

1

Basics of Solar Energy and Sustainable Applications

Namratha Bhandari¹, Sushma², and Santosh L. Gaonkar³

¹Yenepoya (Deemed to be University), The Yenepoya Institute of Arts, Science, Commerce and Management, Department of Chemistry, Mangaluru, 575002, Karnataka, India

²Cambridge Institute of Technology, Department of Chemistry, Bangalore, 560036, Karnataka, India

³Manipal Academy of Higher Education, Manipal Institute of Technology, Department of Chemistry, Manipal, 576014, Karnataka, India

1.1 Introduction to Solar Energy in the Context of Sustainability

Among the most significant and challenging dilemmas confronting the global community today are those related to energy. Projections indicate that global energy consumption is anticipated to escalate by two-thirds by the year 2030, with developing nations surpassing their industrialized counterparts as the foremost consumers of energy. As mentioned by the International Energy Agency (2004), fossil fuels, including coal, natural gas, and petroleum, are expected to remain the predominant energy sources, accounting for over 90% of the projected increase in demand. It is forecasted that the volume of natural gas will experience a twofold increase between 2000 and 2030, rendering it the fuel with the most rapid growth rate due to its relative abundance and comparatively favorable environmental attributes. The transportation sector is anticipated to be the primary driver of the rising demand for oil, which is predicted to persistently ascend. Although wind and biomass energy are projected to grow from a minuscule starting point, renewable energy sources will increasingly contribute to power generation [1].

The global energy landscape is poised to encounter four principal challenges in the forthcoming decades, challenges that necessitate substantial governmental interventions and corporate ingenuity. These challenges encompass accommodating the escalating demands of the developing world, curbing environmental degradation, achieving energy security, and addressing the imminent oil scarcity. Nevertheless, it is evident that a transition to cleaner energy toward a carbon-independent global economy is already underway, a transformation that will profoundly affect the environment and impose challenges for future generations. While scientific evidence may delineate the requisite changes, political and economic dynamics are likely to be even more decisive [1].

1.1.1 Need for Renewable and Eco-Friendly Solutions

In relation to the Sustainable Development Goals (SDGs), the advancement of renewable energy (energy supplies that do not deplete with use) facilitates the attainment of energy security across sectors such as industry, transportation, environmental sustainability, construction, economy, and mechanical labor. On a global scale, clean energy options like solar, wind, hydro, tidal, geothermal, and biomass underpin community development, ecological preservation, and the fulfillment of energy demand. In recent decades, renewable energy has been hailed as a potent solution to the energy crisis [2].

A clean, renewable, and sustainable energy source is imperative for enhancing environmental, social, and economic welfare, thereby catalyzing productivity and economic advancement. Given that this energy source generates minimal waste or pollution compared to fossil fuel energy, it is frequently referred to as clean energy. The global electrical requirements have been met to the extent of 28% by electricity generated from renewable energy sources. Furthermore, it also takes into account the enhancement of air quality, which is indirectly linked to cost-effectiveness and public health [3].

Solar energy stands out as one of the most plentiful, promising, enduring, comprehensive, high-capacity, and environmentally sustainable modalities of renewable and sustainable energy sources. Historically, human societies have depended on solar radiation for culinary purposes and the desiccation of textiles. Nevertheless, due to its current status as the most feasible and cost-effective renewable energy source, it is employed in a myriad of applications. The harnessing of solar energy, or sunlight, for diverse commercial and industrial applications – such as electricity generation, thermal water heating, and solar refrigeration – is indeed achievable. Photovoltaic (PV) solar cells convert the luminous energy emitted by the sun into electrical energy. In conjunction with wind energy, it represents a low-carbon technological advancement in energy production. Despite the inherent challenges pertaining to the practical application of solar energy through innovative and clean technologies, the variability and decentralization of natural solar irradiation remain significant obstacles [3].

1.2 Solar Energy Essentials and Photovoltaic Technology

The cumulative energy output of the sun is quantified at 174 PW, with less than 1% of this solar energy successfully reaching the Earth. Through various technological advancements, this solar energy can be directly or indirectly harnessed for thermal applications or converted into electrical energy utilizing PV systems. The operational mechanism of PV technology is predicated on the principle of the PV effect, as electricity constitutes the most significant portion of our energy demands. A variety of solar reflecting collectors can be employed to produce thermal energy from sunlight, fundamentally relying on the thermosiphon effect or principles associated with radiation, reflection, and convection [4].

The wavelength spectrum of solar energy ranges from 300 to 3,000 nm and can be classified into three primary regions: the visible spectrum (350–750 nm), the infrared spectrum (exceeding 750 nm), and the ultraviolet spectrum (below 350 nm). These components of sunlight collectively constitute the solar spectrum. The predominant sources of solar energy originate from the visible (47%) and infrared (46%) segments of solar radiation. Although operational methodologies vary according to the technology implemented, the heat and light emitted by solar radiation can be captured for beneficial applications. Thermal collectors harness energy from both the visible and infrared spectra, whereas PV technology facilitates the conversion of visible light into electrical energy. Thus, solar radiation has the potential to yield either thermal or electrical energy [5].

1.2.1 Working Mechanism of Photovoltaic (PV) Cells

The PV effect is fundamental to the operation of PV cells. This phenomenon entails the generation of electromotive force in heterogeneous materials upon exposure to light of designated wavelengths. When light interacts with a material, it incites the production of voltage and electric current. Semiconductors exhibit PV attributes that allow photons or radiant energy to be converted into electric current upon interaction with their surface. The architecture of a conventional PV cell is depicted in Figure 1.1.

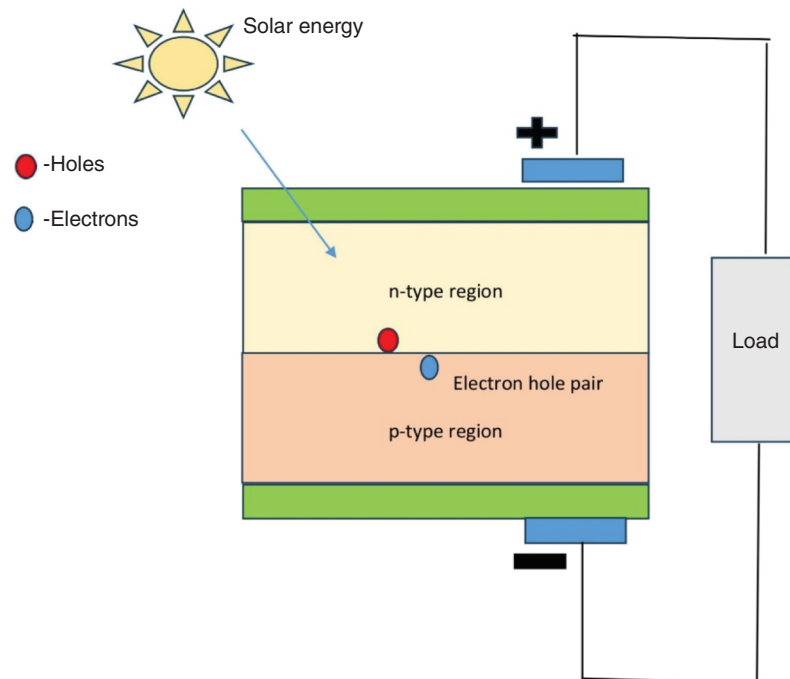


Figure 1.1 Diagram of a typical photovoltaic cell (silicon based).

Semiconductors such as silicon and germanium comprise three distinct energy bands: the valence band, the forbidden band, and the conduction band. The forbidden band is extensive, necessitating that an electron acquires sufficient energy to transition from the valence band to the conduction band. The energy requisite for an electron to effectuate this transition is called bandgap energy.

In silicon-based semiconductors, the bandgap energy is roughly quantified at 1.12 eV, whereas alternative semiconductors such as cadmium telluride and gallium arsenide exhibit energy gaps of 1.5 and 1.42 eV, respectively. The appearance of a 1.12-eV bandgap signifies that photons possessing the corresponding energy are capable of energizing electrons, which, in turn, facilitates the flow of electric current.

To fabricate n-type and p-type regions in conventional PV cells, trivalent and pentavalent dopants are deliberately introduced into specific areas of silicon. An antireflective layer composed of TiO_2 is applied to the uppermost surface of the PV cell in order to mitigate light reflection. Upon the incidence of solar radiation on a PV cell, the generation of electron-hole pairs occurs. As the holes migrate toward the n-type region and the electrons drift toward the p-type region, a p-n junction is formed. Electrons traverse through a conductive wire that connects the cathode of the n-type silicon to the anode of the p-type silicon. Moreover, metallic grids are incorporated within the cell to facilitate the extraction of electric current. The positive charge inherent in the p-type material exerts an attractive force on the electron, compelling it to traverse the external load and initiate the flow of electricity [6].

