

1.6 Factors affecting photovoltaic performance

The PV performance is prone to changing outdoor conditions; there are various factors that govern its overall output as presented in Figure 1.9.

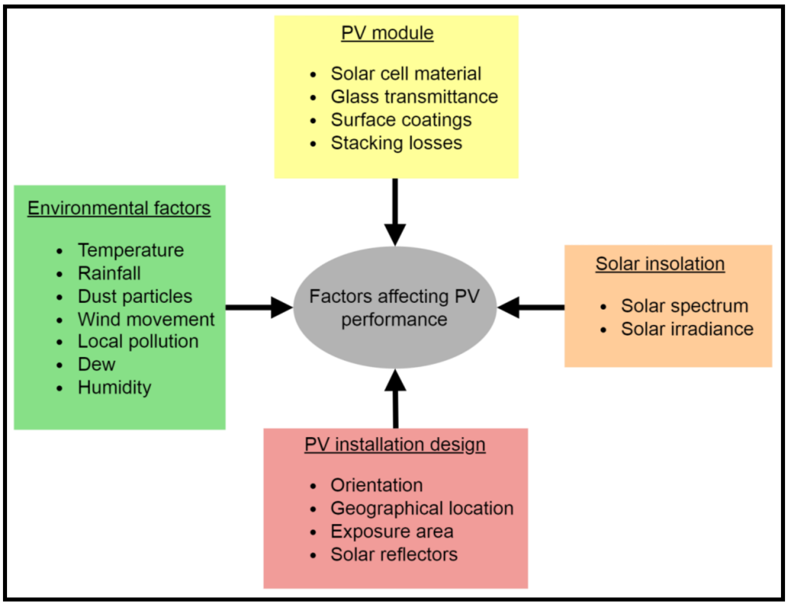

Figure 1.9 Various factors affecting solar photovoltaic performance [34].

1.6.1 PV modules

The PV module is made of different materials stacked together, and the topmost layer is the glass, followed by anti-reflective coatings, solar cells, and backsheet. The solar cells are interconnected by the connecting wires, through which electrons are passed to produce electricity. The transmittance of the glass surface should be high so that maximum light gets transmitted to the solar cells. Generally, low-iron glasses are used for this purpose. Anti-reflective coatings are used to reduce the reflection of light from a solar cell so that the light absorption by solar cells increasing the overall efficiency. A bare silicon solar cell has a reflection of 35% [35]. Therefore, an anti-reflective coating is required. Commonly used anti-reflective coating are silicon nitride and titanium oxide [36]. The material of the solar cell is an important factor because the efficiency varies with the material they are made of. Solar cell made of silicon is trending in the market because it has higher efficiency; however, researchers are working on new materials solar cells to obtain reduced processing cost of a solar cell. The stacking losses in the module occur due to various attributes such as asymmetric geometry of the PV module, dependency of the encapulant stiffness on temperature, and back surface material of PV module (either polymer backsheet or glass) [37].

1.6.2 Solar insolation

Solar insolation plays an important role as it is the source of electricity generation in the module. The output in actual conditions varies compared to rated output (provided by the manufacturer). This is because of the difference in the content of spectral light between the reference spectrum and actual spectrum. It is reported that this difference can reach up to 35%. Both shape and power of spectrum has significant contribution in different PV module technology performance, with relative errors recorded up to 11% [38]. Moreover, PV performance also shows seasonal dependency because of solar spectrum depending on seasonal change. Therefore, the effect of spectral variation along with integrated global insolation must be considered while evaluating the PV performance. This is to address the non-linearity of I_{sc} that can be caused due to negligence of spectral content [39].

1.6.3 PV installation design

PV installation design is another component affecting the performance of the PV module. The modules must be orientated towards the correct direction and angle to obtain the maximum possible output. For locations in Northern Hemisphere, PV modules installed facing toward the true south receive the maximum solar intensity and duration of sunlight. The other directions receive some shading effect, especially during the winter season because of the shift in the sun's path. Similarly, for the locations in Southern Hemisphere, PV modules must be installed true north [40].

1.6.4 Environmental factors

Importantly, environmental factors also significantly affect the output and performance of PV module. Some of these environmental factors are listed below:

Temperature: Temperature has a significant effect in PV performance. The efficiency decreases with the increase in temperature, attributed to an enhanced internal carrier recombination rate because of an increase in carrier concentration [41]. A decrease in electrical parameters, including power output, fill factor, and conversion efficiency of -0.65%/K, -0.2%/K, and -0.08%/K, respectively, with the rise in temperature, is reported [42].

Rainfall: Rainfall has both positive and negative impacts on PV performance. Heavy rain helps in the removal of dust particles or soiling, while light rain encourages the soiling of the PV surface. The study conducted in IIEST Sibpur, India, concluded that under wet condition with rainfall of 24 hours, larger particles of size 1-10 μm have higher collection efficiency than smaller particles of size less than 1 μm [43]. Moreover, hailstorms can seriously damage solar power systems.

Dust particles: The impact of dust particles on PV performance is affected by the composition of dust particles and accumulation rate based on seasonal variations and environmental conditions. It is crucial to understand the effect of dust accumulation on PV performance so that the associated loss and its mitigation can be determined [44]. The power output of PV can reduce by up to 15-17% per month due to dust particle deposition [45, 46]. It is reported that the rate of dust accumulation varies with respect to the exposure time, and its impact is location specific [47, 48].

Wind movement: It is recommended that wind direction and wind speed must be one of the factors of consideration while site selection for the installation of PV plants. A case study in the Hadley PV plant, UK, reported that the southerly wind enhances the PV performance by cooling the PV panels. The heating of the PV panel occurs due to a rise in temperature of the PV surface and thus decreases the efficiency. In fixed-tilt PV plants, panels are ideally oriented south. Therefore, when the wind blows from the south, it convects against the PV surface leading to a cooling effect. On the contrary, northerly wind strikes at the back of the panel, thus being unable to contribute to cooling as much as compared to southerly wind [49].

Local pollution: The phenomena due to the environment where the aerosol/airborne particles get deposited and accumulate on the PV surface, which impacts its performance; this is known as the soiling of PV [50]. The optical nature gets altered due to the soiling of the PV surface. The incident light gets reflected and absorbed by these particles, and also the light transmitted to the PV cells gets reduced [50, 51]. From the studies conducted worldwide, it is noted that atmospheric aerosol (anthropogenic) can decrease the capacity factor of PV systems at fixed tilt by 4-34% [52, 53].

Dew: Dew formation on the surface of the PV module is found to negatively affect the energy yield of PV depending on the environmental conditions of the location [54]. This can also increase the revenue involved in maintenance as it has the potential to increase the dust particle deposition on the PV surface [55]. The study conducted in a controlled environment reported that incident solar radiation increases, and hence the module performance parameters increase with dew formed on the PV module surface. This is because of the reduction in the reflection of solar radiation from the surface of the module. Dew formation also adds to the increase in performance by reducing the module temperature which is known for its negative impact on PV performance [56]. Therefore, dew acts as an important parameter for the locations with high dew occurrence.

Humidity: Water droplets settle on the PV surface due to the factor called relative humidity [57]. The power generation in humid locations is reported to reduce up to 60-70% due to an increase in the adhesive nature of the PV surface that attracts dust or soiling on the PV surface [58].

Since, this work emphasis more on the effect of temperature and PV soiling, a further details has been reported on these two topics in the next sections.