1.2.2 Types and Generations of PV Technologies

The PV technology can be classified into four primary generations. Essentially, the generations of PV cells delineate the stages of their technological advancements over time [7, 8]. Since the inception of PV technology several decades ago, it has been systematically classified into four notable generations (Figure 1.2).

First Generation: This employs silicon and gallium arsenide (GaAs), specifically focusing on monocrystalline and polycrystalline silicon variants. These cells are predominantly utilized due to their comparatively high efficiency. This primary generation of solar cells relies on materials stemming from substantial crystalline silicon layers.

Second Generation: This generation came into existence to bring about cost reduction. Thin-film technologies are instrumental in realizing this reduction by minimizing material consumption and enhancing quality. This category includes PV cells fabricated from cadmium telluride/cadmium sulfide (CdTe/CdS), microcrystalline silicon ($\mu\text{c-Si}$), amorphous silicon (a-Si), and copper indium gallium selenide (CIGS). Despite offering improved mechanical features designed for flexible applications, their efficiency may be compromised. The primary generation of solar cells demonstrated microelectronics, yet the transition to thin

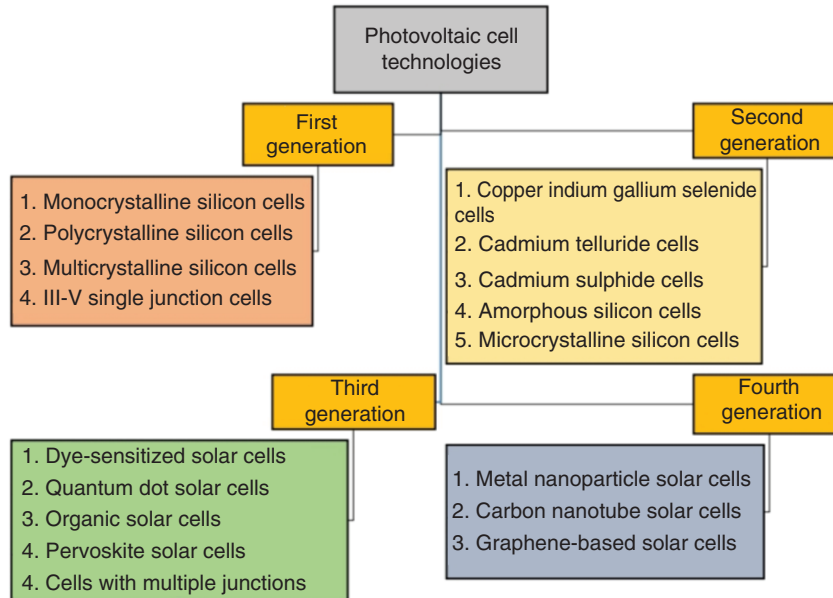


Figure 1.2 Different generations of PV technologies.

films necessitated the development of novel growth methodologies and extended into other domains such as electrochemistry.

Third Generation: This generation exemplifies PV techniques that employ advanced chemical substances. This employs dye-sensitized solar cells, quantum dots (QDs), nanocrystalline films, and organic polymers. The third generation represents a diverse array of methodologies for applications ranging from architectural integration to extraterrestrial utilization. These include economical but less efficient systems to costly and high-output systems. Presently, third-generation solar cells epitomize the forefront of advanced research concentrated on fabrication technologies and enhancements in efficiency.

Fourth Generation: This generation amalgamates the robustness of sophisticated inorganic nanostructures with organic nanomaterials, concurrently addressing the issues of limited flexibility and cost-effectiveness associated with thin-film polymers. The integration of nanomaterials into PV technology is anticipated to augment charge separation and transport within the solar cells, culminating in more efficient solar cell devices distinguished by their requisite longevity and economical production costs. Graphene emerges as an exceptionally promising material for solar technology due to its remarkable properties and diverse allotropic forms spanning all four dimensions. Each iteration of solar cells offers a unique array of advantages and disadvantages, specifically tailored for distinct applications. Nonetheless, first-generation solar cells continue to dominate the market today, attributed to their superior efficiency and reliability.

1.3 Emerging Solar Technologies and Innovations

1.3.1 Advanced Materials

Scholarly investigations are being conducted to identify novel materials that possess the potential to diminish costs and augment operational efficiency, in conjunction with those presently employed in the fabrication of solar cells. Consequently, these materials are frequently categorized as emerging photovoltaics (EPVs) or innovative solar cells. In addition to conventional substances such as silicon, glass, and metals, several advanced materials (AdMs) have been delineated for the production of solar cells. AdMs are deemed significant due to their enhanced properties and functionalities when contrasted with traditional materials.

1.3.1.1 Perovskites

The chemical composition of perovskite is articulated as ABX_3 , wherein X denotes an anion, A represents a sizable cation, and B corresponds to a diminutive cation. This particular material possesses the capability to absorb light through a synergy of metal halides. The A-site cations encompass monovalent cations such as methylammonium ($CH_3NH_3^+$) and formamidinium ($(NH_2)_2CH^+$), including their respective mixtures. The X site is constituted by a halide anion (Cl^- , Br^- , I^-), while the B-site incorporates bivalent metallic cations derived from Group IV of the periodic table.

Through the attainment of optimal bandgap tuning, these materials can manifest the requisite electrical and optical characteristics. A quintessential perovskite solar cell is composed of several superimposed layers of functional semiconductor materials, specifically fluorine-doped tin oxide (FTO)/electron transport layer (ETL)/perovskite/hole transport layer (HTL)/Au. These charge carrier extraction layers are situated on opposing sides of the perovskite light absorption layer. Selenium-based perovskites, serving as active absorber materials, are acknowledged for their capacity to enhance power conversion efficiency [9].

1.3.1.2 Quantum Dots (QDs)

QDs epitomize another vital class of materials that can be harnessed for solar energy conversion owing to their size-dependent optoelectronic attributes. The fabrication of QD-sensitized solar cells (QDSSCs) is cost-effective and simple, making it a promising candidate in this field. Anticipated high performance is a result of bandgap tuning within QDs and the production of multiple excitons in this solar cell architecture. Several varieties of QDs have been investigated, including CdS/CdSe, CuInS₂, PbS, Zn-Cu-In-Se, and perovskite QDs (PQDs). The most prevalent QDs utilized in solar cell applications are predicated on Cd chalcogenides, particularly CdS and CdSe (CdTe), due to their efficiency, economic viability, and ease of manufacturing [10].

1.3.1.3 Organic Polymers

These materials, commonly referred to as plastic solar cells, are characterized by their cost efficiency, lightweight nature, and flexibility. Although their efficiency

presently lags behind that of conventional silicon-based solar cells, ongoing research is focused on elevating the stability and functioning of organic solar cells. In contrast to silicon-based devices, polymer solar cells exhibit flexibility, molecular-level customizability, reduced weight, potential disposability, and lower production costs. Furthermore, they may exert a diminished negative impact on the environment. Additionally, polymer solar cells possess the capability to be transparent, thereby facilitating applications in flexible electronics, windows, and walls. A notable example within this category is poly(3-hexylthiophene) (P3HT) [11, 12].

1.3.1.4 Copper Indium Gallium Selenide

In a thin-film solar panel technology, this holds promise for low production costs and high efficiency. Solar panels containing this compound are lightweight, flexible, and available in a variety of colors and shapes [13].

1.3.1.5 Carbon Nanotubes (CNTs) and Graphene

Graphene is a two-dimensional material with remarkable electrical and optical properties that could be useful in the advancement of solar panel technology. Research is currently ongoing to determine how to incorporate graphene into solar panels to increase their efficiency. They may possess high mechanical flexibility, high specific surface area, high conductivity, and high transparency in the visible spectrum [14].

1.3.1.6 Dyes

These materials are used in dye-sensitized solar cells because they are inexpensive, nontoxic, easy to prepare, and simple to manufacture. The two main types of dyes used in solar cells are called organic and inorganic dyes. Nowadays, ruthenium (Ru) dyes are recognized as the most important inorganic dye for the highly effective production of solar cells [15].

1.3.1.7 Transitional Metal Dichalcogenides (TMDs)

TMDs display tunable energy band structures, superior optical transparency, and remarkable carrier mobilities. When juxtaposed with conventional direct-bandgap semiconductors, TMDs can attain light absorption coefficients that are considerably higher, often by an order of magnitude. In PV applications, whether in single-junction or tandem double-junction configurations, TMDs exhibiting bandgaps within the range of 1.0–2.5 eV demonstrate efficient operation. Moreover, heterostructures can be fabricated without the necessity for lattice matching, as the surfaces of stacked TMDs lack dangling bonds. This significantly enhances the efficacy of the PV process. Such attributes afford TMD-based PVs a plethora of innovative design prospects.

Recently, van der Waals (vdW)-layered semiconductors, including tungsten diselenide (WSe_2), molybdenum disulfide (MoS_2), and rhenium disulfide (ReS_2), have garnered attention as potentially effective absorbers for thin-film PV systems owing to their remarkable electrical and optoelectronic attributes. vdW semiconductors exhibit robust light-matter interactions. Consequently, by maintaining nanoscale thickness, vdW semiconductors are anticipated to facilitate the advancement of high-performance PV devices with power conversion efficiencies exceeding 25% [16].

1.3.2 Advanced Designs in Solar Cell

To augment energy output and efficiency, novel and innovative designs are being conceived for solar cells. Bifacial PV systems have garnered considerable attention as a cutting-edge technology capable of enhancing energy generation while simultaneously reducing land utilization and overall costs. Unlike conventional PV models, bifacial solar cells harness photons from both direct solar radiation and reflected light that impacts both the frontal and rear surfaces of a solar module [17].

PV cells are increasingly being conceptualized for incorporation into architectural designs within built environments. These cells become integral components of the structure's design, strategically placed on the building's façade, rooftop, or fenestrations. Such solar technologies are designated as building-integrated photovoltaics (BIPVs). BIPV signifies a highly advantageous low-carbon innovation that proffers a multitude of advantages, including, but not limited to, weather resistance, thermal insulation, energy autonomy, and economic efficiencies. BIPVs not only produce electrical energy but also fulfill both aesthetic and functional purposes within architectural frameworks. Lightweight and pliable solar cells are manufactured through advanced printing methodologies [18–20].

1.3.2.1 Concentrated Solar Power (CSP) Systems

CSP systems employ CSP technology, wherein solar irradiance is focused onto a thermal receiver to facilitate electricity generation. Empirical evidence has established that locales characterized by elevated direct normal irradiation (DNI) are particularly conducive for the application of CSP technology.

The four predominant classifications of CSP technologies are as follows: first, parabolic trough systems, which are composed of highly reflective curved mirrors aligned in parallel configurations, occasionally extending beyond 100 m in length. The receiver tube, constructed from stainless steel pipes, is referred to as the absorber tube. A selective coating is applied to these tubes to effectively capture high-energy or short-wavelength solar radiation. Second, linear Fresnel reflectors (LFRs) concentrate solar energy onto a stationary, flat receiver via linear arrangements of mirrors, akin to a parabolic trough. Third, solar towers that deploy numerous heliostats to direct light onto a singular central receiver located atop a tower. This receiver may utilize molten salt or facilitate direct steam generation through a concentrated thermal flux, thereby achieving exceedingly high temperatures. Finally, the parabolic dish CSP configuration focuses the DNI at its center using a parabolic structure. The concentrated thermal energy is primarily transformed into mechanical energy through Stirling engines situated at the focal point, which can subsequently be converted into electrical energy. The entire assembly is designed to track solar movement throughout the diurnal cycle.

Scholars are curious about CSP technology because it serves as an efficient renewable energy source for electricity generation. With more than 16% solar-to-electricity efficiency, CSP technology is capable of generating substantial amounts of electricity in diverse locations worldwide. Comparing approximately 143 CSP projects globally, there are 114 currently operational, 20 that have been decommissioned or are non-functional, and 9 under construction [21, 22].

1.3.2.2 Integration with AI and IoT for Smart Energy Solutions

Energy production and its use can be combined with contemporary technologies such as the Internet of Things and artificial intelligence. This makes it possible to develop more intelligent and effective energy systems in any industry. The electrical networks created with the aid of new technologies are known as smart grid technologies. In contrast to conventional grids, smart grid technology includes components such as dispersed energy generation grids, consumers sharing data, and cutting-edge technologies such as computer vision, IoT sensors, and AI analytics.

Smart grid technologies can be classified based on the technology they employ. IoT sensors are the main tool used by basic IoT-based grids for asset management and data collection. Engineers can use the data to keep an eye on the condition of every grid node, enabling them to make prompt choices about maintenance, repair, and power distribution. Additionally, customers can effectively monitor their power usage based on the IoT infrastructure.

Other kinds of grids use AI analytics to interpret IoT data, identify patterns, and forecast outcomes. These technologies, for example, are able to forecast future malfunctions and peak energy demands. The AI pattern can also detect the weather patterns and detect the amount of sunlight that can be trapped. This can help in planning energy storage and maintain the electricity even during the rainy season [23].

1.4 Design and Implementation of Solar Energy Systems

1.4.1 Elements of a Solar Power System

The primary components found in every solar power system include:

Solar Panels: These capture electrons from light and generate direct current (DC).

DC is then converted into usable alternating current (AC) electricity by the inverter. Individual panels comprise solar cells that consist of silicon wafers connected by wires and encased in a glass layer, with a frame and backsheet providing protection. Typically, a panel string consists of 4–10 panels linked in series and connects to a designated input on a string inverter. Collectively, all the panels that make up the system are known as the solar array.

Inverters: Acting as the central processing units of a solar power system, inverters perform the conversion of DC power to AC power, the type used by household appliances. They also manage the flow of electricity among the various components of the system. There are several types of inverters available, including microinverters, storage-ready inverters, string inverters, and string inverters with PV optimizers.

Racking: The racking system is the primary framework that holds the solar panels in place. Racking systems incorporate flashings and mounting rails that attach the rails to the rooftop or ground. Since roof-mounted systems are typically the most convenient and cost-effective option, they are widely used for residential solar installations. Ground mounts, which are standalone support structures

made of metal pipes anchored into concrete footings, require additional time and resources for installation.

Batteries: Off-grid and battery backup solutions require a local battery bank to store extra energy nearby. This is particularly useful during severe weather, power outages, or other interruptions. There are three main types of batteries: flooded lead-acid batteries, sealed lead-acid batteries, and lithium batteries. Additional components of a traditional solar PV system include combiners, disconnects, breakers, meters, and wiring [24].

Solar Architecture: This concept focuses on integrating solar energy into buildings to minimize energy use. It encompasses both active solar systems and passive solar design.

Active Solar Systems: These systems convert solar energy directly into usable energy forms, such as solar panels. Solar thermal (ST) collectors harness solar energy for heat, and solar water heaters utilize solar energy to heat water for household applications.

Passive Solar Design: This strategy involves incorporating standard building materials for the collection, storage, and distribution of solar energy in a natural manner. Unlike active systems that require intricate solar collectors paired with fans, pumps, storage, or heat exchange units, passive systems rely on natural convection, conduction, and radiation for heating. Essentially, a passive solar home retains heat in thermal mass elements that absorb heat as sunlight enters through south-facing windows. Moreover, well-designed passive solar residences utilize overnight ventilation to maintain comfort during the cooling season and ensure ample daylight throughout the year.

For passive solar home design to be effective, it must incorporate several fundamental components that function in harmony:

Windows Oriented Correctly: Solar-collecting windows or equipment should ideally be positioned within 30° of true south and remain unshaded by trees or other structures between 9 a.m. and 3 p.m. every day throughout the heating season. To maintain coolness, these windows should be shaded during the spring, autumn, and cooling seasons. Keeping the glass of the windows clean is essential.

Thermal Mass Elements: Passive solar homes often utilize thermal mass materials such as concrete, brick, stone, and tile. During the heating season, these materials absorb heat from sunlight, whereas in the cooling season, they retain heat from the home's warm air. Other thermal mass options, such as water and phase change materials, enhance heat storage. In well-insulated homes in temperate climates, the thermal mass from walls and furniture may suffice, negating the need for additional thermal storage. Nothing should obstruct sunlight from reaching the thermal mass materials.

Heat Distribution Mechanisms: Heat captured by solar energy is transferred to various parts of the home through the processes of conduction, convection, and radiation.

Regulation Strategies: In summer, roof overhangs of appropriate size can shade vertical south-facing windows. Additional strategies for heat control include

low-emissivity blinds, awnings, movable vents, and dampers that either allow or block heat flow, as well as electronic devices, such as differential thermostats that activate fans, and adjustable insulating shutters [25].

Modern solar architecture incorporates intelligent technologies to track energy consumption within the building and can adjust heating, cooling, and lighting in response to weather conditions. Moreover, it is feasible to include electric vehicle (EV) charging systems powered by solar energy [26, 27].

1.4.2 Methods for Optimal Energy Harvesting

1.4.2.1 Maximum Power Point Tracking (MPPT)

MPPT is an established technique for optimizing the operating point that connects PV arrays to a power converter to maximize power output. MPPT strategies are employed to enhance energy extraction in PV systems under various environmental circumstances, including temperature and solar radiation.