1.7 Effect of temperature on photovoltaic performance

The cell temperature of a PV module is dependent on various parameters like physical properties of PV cell technology, the module and its configurations and the environmental conditions. The nature of temperature in the PV module is dynamic. It is determined using thermal energy exchange with the layers of module and between module and its environment through different modes of heat transfer [59]. The solar spectrum incident on the surface of PV module is not completely absorbed by the cells. Some portion of incident spectrum gets reflected back, while some portion of it gets absorbed by different layers before it could reach the cells. The part of the solar spectrum absorbed by the solar cells in the PV module determines the total amount of current generated and the unused part of the solar spectrum contributes in generating internal heat, resulting the rise in cell temperature of the PV module [60]. This rise in temperature affects the electrical parameters, mostly the V_{oc}. This is because V_{oc} depends on the diode saturation current (I_o) which in turn depends on the intrinsic carrier concentration (n_i) and the parameter n_i is a function of bandgap. The bandgap is known to reduce with increase in temperature. The expression for I_o from one-side of p-n junction is:-

$$I_o = qA\frac{Dn_i^{\,2}}{L_d N_D} \tag{1.5}$$

where q is the electronic charge (C), A is the area (m^2), D is the diffusivity of the minority carrier. L_d is the minority carrier diffusion length. N_D and n_i are the doping and the intrinsic carrier concentration, respectively. All the parameters in equation (1.5) depend on temperature. However, the significant effect of n_i dominates. The open-circuit voltage of the solar cell is given by:-

$$V_{oc} = \frac{nk_BT}{q}\ln\left(\frac{I_{ph}}{I_o}+1\right) \tag{1.6}$$

where n is the ideality factor, k_B is the Boltzmann's constant (1.38×10^{-23} J/K), T is the temperature (K), I_{ph} is the photocurrent generated by the PV module (A), I_o is the diode reverse saturation current (A). The change in I_o due to change in temperature is much higher compared to change in I_L. Further, the change in n_i with temperature is higher than change in I_o. In real scenario, the parameters such as carrier lifetime and diffusivity also changes with temperature. However, its effect is low.

The short-circuit current I_{sc} increases slightly as the temperature increases. The reason is as the bandgap, E_G decreases with temperature and more photons are available with sufficient energy generating electron-hole pairs. Therefore, with increase in temperature V_{oc} decreases and I_{sc} tend to slightly increase with temperature. However, the effect of temperature is greater on V_{oc} compared to I_{sc} [1, 61]. Overall, the efficiency of the PV module is decreased with rise in cell temperature.

1.8 Influence of marine environment on PV performance (floating PV)

PV modules installed in tropical and oceanic regions has a higher operational and maintenance requirement compared to the modules installed in other region. The climate in these regions is extremely humid and may include a high concentration of salt and minerals, resulting corrosion of various PV system components. The high concentration of salt can corrode the metal compounds in the solar module components, leading to potential fire hazard, while the high humidity can result the module capsules to delaminate [62]. However, the installed capacity of PV system near the ocean, especially the floating photovoltaic has significantly increased over the decades because of certain advantages mostly related to negligible land occupation and better energy yield [63]. The floating PV system and their components is shown in Figure 1.10.