1.4.2.2 Photovoltaic Thermal Hybrid Systems

These systems generate both thermal and electrical energy by capturing and converting renewable solar energy. To optimize efficiency, the thermal unit of the collector utilizes the excess heat generated by the PV module [28].

1.4.2.3 Agrivoltaic Systems

“Agrivoltaics” refers to the practice of producing PV electricity while simultaneously cultivating crops on the same land. To mitigate excessive shading on the crops below, the PV arrays are elevated 2 m above the ground and spaced further apart. They are classified based on system type (closed or open), structure type (overhead, interspace, and PV-integrated greenhouses), module tilt (fixed, one-axis, and two-axis tracking), and application type (grassland, arable, horticultural, and aquaculture). Furthermore, while not typically classified as agrivoltaics, the use of livestock under enclosed, opaque structures is also addressed [29, 30].

1.4.3 Examples of Successful Solar Projects

Solar projects provide valuable perspectives into the practical application of solar technologies while also emphasizing the different possible uses and benefits of solar energy. These examples showcase a diverse array of projects, each facing distinct challenges and yielding different results, aiding electricians and solar installers in grasping the complexities associated with the installation and upkeep of solar panels.

Following a publication focused on the enhanced performance of solar PV in aquatic environments, floating photovoltaics (FPVs) garnered increased attention and interest. Tengeh Reservoir in Singapore serves as a prominent example of an effective FPV application. Similarly, the Yamakura Dam in Japan stands out as a notable case of FPV being utilized as a sustainable energy solution. Situated in the Chiba Prefecture, the dam’s location is favorable for FPV installations, thanks to its

abundant solar radiation and scarce land availability. This project ranks among the largest FPV installations globally and employs a modular floating platform design, which minimizes environmental disruption and facilitates easier installation and maintenance [31].

An isolated region in northern Australia is poised to become the site of the world's largest solar farm. Large-scale solar installations have flourished in Australia's vast open spaces. The development of a 100-MW solar farm exemplifies a significant contribution to the local energy supply. This case study investigates the environmental considerations necessary to mitigate impact on surrounding ecosystems, along with the logistical challenges involved in large-scale deployments [32].

Korean researchers conducted another intriguing study utilizing agrivoltaic technology to assess the growth of garlic and kimchi cabbage. They monitored the growth and quality of these crops. The study took two years to conclude. They found that the weight of garlic and kimchi cabbage cultivated in agrivoltaic conditions was reduced by 15% and 18%, respectively, compared to those grown in typical scenarios. In these microenvironmental alterations, their sulfur compound contents remained persistent. This means that there was no substantial difference in the sensory attributes of kimchi cabbage and garlic grown with agrivoltaics compared to those grown customarily. This is a classic example of sustainable agriculture under agrivoltaic systems [33, 34].

1.5 Smart Solar Systems: Role of Artificial Intelligence and IoT

Modern technologies like AI and the IoT are used in smart solar systems to monitor, control, and optimize solar energy. The term AI refers to a wide range of methods and strategies intended to allow robots to mimic or improve human abilities. Crucially, there are no general guidelines for deciding whether an AI method is best for a particular use case. A number of variables influence the decision, including the problem's nature, the amount of data at hand, the algorithm's complexity, the difficulty of implementation, and the required level of accuracy and generalization. Combining AI and the IoT has emerged as a game-changing tactic for enhancing solar energy monitoring and control in the quickly developing field of renewable energy [35].

1.5.1 Predictive Maintenance and Performance Optimization

By integrating AI into solar systems, operators can monitor temperature, irradiance, dirt accumulation, and inverter efficiency. AI will identify any malfunctions in these units and enable prompt repairs. They support ongoing system monitoring. In order to predict weather patterns, identify issues, and plan maintenance in advance, AI systems examine both historical and real-time data. These features increase the longevity of PV installations and help prevent system failures. Additionally, by

precisely forecasting energy demand, AI helps integrate smart grids and enhances the reliability of solar power networks [36].

A kind of AI called machine learning (ML) allows systems to learn from data and gradually get better at what they do without explicit programming. Its main goal is to create algorithms that can recognize patterns and reach conclusions with little assistance from humans. The literature claims that ML works particularly well for solving complicated issues where conventional methods are either ineffective or challenging to use. Because it can readily adjust to new data, ML thrives in dynamic contexts. ML can be broadly divided into the following paradigms, each of which is appropriate for a particular kind of issue in solar systems:

Supervised Learning: Labeled datasets, in which every input has a corresponding output, are used to train models. This method works well for both classification and regression tasks. Based on labeled historical data, it can be used in solar panel monitoring to categorize panel conditions (e.g., normal, dirty, or damaged).

Semi-Supervised Learning: A significant amount of unlabeled data is combined with a modest amount of labeled data in this hybrid approach. After learning correlations between labeled and unlabeled examples, the model labels the remaining dataset using the labeled data as a guide. In PV system analysis, where there may be a dearth of labeled defect data but a wealth of sensor or picture data, this model is helpful.

Unsupervised Learning: Using methods like clustering and dimensionality reduction, this method uses unlabeled data to find underlying patterns or groupings. Without the need for labeled data, it can be used to detect anomalies or classify related failure types in PV systems.

Reinforcement Learning: Models gain knowledge by interacting with their surroundings and getting feedback in the form of sanctions. This technique can be used to optimize solar panel cleaning schedules [37].

1.5.2 Data-Driven Energy Management

For optimal performance, an AI system examines environmental factors and data from solar panels. This involves orienting the solar panels and making the inverter run as efficiently as possible. By allocating energy to high-demanding appliances during the hottest summer months, it can also aid in load management. It evaluates the battery's stored energy and controls it during the rainy season. In addition to monitoring, control systems are essential for dynamically modifying panel operations in response to real-time data, increasing responsiveness and efficiency. Maintaining system performance and increasing operational longevity are two more important functions of fault detection [38].

1.5.3 Remote Monitoring and Automation

The IoT is crucial for monitoring and automation. It can provide access to operators to real-time data on system performance. They may resolve problems without physically visiting the locations. Based on real-time data, they can automatically optimize

energy by adjusting the angle of panels or inverter configurations. These technologies facilitate real-time problem identification through the use of IoT-enabled monitoring devices. AI adds sophisticated data analytics to IoT capabilities to enhance energy forecasts, optimize panel orientation, and lower operating costs [39]. AI and IoT, collectively termed as AIoT, represent a cohesive strategy that blends intelligent data processing with networked equipment to facilitate increased efficiency of solar energy systems [40].

1.6 Solar-Powered Architecture and Urban Integration

1.6.1 Building-Integrated Photovoltaics (BIPVs)

Buildings are now a key component of the energy transformation. Installing PV devices in urban and suburban settings calls for particular methods that integrate the solar elements into the structure and building envelope (such as the roof or facade), perhaps taking the place of traditional building materials. The term BIPVs is frequently used to describe this integration. Building-attached PVs (BAPVs) and building-integrated PVs are the two primary categories of PV systems installed on buildings. Since BIPV panels are a component of the building, the BIPV technology lowers the overall cost of construction and mounting in this case. The parts of BAPV are generally not directly attached to the building.

BIPVs, on the other hand, are PV modules that may be integrated into a building's roof or facade in place of traditional building materials like tiles. As a result, BIPVs affect how well a building functions and are a crucial component of the structure's energy system. A lot of elements need to be taken into account in order to establish a cost-effective BIPV system, such as the PV module's temperature, partial shadowing, installation angle, building direction, and system orientation. The capacity to attain high power output and efficiency in building applications is significantly impacted by each of these factors.

Depending on the technology or market, the BIPVs can be silicon or nonsilicon and come in solar cell glazing, PV foils, PV tiles, and PV modules. The main surfaces of buildings where PV cells can be installed are facades, flat roofs, and slanted roofs. The various types of BIPV systems are given in Figure 1.3. Among the characteristics used to assess the different BIPV devices are solar cell efficiency, maximum effect, fill factor, open circuit voltage, and short circuit current. A PV module is the fundamental unit of BIPV technology. Modules of solar cells are put together, and these modules are connected to create a site-specific array.

Solar energy is captured by BIPV systems and transformed into heat and electricity. The electricity produced by the BIPV can be stored in DC batteries or used to power DC equipment. The output of the PV system is either converted to AC electricity for general use or connected to the utility grid or inverters. Additional parts known as "balance-of-system" (BOS) components include the inverter, switches, controls, meters, power conditioning equipment, wiring, supporting structure, and storage components [41, 42].