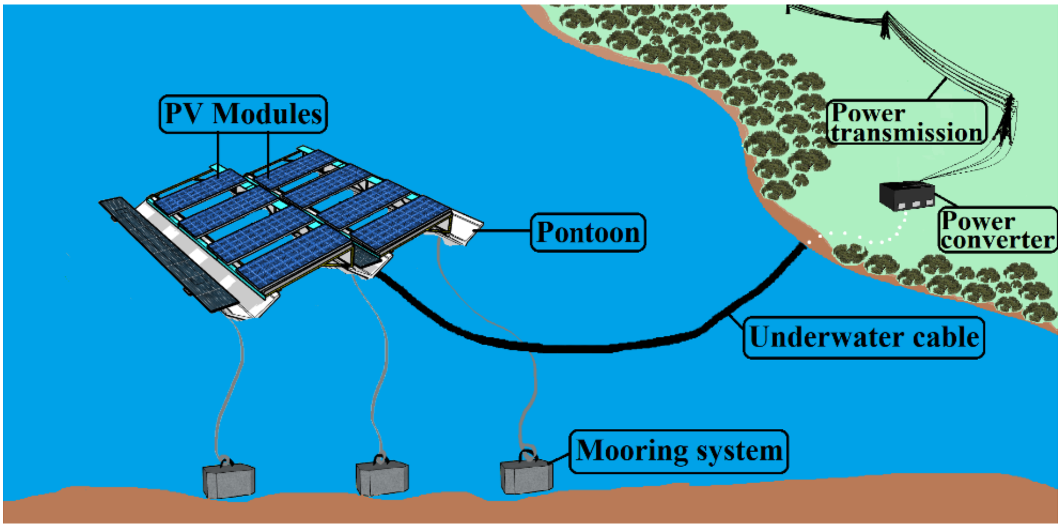

Figure 1.10 Layout of floating photovoltaic system along with their components [64].

The main factors of marine environment that affects PV performance are salt spray and seawater. These factors have varying influence on PV module. The electrical outputs of PV module are reported to change with change in salt spray and seawater as these factors affects the solar irradiance and temperature received by the PV surface. As salt spray on the PV surface, the water mist with a lot of salt deposition could be observed. Thus, it affects the solar irradiance incident on PV module by the scattering and absorption phenomena. Simultaneously, salt spray tends to evaporate and dissipate heat, thus influencing the temperature of PV module. The combined effect of salt spray on PV module electrical output is 10% reduction in maximum power. As seawater fills the PV surface, the water film is formed on it, and the evaporation of the seawater tends to cool the PV surface. Simultaneously, the water deposited affects the solar radiation intensity incident on PV surface by the phenomena reflection and refraction. It has been reported that the combined effect of seawater on PV module electrical output is a 20% increase in maximum power [65]. It is evident that salt soiling has an effect on I_{sc}. A study of 4 weeks of PV module in the marine environment showed that normalized I_{sc} of PV module with respect to the radiation in STC, compared with I_{sc} from the datasheet, 23.6% of percentage decrease in I_{sc} has been observed [62, 66, 67].

1.9 Effect of soiling on photovoltaic performance

Soiling has a significant effect on the performance of PV panels. Soiling refer to accumulation of dust, dirt, leaves, pollens, snow, bird droppings, and other particles on PV module surface. The loss in power output of PV module associated with this act is termed as soiling loss. The soil shading is divided into two categories, namely, soft shading and hard shading [34]. Soft shading is due to dust or other particles in the atmosphere which reduces the incident spectral intensity absorbed by solar cells. This type of shading affects the current parameter while the voltage parameter remains unaffected. Hard shading is due to blockage of incident sunlight in a definite shape by some solid dust. In this type of shading the cells are either blocked partially or completely. The current flows as long as there are some unshaded cells which receives sunlight. However, such condition may arise hot spot in the PV module [68]. Soiling depends on various factors, such as tilt angle and orientation, environmental factors (rainfall, temperature, wind, humidity, local pollution, and pressure), site characteristics, dust properties, glazing characteristics, PV technology and cell configuration [34], and seasons of the site [69]. Therefore, researchers have studied the effect of dust accumulation on the PV either by considering PV modules [70, 71] or proxy glass samples [72, 73]. Such studies are site-specific since the concentration of dust particles depends on the geographical locations and the kind of dust particles available. For instance, desert locations are more susceptible to soiling, studies in sites such as Middle East North Africa, North East Asia and South west Asia have reported an PV efficiency drop up to 70% [74]. The finer dust particles have a greater influence on the solar spectrum and light transmission compared to the coarser particles, which is due to the uniform distribution of the finer particles on the module surface, thus minimizing the gap between the particles from which the light can pass [75]. Thus, soiling on PV module can significantly decrease the output by creating shading and its impact changes with the amount of the accumulation.

1.10 Motivation of the research

Solar photovoltaic is fast growing renewable energy technology and their installation is a part of global development plan. With the deeper understanding of the PV system, the following factors have motivated to carry out this research work:

- There is a need to precisely predict the overall performance (in terms of optical, thermal and electrical).
- Most of existing models consider the parameters solar radiation and temperature, neglecting the effect of solar spectrum. However, solar spectrum plays a pivotal role in assessment of PV output.
- The diurnal and seasonal change affects the PV performance significantly.
- PV soiling is one of the concern areas of study. Soiling is very site vulnerable as it depends on the environmental parameters of the site.
- There exists a complex relationship between the soiling and environmental parameters. Also, the relationship that governs is one season may not be applicable in another season.