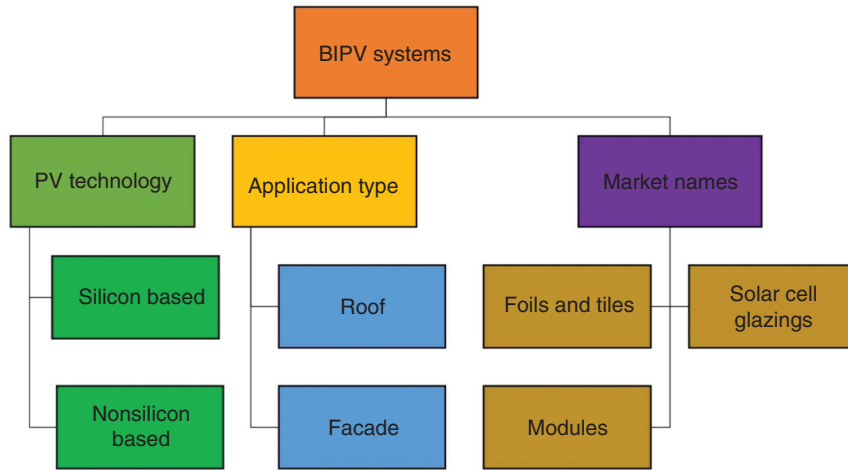


Figure 1.3 Different types of BIPV systems.

When a PV system is embedded onto the building's facade, the system's exterior air enters from the bottom and exits from the top. It absorbs the heat from the PV modules during this operation, lowering their temperature and increasing their lifespan and efficiency. In certain applications, the system uses an air duct and a fan to pull hot air into the space, lowering the winter heating load. These systems, known as BIPVT systems, use solar energy to generate electricity and heat.

The multifunctional PV façade is one of the more sought-after BIPV options in the construction industry. It is a creative, practical method that is very helpful for giving buildings that require retrofitting or new construction both active and passive benefits.

The building will achieve the following benefits from this solution:

- By using sustainable ideas like distributed generation, in situ power generation can prevent losses from energy transit.
- Depending on the design and PV glass combination, thermal envelope benefits could result in energy savings of between 15% and 35%. Additionally, envelope solutions and heat recovery applications can be used together as a preheating flow throughout the winter.
- The light entrance directly relates to semitransparent PV glass design based on the illumination requirements.
- From the perspective of satisfying the same standards for construction applications, the acoustic benefits resulting from the behavior of multifunctional façades are comparable to those of traditional glass façades.
- Aesthetical added value is linked to a visually appealing feature of silicon technology that is used in useful solutions like double-skin or ventilated façades.
- Installation is simple. It requires a straightforward mounting and structural system made up of aluminum profiles, brackets, and staples.

- Protection from the negative effects of the atmosphere is observed. For example, installation of a vented façade makes the internal structure less vulnerable to weather conditions.

This method cannot be implemented for all the buildings. It will rely on factors such as aesthetic standards, compatibility, and the dimensional requirements [43, 44].

1.6.2 Green Building Standards and Solar Design

Green building regulations and solar design are defined as a set of rules and standards that can assess a product's performance. Organizations such as ANSI, ASTM, or American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) utilize consensus-building techniques to create common standards related to construction practices. Some of the standards used to evaluate green buildings include the following.

ASHRAE focuses on the sustainability, indoor air quality, building systems, and energy efficiency, thereby conserving local ecosystems, enhancing resilience to threats, and promoting sustainability [45]. Building Research Establishment Environmental Assessment Method (BREEAM) provides a comprehensive assessment of sustainable values such as net-zero carbon, whole-life performance, biodiversity, circularity, resilience, health and social effect, transparency, and reporting [46]. The LEED (Leadership in Energy and Environmental Design) ensures that buildings not only provide cost-effective and healthy environments but also lay the groundwork for green constructions with low-carbon emissions [47]. The LEED certification's "green" emblem is widely recognized. The US Green Building Council is responsible for these building standards and guidelines. It ensures that buildings not only provide cost-effective and healthy environments but also lay the groundwork for green constructions with low-carbon emissions. The LEED standard is a leading framework that considers every aspect of top-notch building design [47]. The WELL Building Standard (WELL) provides a framework for monitoring elements that affect occupant health and well-being. Performance metrics are used to analyze elements that affect well-being, such as ventilation, hydration, illumination, comfort, nutrition, fitness, and mental clarity. Because of its performance-based nature, each WELL concept is tested on-site using performance testing and metrics [48].

Since its inception in 2005, the Green Mark Certification has undergone numerous updates and upgrades. To promote sustainable design, the system assesses the performance and environmental impact of new and existing structures. Green Mark accreditation is not just for buildings; parks and infrastructure projects are also eligible. The grading system for each project category varies. The criteria cover a wide range of properties, including existing buildings, landed homes, schools, and both residential and nonresidential constructions [49].

The Excellence in Design for Greater Efficiencies (EDGE) rating, designed by the World Bank Group's International Finance Corporation, emphasizes efficiency and zero-carbon buildings, setting it apart from other evaluations that focus on

overall building performance [50]. Home Energy Rating System (HERS) index is a nationally recognized methodology in the United States developed by the Residential Energy Services Network (RESNET) in 2006. The evaluation involves building plans and on-site inspections and is exclusively for residential properties. A certified RESNET Home Energy Rater will assess the building's performance. Compared to similar properties, the score reflects how energy-efficient the home is. Based on Energy Star performance criteria, the rater will also identify potential energy efficiency improvements. A lower score indicates better energy efficiency or reduced energy consumption [51].

Green building standards offer guidelines for sustainable design and construction. Following these criteria can provide monetary and environmental value, as well as considerations for building inhabitants' health and well-being. As a result, occupants of green buildings enjoy enhanced comfort, work performance, and overall health. Increasing energy efficiency in an environmentally friendly structure can lower energy costs, resulting in savings for building owners. Similar benefits can be obtained from renewable energy sources. Green buildings typically deliver a higher return on investment than regular high-performance facilities [52].

1.6.3 Urban Planning and Decentralized Solar Systems

The concept of solar urban planning spans multiple sectors and addresses a wide array of urban challenges, including social, environmental, institutional, and techno-economic dimensions. Consequently, it has various implications for city management and urban governance. The decentralized energy system (DES) is an important method for changing urban planning. A DES reduces reliance on fossil fuels and increases eco-efficiency by making better use of renewable energy sources clubbed with heat and power. Because end customers are distributed around a region, implementing a similarly decentralized energy production model can reduce associated expenses, both financially and environmentally, while also lowering transmission and distribution inefficiencies. A decentralized structure is based on distributed generation, energy storage, and demand response [53, 54].

1.6.3.1 Distributed Generation

This is the basic component of a DES. It is feasible to produce electricity and heat in a decentralized manner. However, heat has traditionally been generated on-site because it cannot be transported over long distances. Since heat is a consequence of different energy generation processes, this coordination improves the system's efficiency in producing both electricity and heat. Distributed generation facilities can either link to the grid or service a single site without sending excess power to the grid.

1.6.3.2 Grid Connected

Commercial or industrial activities that have their own power production facilities but can sell excess electricity to the grid that serves areas far from the main grid are examples of distributed electricity generation connected to a central grid. As

countries improve their central grid networks, mini-grids can be developed to form a distribution network that connects to a larger transmission network.

1.6.3.3 Off-Grid

Even on a lesser scale, energy storage and electricity demand management are critical components of an off-grid DES. The classic example is a single-family solar home system that includes battery storage. Users control their own loads to adjust for supply changes in this case.

1.6.3.4 Energy Storage

One major limitation in power distribution has been that electrical energy must be generated on demand and cannot be stored. In a decentralized framework, having a greater number of generating sources can complicate supply management to accurately fulfill demand. Nevertheless, energy storage options such as batteries, compressed air, and pumped hydro storage can help maintain grid stability by storing energy when supply exceeds demand and reintegrating it into the system during peak usage periods.

1.6.3.5 Demand Response

Decentralized power connected to the grid allows for demand-response technologies that enhance grid stability management. Historically, the primary concern of grid management has been supply management. However, innovations such as smart metering and smart grid technology allow for real-time communication and supervision. Consequently, many power users may also become energy producers due to distributed generation and storage capabilities. Implementing smart grid technologies is essential for facilitating the administration of a fully DES. Moreover, heat generated by combined heat and power (CHP) systems can be utilized at a single location, reducing the infrastructure needed to transfer heat to multiple buildings.

A decentralized system provides various advantages. CHP improves the overall efficiency of the heat and power system, reducing harmful greenhouse gas emissions. This improvement is made feasible by the decentralization of electricity generation. Distributed generation sources often have cheaper capital costs per project than huge central power facilities. Off-grid distributed power can sometimes save money on transmission and distribution network building. Lowering transmission losses enables deferral of investments in large central power plants while progressively growing capacity through distributed generation. Decentralized firms are responsible for the construction, operation, and maintenance of energy-producing facilities, creating work opportunities. Because of their smaller size and shorter construction timetables, distributed generation projects offer more planning flexibility than bigger central power facilities. Decentralized energy grids can also help with energy efficiency measures. When smart meters provide more comprehensive information about energy flows, customers may become more aware of their consumption. Energy consumers can become producers by generating energy on-site, increasing their financial incentive for efficient production and consumption. A decentralized system is extremely useful in rural areas with sparse

inhabitants, especially when isolated, off-grid units and mini-grids are used, which are frequently less expensive than building the central grid. They are capable of electrifying remote areas in a timelier manner.

1.7 Environmental, Economic, and Social Benefits of Solar Energy

Solar energy possesses substantial significance for both ecological preservation and the economic stability of any nation. It is integral to enhancing the cost efficiency of a nation's economic framework. Among its various advantages, it directly contributes to employment opportunities and nurtures the development of micro-industries. Economic determinants appear to be the predominant catalysts for the advancement of solar energy technologies. Additional factors beyond economic considerations involve issues related to pollution, global warming emissions, and the security of energy supplies, among others. Nevertheless, the production cost of energy predominantly shapes design decisions. Environmental considerations, however, are progressively acknowledged as crucial components in these evaluative processes. A more reliable national energy supply enhances safety and security within the country [55].

1.7.1 Reduction of Carbon Footprint and Greenhouse Gas Emission

The most salient advantage of renewable energy systems is their capacity to diminish environmental contamination. This reduction is achieved through a decline in atmospheric emissions attributable to the substitution of traditional fuels and electricity sources. The principal ramifications of air pollutants encompass their effects on public health, agricultural productivity, architectural integrity, historical monuments, forest ecosystems, and broader ecological systems. It is observed that the societal costs of pollution are substantially influenced by the geographical positioning of emission sources [56].

The extensive application of fossil fuels results in land degradation and deforestation, as well as air and water pollution, adverse health effects, and the buildup of solid waste. These features contribute to the urgent issues of global warming, the formation of smog, and threats to terrestrial, aquatic, and marine biodiversity, among other concerns. In addition, the combustion of coal produces sulfur dioxide, which is linked to the formation of acid rain. The extraction methodology known as "strip mining" inflicts substantial harm on the environment by disturbing extensive tracts of the landscape [57].

Regarding environmental considerations, solar energy technologies present additional beneficial outcomes, such as the rehabilitation of degraded terrains and a reduction in the requisite transmission infrastructure for electrical grids. Solar energy provides environmental benefits since it is exclusively derived from sunlight and does not release carbon dioxide into the atmosphere, thus assisting in the

alleviation of the greenhouse effect. Furthermore, nitrogen oxides and sulfur oxides are not emitted, facilitating the reduction of acid rain [58].

An additional advantage of solar energy is that when individuals utilize electricity generated by solar power plants, they can circumvent reliance on diesel generators, kerosene, or batteries for their everyday lighting requirements. This is especially pertinent in developing countries. Batteries, including those employed in flashlights, present a considerable risk to soil and groundwater if not disposed of correctly, as they contain lead-acid cells [59].

In addition to the ecological advantages, alternative energy sources present additional benefits that significantly enhance the overall quality of life: Solar energy facilities function with minimal noise, in stark contrast to diesel generators. The expansion of solar energy installations is a straightforward process through the incorporation of additional solar panels. Moreover, solar panels are typically accompanied by comprehensive warranties extending up to 25 years, which is substantially longer than those associated with conventional power plants. In terms of spatial dimensions, small- to medium-sized solar energy installations occupy a considerably reduced footprint when compared to coal or other fossil fuel-based energy generation methods [60].

While the establishment of ST systems necessitates a considerable quantity of materials, their operational consumption remains minimal. During this phase, the primary potential environmental concern arises from the replacement of coolants, which can be effectively managed through appropriate practices. Any inadvertent coolant leaks may result in fire hazards and gas emissions from vaporized coolant, adversely affecting public health and safety. In contrast, the widespread adoption of ST technologies will substantially diminish reliance on conventional fuels, thereby mitigating the environmental repercussions associated with these fuels [60].

The paradigm of sustainable development is firmly rooted in an economic perspective. It also encompasses the requisite actions to attain collective long-term goals pertaining to climate advantages, access to clean air, and energy objectives. The global market for integrated PV solar technologies is experiencing rapid growth, generating opportunities that enable solar energy enterprises to capitalize on significant governmental support through underwriting, subsidies, favorable trading licenses, and the cultivation of a skilled labor force. Concurrently, the intensified competition has invigorated the impetus to persist in investing in research and development from both public and private sectors [61].

1.7.2 Cost-Effectiveness and Energy Independence

The fiscal benefits of solar energy applications can be delineated as follows: It serves to extend the duration of the productive workday (Figure 1.4). It provides consistent and high-quality illumination at a reduced expenditure in comparison to alternative energy sources or the conventional electrical grid. Solar energy facilitates the generation of both direct and ancillary employment opportunities. Furthermore, it contributes to the conservation of the nation's foreign currency reserves. This phenomenon arises from the fact that a portion of the revenue derived from exports,

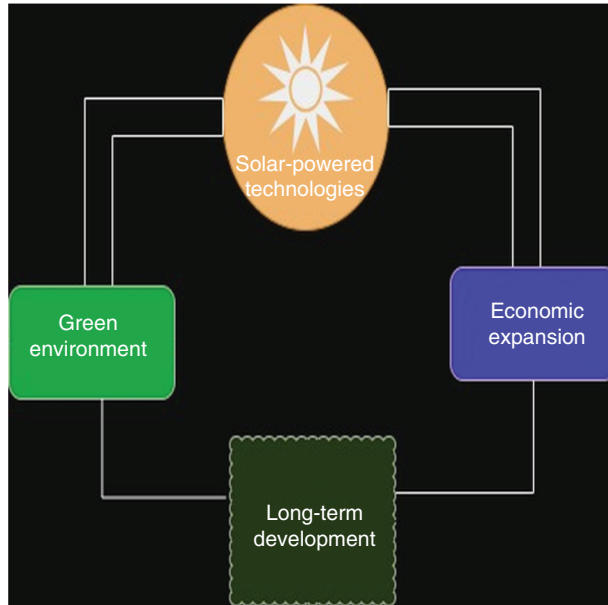


Figure 1.4 Analytical structure for solar energy utilization.

which would typically be earmarked for the procurement of various spare components for power generation equipment, can now be preserved. Additionally, the financial resources conserved can be reallocated to other critical sectors such as healthcare and education that require financial support [62].

It is imperative to acknowledge that solar energy is environmentally benign. Moreover, when evaluating the economic indicators of alternative power generation modalities of comparable capacity over their operational lifespan, the economic efficacy of solar energy systems surpasses that of their counterparts for each unit of energy produced. For this reason, financial investment from governmental entities and business leaders is crucial to mitigate the costs associated with the deployment of solar panels for industrial, commercial, and residential applications. Moreover, the use of solar energy would promote the growth of micro-enterprises within the nation [63].

As solar energy is generated locally, frequently at the site of consumption, pricing and availability are insulated from blackouts, geopolitical instabilities and are independent of extensive supply chains. Innovative technologies, including PV roof shingles, windows, and adaptable fabrics that can be economically integrated into both new and existing infrastructures, are gaining traction. It is particularly noteworthy that solar energy facilitates, at least to some extent, the diminishment of certain routine labor expenditures. For example, a homeowner who has a solar system installed on their roof or facade stands to gain from this advantage [64].

There exists no stipulation for specialized safety regulations pertaining to solar energy installations, nor for limitations on emissions, guidelines for waste management, mechanisms for pollution control, or the establishment of monitoring

stations. The use of biomass is the sole exception, which requires minimal administrative regulations that need not exceed the existing frameworks applicable to agriculture and can be administered by the currently established agricultural regulatory bodies. Consequently, this circumstance results in diminished administrative costs [65].

1.7.3 Social Equity and Access to Clean Energy

The implementation of solar energy would invigorate new development and manufacturing activities across various industrial sectors, not solely in the production of solar energy converters but also in the apparatus necessary for solar energy applications. Small enterprises and artisanal crafts would receive a renewed impetus. Moreover, renewable energy has the capacity to advance gender equality by mitigating the adverse health repercussions experienced by women and various developing countries, which arise from their habitual dependence on firewood as a primary fuel source [66].

1.8 Challenges and Limitations in Solar Energy Adoption

The domain of solar energy system development within developing nations represents a compelling sphere wherein opportunities and challenges coexist in a balanced manner. This narrative unfolds within the context of escalating global energy demands, sustainability objectives, and the transformative capacity of solar PVs.