- Knowledge of a cleaning schedule of PV module is a need to minimize the maintenance cost and increase the energy production.

Therefore, in this work, a model has been developed which is solar spectrum dependent and is capable of predicting the diurnal and seasonal electrical, thermal behavior of the PV module. Deposition of dust on the surface of the PV module can significantly degrade its performance. Thus, in the present work, the effect of soiling on PV performance has been analyzed. The seasonal effect of soiling on PV and their correlations with the environmental parameters are determined. A novel method is utilized to evaluate the effectiveness of different cleaning cycles. Moreover, the developed modeled is experimentally validated for different PV technologies under varying seasons.

1.11 Research objectives and their significance

The existing PV models, their complexity, correlation with environmental parameters, and their level of output predictions were investigated. Based on these understandings the following sets of objectives are considered in this work:

(i) To develop a spectrum-based electrical-thermal model for performance analysis of different photovoltaic module technologies.

The effect of solar irradiance under the effect of varying environmental parameters is generally considered for the performance evaluation of the photovoltaic module. However, the effect of environmental parameters on the change in the solar spectrum cannot be ignored. So, a spectrum-based model needs to be developed that inter-related spectrum with an opto-electric-thermal model for precise prediction of the electrical performance of the photovoltaic module under real operating conditions.

(ii) To study the effect of soiling and environmental parameters on the energy generation of different module technologies.

The dust accumulated on the surface of the photovoltaic module affects not only the amount of solar radiation and temperature, but also the solar spectrum that goes through the module surface. The environmental parameters which encourage soiling on PV surface essentially needs to be determined so that strategies and recommendations on cleaning cycles can be made. Therefore, the effect of soiling on the energy output of the PV module needs to be studied to analyze its diverse effect on spectrum and irradiance.

(iii) To validate the developed spectrum-based model with the experimental output of different module technologies.

The validation of the developed model needs to be carried out for a set of known parameters for different seasons. The power output and energy yield from the developed model will be validated with the experimental output of different module technologies. Therefore, the validated model under known atmospheric conditions of the locations will generate the precise prediction of the PV performance of the location for different seasons throughout the year.

1.12 Structure of the thesis

Chapter 1: Introduction presents an introduction to the basic terminologies and matters that are related to the present work. The motivation of the work, objectives and their significance are also mentioned in this chapter. Moreover, the structure of the thesis is also presented in this chapter. Chapter 1 is the present chapter of the thesis.

Chapter 2: Review of Literature provides a review of the literature of earlier publications similar to the present work. The publications which were motivating and helped in processing the current work are mentioned here. The sources, websites, and governing equations that are used in this work are presented in the chapter of the thesis. Previously reported electrical and thermal models, their integrated models, spectrum based integrated models are reviewed. The effects of other significant parameters such as soiling and environmental parameters are also discussed. Moreover, the review includes seasonal variability in PV performance due to varying spectrum, temperature, and other environmental parameters.

Chapter 3: Materials and Methodologies demonstrate the step-by-step process followed in this work. The materials and methods used to obtain the outcome of the work are provided in this chapter. Various simulation tools, software utilized, and governing equation to carry out the modeling and analysis in this work are also described. The instruments, their specifications, and set-up while carrying out the experiments are also mentioned in this chapter.

Chapter 4: Results and Discussion deals with the results obtained from the various sections of the work (based on the objectives set) and analyses and discuss the findings, the reason for the cause, and recommendations based on the results addressed in this chapter of the thesis. In addition, the error analysis and validation of the developed model with experimental results are shown.

Chapter 5: Conclusion and Future scope give the brief of findings and recommendations obtained from the analysis of the results of the present work and provide some possible future work that can be carried out further.