1.8.1 Intermittency and Storage Issues

Solar energy exhibits inherent variability, generating electrical power solely during daylight hours. There is a diminished efficiency under overcast conditions and complete inoperability during sandstorms. This inherent inconsistency engenders a disparity between the production of energy and its consumption. To ensure a stable supply of solar energy, regardless of meteorological conditions, the development of cost-effective, high-capacity energy storage systems is imperative. At present, silicon-based solar PV devices predominate within the solar energy market; nevertheless, these PV systems are associated with certain disadvantages, including elevated material expenses and protracted manufacturing timelines. Advancements in battery technology, including enhancements in lithium-ion batteries or alternative forms such as solid-state batteries, may yield the requisite innovations to resolve the storage conundrum [67].

1.8.2 Policy, Regulatory, and Infrastructural Barriers

The regulatory landscape governing solar energy exhibits considerable variation across different countries and regions, thereby influencing the execution and feasibility of solar initiatives. Discrepancies in permitting processes, zoning laws, and

grid interconnection policies can render the solar system assimilation a challenging endeavor. Hence, it is essential that the government regulations are streamlined and supportive policies are enacted [68].

Nigeria exemplifies a pertinent case, illustrating the adverse ramifications of regulatory uncertainty. The energy sector in this nation is regulated by a complex array of laws that permit diverse interpretations, engendering ambiguity. As a result, potential investors in solar projects frequently find themselves ensnared in an intricate maze of contradictory regulations and unclear administrative procedures. The absence of legislative clarity obstructs private investments and decelerates the advancement of solar PV, thereby hindering Nigeria's progress toward a sustainable energy future [69].

Conversely, Chile serves as an exemplary model showcasing the profound influence of conducive policy frameworks. This unequivocal and consistent policy not only attracted substantial private investments but also positioned Chile at the vanguard of solar energy developments. The enactment of transparent regulations and progressive policies cultivated an atmosphere that stimulated innovation, invigorated investment, and expedited the expansion of solar power system [70].

Another illustrative case is that of the United Arab Emirates (UAE). In a region traditionally reliant on fossil fuels, the UAE undertook unprecedented initiatives by instituting rigorous regulations that fostered renewable energy, particularly solar PVs. By implementing feed-in tariffs and power purchase agreements with predetermined pricing for solar energy, the UAE established a dependable revenue stream for investors, culminating in the rapid advancement of the solar industry. This proactive policy orientation revolutionized the nation's energy sector and exemplifies the considerable impact of supportive regulations [71].

1.8.3 Technological and Economic Constraints

The expenditures associated with solar power systems impose a significant initial financial strain on numerous individuals and governmental entities. The context of India exemplifies the economic challenges correlated with the adoption of solar PVs. Despite the nation's ambitious objectives and substantial solar energy potential, it has faced impediments due to budgetary limitations. During its initial phase, the Indian solar sector relied heavily on foreign investment, as local financial institutions exhibited reluctance to fund an untested technology. Many initiatives were established to consolidate resources and leverage economies of scale to reduce costs, underscoring the collaborative efforts required to confront financial obstacles [72]. Bangladesh offers another compelling instance, having endeavored to improve electricity access in remote regions through its extensive solar home system program. Despite achieving notable successes, the upfront investment remained a significant barrier for many low-income households [73].

A fundamental obstacle to the effective integration of solar PV systems in developing nations is the inadequacy of infrastructure essential for a transition to sustainable energy. The rudimentary condition of grid infrastructure, coupled with erratic power supply and limited storage capabilities, raises concerns regarding the viability

of solar arrays. Sub-Saharan Africa exemplifies the substantial infrastructure challenges that frequently impede the positioning of solar power systems. The region contends with the absence of grid networks, complicating the incorporation of intermittent solar energy resources [74]. For instance, Nigeria struggles with an unreliable electrical supply due to outdated and insufficient grid infrastructure. This limitation obstructs the incorporation of surplus solar energy into the grid, thereby diminishing the benefits of solar installations and hindering efforts to electrify rural locales [75].

Although the cost of solar PV systems has markedly diminished over the preceding decade, the upfront expenditures associated with installation and configuration remain a significant barrier for numerous residential and commercial entities. Furthermore, the variability in subsidy programs and financial incentives across different geographical areas can either facilitate or hinder the proliferation of solar energy technologies. Consistency in economic policy is imperative for both investors and consumers to engage in long-term commitments to solar power [63].

Despite the significant advancements in solar panel technology in terms of efficiency and durability, there persists an urgent requirement for continuous technological innovation. Present-day solar panels only convert a limited fraction of the solar energy they capture into usable electrical power. Enhancing the efficiency of PV cells is imperative for optimizing the output derived from solar installations and for reducing the overall cost. Consequently, considerable expectations are directed toward innovations that can substantially elevate the efficiency levels of solar panels [76].

The traditional grid infrastructure was conceptualized to support centralized power generation, rather than the intermittent and decentralized power sources represented by solar panels. It is essential to upgrade grid infrastructure to effectively cope with the variability and decentralization of solar energy production. This process entails the enhancement of grid flexibility through the implementation of advanced technologies such as smart grids and demand response systems, which possess the capacity to dynamically adjust in order to equilibrate electricity supply and demand [77].

Furthermore, a substantial obstacle to the implementation of solar PV technology in developing countries is the deficiency of technical expertise. The complex procedures involved in the planning, installation, and maintenance of solar PV systems necessitate the presence of skilled professionals and technicians. Regrettably, the lack of such expertise is a major setback to the successful execution of solar initiatives. Sub-Saharan Africa exemplifies the repercussions of inadequate technical knowledge. For example, Tanzania grapples with a deficit of experienced solar professionals [78].

1.8.4 Environmental Challenges

The detrimental environmental impacts of solar energy systems may encompass land displacement and the potential for air and water pollution arising from manufacturing activities, routine maintenance, and system dismantlement. Nevertheless,

concerns regarding land use are mitigated when solar collectors are installed on rooftops; maintenance requirements are minimal, and the pollution generated from deconstruction is commensurate with that produced by the demolition of a conventional system of similar capacity. The pollution associated with the production of solar collectors is estimated by evaluating the embodied energy expended in their fabrication and assembly, alongside estimating the pollution correlated with this energy input [79].

Beyond routine operations, there exists a potential risk of water contamination due to leaks from heat transfer fluids. Additionally, solar converters can attain elevated temperatures when coolant is depleted (up to 2000°C). At such high temperatures, there exists a risk of combustion, alongside the potential for outgassing from panel materials and the emission of heat transfer fluids as gases or through combustion [80].

1.8.5 Awareness and Discernment

Finally, a latent yet significant impediment to the adoption of renewable energy, particularly in developing nations, is public understanding and recognition. The proliferation of solar PV technology is significantly shaped by societal perceptions and levels of awareness. Misunderstandings regarding the reliability, economic ramifications, and advantages of solar energy can hinder its extensive adoption. The potential of solar energy may be undermined by misconceptions regarding its benefits or misinterpretations about its reliability and cost in comparison to conventional energy sources [81].

Pakistan serves as a salient example that exemplifies the impact of public perception. Doubts concerning solar energy tend to persist in regions where fossil fuels have historically dominated. The reliance on imported fossil fuels has precipitated persistent power shortages, prompting governmental initiatives to advocate for solar energy solutions. Nevertheless, certain demographics within the populace remained skeptical due to a lack of understanding regarding the advancements in solar technology and its potential to mitigate energy deficiencies. Consequently, the government launched public awareness initiatives, underscored successful solar projects, and educated the public about the advantages of solar energy. This endeavor to transform perceptions cultivated a more favorable environment for the adoption of solar PV [81].

1.9 Future Outlook and Research Directions

The erratic availability of renewable energy resources, solar irradiation, constitutes a considerable challenge. Although energy storage solutions possess the potential to alleviate this predicament, their overall cost-effectiveness and efficiency in energy conversion remain suboptimal. Consequently, hybrid renewable energy systems have been developed as a more economically viable and efficient technology to address these challenges.

1.9.1 Innovations in Nanotechnology, Storage, and Grid Integration

The enhancement of solar energy absorption has been documented to be significantly improved through the incorporation of nanomaterials, attributed to their exceedingly diminutive dimensions and considerable surface area. Nanoflowers, nanospheres, nanorods, QDs, nanocomposites, nanotubes, and nanoparticles are the quintessential nanomaterials of interest in this domain. These materials are employed to increase the absorption capacity of solar devices. The primary attributes to be considered in these contexts include not only the morphology and dimensions of the nanomaterials but also the optical characteristics of the resultant device. The configuration of the nanomaterials across various layers and electrodes within solar cells can significantly enhance solar radiation absorption through the mechanism of surface plasmon resonance and concurrently establish uninterrupted charge transport pathways to the electrodes [82].

Gold and silver nanoparticles have an impact on the concentration of light within solar cells, thereby augmenting the overall efficiency of the cell. Nanorods composed of either metallic or semiconductor materials function innovatively by enabling the manipulation of the electrical properties of solar devices via light interaction. A notable enhancement in solar energy collection is observed with the utilization of nanospheres, which are fabricated from self-assembling nanoparticles. Nanospheres are deemed to be more cost-effective than their nanofabricated counterparts. Bidirectionally aligned hierarchical nanocomposites serve as classic examples of nanocomposites employed in effective solar-driven atmospheric water harvesting. Additionally, nanoflowers are recognized for their proficiency in facilitating effective charge transport [82].

In order to leverage nanomaterials for solar energy applications and sustainability challenges, it is imperative to enhance their scalability to a significant degree. The optimization of processes for their industrial-scale production and the identification of critical breaking points represent the primary objectives of their effective manufacturing for prospective applications [82].

A review of the current studies in energy storage technologies indicates that challenges relating to energy density, cost, and material sustainability persist. Lithium-ion batteries have been predominant in these technological advancements, providing enhancements in energy density, cycle longevity, and cost-effectiveness. Furthermore, solid-state batteries, which employ solid electrolytes, hold the promise of elevated energy densities and improved safety compared to conventional lithium-ion batteries. Flow batteries, vanadium redox flow batteries (VRFBs), zinc–bromine, compressed air energy storage (CAES), and AdMs flow batteries have proven their worth in prolonged energy storage applications [83].

Innovations in the formulation of electrolytes and advancements in membrane technologies are anticipated to enhance operational efficacy and diminish expenses, thereby rendering these systems increasingly competitive within the context of grid-scale energy storage applications. The integration of these systems with solar power has the potential to yield a stable energy supply, effectively addressing the challenges associated with intermittency [83].

Consequently, smart grid technology presents a transformative paradigm for the distribution and management of electrical energy. The incorporation of renewable energy sources, such as solar energy, into the grid is crucial for minimizing greenhouse gas emissions. This type of integration can facilitate the creation of enhanced employment opportunities, thereby invigorating the economy [84].

1.9.2 Policy Support and International Cooperation

Several constraints, including poor coordination and consistency in the policy framework; insufficient support at lower levels, a scarcity of innovative regional policies; an unhealthy and fragmented financing and investment system; and insufficient funding for technical research and development in renewable energy, could impede the adoption of solar energy in any country [85].

Renewable energy has consistently been a significant topic at international environmental conferences organized by the UN and other global entities. Energy policy represents a strategic approach where governments address energy development matters alongside the growth of the energy sector, which encompasses energy production, distribution, and consumption. Legislation, international agreements, and investment incentives are all possible components of energy policy [85].

A range of policies have been established and enacted to encourage renewable energy use. These strategies primarily aim to lessen the environmental effects of the energy industry, decrease dependence on fossil fuels, and foster new industrial growth. Notable success stories include the use of solar energy in countries such as the United States, Canada, Germany, Spain, Australia, China, and France. At a global scale, the International Solar Alliance has been formed to advance the deployment of solar energy. Various financial mechanisms, such as capital subsidies for residential users and financing options like low-interest loans, have improved access to rooftop solar systems for consumers. Different countries around the globe have initiated dedicated programs targeting lower-income consumer segments [85]. Tax credit programs have also emerged as a critical instrument in the expansion of the solar segment across countries [86].

1.9.3 Vision for a Sustainable Solar-Powered Future

Urban centers exhibit a pronounced reliance on fossil fuels, functioning as pivotal sites for energy utilization and notable contributors to greenhouse gas emissions. While there exists no city globally that predominantly employs solar energy, a multitude of urban areas and local administrations are making significant advancements in pursuit of this objective. Cities such as Chicago, San Francisco, Santa Monica, Sacramento, Austin, Freiburg, Hannover, Barcelona, Sydney, Perth, Malmo, and Stockholm exemplify effective solar advocacy. A judicious initial measure for these municipalities is to mandate that all newly constructed edifices – regardless of being residential, educational, or commercial – integrate passive solar energy principles and adhere to local climatic conditions in their architectural designs. The process

for solar design will vary depending on geographical and climatic factors; however, this is the most viable option that any design (and city) should capitalize upon [87].

The amalgamation of solar PV technology with the burgeoning EV sector possesses the capability to expedite the transition toward sustainable and environmentally conscious transportation. Solar panels integrated into vehicle structures function as sunlight collectors, converting solar energy into electrical energy. This generated electricity powers the vehicle's propulsion system or is adeptly stored in batteries for subsequent utilization. Efficiency is paramount when capturing solar energy for vehicular propulsion. The solar panels must exhibit a high degree of efficiency to generate sufficient power within an appropriate timeframe for operation [87].

In a comparable manner, the deficit in electricity and elevated fuel prices adversely affect the water supply necessary for irrigation. The adoption of solar energy for water pumping represents a viable alternative to conventional electricity- and diesel-driven pumping systems. Within a solar-powered irrigation framework, the sprinkler system, in conjunction with a solar water pump, operates to diminish water consumption and reduce electricity usage. The initial investment, alongside operational and maintenance costs, associated with diesel pumps is two to four times higher than those associated with a PV pump. Environmentally sustainable solar pumping systems incur lower maintenance costs and eliminate fuel expenditures. The solar-powered irrigation system makes a substantial contribution to the socioeconomic development of rural populations in any country [88].

Solar energy generation can and should take place within urban contexts, integrating into land-use and physical configurations while becoming an important and meaningful component of the urban economy.

1.10 Conclusion

PV cells harness solar energy to generate electricity. The efficacy of PV cells has experienced a substantial enhancement, as materials derived from perovskites have supplanted traditional silicon. A novel roadmap for the optimal utilization and management of solar energy has been enabled by the advent of emerging technologies such as CSP and the amalgamation of solar energy systems with AI and IoT. This chapter further examines a selection of case studies pertaining to the successful implementation of PV cells.

The deployment and utilization of renewable energy resources ensure a more pristine ecological environment. A significant consequence of this is an improved populace, which ultimately leads to an augmented quality of life. Such enhancement is anticipated to elevate the Human Development Index (HDI) and contribute to a reduction in both infant and maternal mortality rates.

Emerging technologies and an array of nanostructures have been scrutinized to revolutionize the technologies related to solar energy harvesting. These advancements have facilitated the resolution of established energy conversion processes that previously exhibited numerous drawbacks concerning light absorption, charge carrier dynamics, and the stability of the devices.

Recognizing its ability to meet current and future energy demands, nations around the world have implemented enabling laws and regulations to promote the spread of solar energy systems, such as capital subsidies, tax breaks, and creative business models. Furthermore, over the past decade, the costs of solar modules have decreased by more than 80%, aided by government incentives, making solar energy systems economically viable on a worldwide scale.

The adoption of solar energy harbors the potential to reconcile the dichotomy between economic development and environmental degradation, thereby engendering a new paradigm of economic vitality. No market exhibits greater promise than that of solar technologies, which has primarily been overlooked thus far. Entirely new industrial sectors can emerge, facing minimal acceptance challenges from the public, in stark contrast to the growing resistance encountered with traditional manufacturing hubs. This scenario, in turn, ensures protection for new investments.

List of Abbreviations

AI	artificial intelligence
BAPV	building-attached photovoltaics
BIPV	building-integrated photovoltaics
CHP	combined heat and power
CSP	concentrated solar power
DES	decentralized energy system
DNI	direct normal irradiation
ETL	electron transport layer
FPV	floating photovoltaics
HERS	home energy rating system
HTL	hole transport layer
IoT	Internet of Things
LEED	leadership in energy and environmental design
ML	machine learning
MPPT	maximum power point tracking
PV	photovoltaic
QD	quantum dot
SDGs	Sustainable Development Goals
TMD	transition metal dichalcogenides
vdW	van der Waals

References

- 1 Dorian, J.P., Franssen, H.T., and Simbeck, D.R. (2005). Global challenges in energy. *Energy Policy* 34 (15): 1984–1991. <https://doi.org/10.1016/j.enpol.2005.03.010>.
- 2 Jaiswal, K.K., Chowdhury, C.R., Yadav, D. et al. (2022). Renewable and sustainable clean energy development and impact on social, economic, and environmental health. *Energy Nexus* 7: 100118. <https://doi.org/10.1016/j.nexus.2022.100118>.
- 3 Obaideen, K., AlMallahi, M.N., Alami, A.H. et al. (2021). On the contribution of solar energy to sustainable developments goals: case study on Mohammed bin Rashid Al Maktoum Solar Park. *International Journal of Thermofluids* 12: 100123. <https://doi.org/10.1016/j.ijft.2021.100123>.
- 4 Bhatia, S.C. (2014). Solar radiations. In: *Advanced Renewable Energy Systems*, 32–67. India: Woodhead Publishing. <https://doi.org/10.1016/b978-1-78242-269-3.50002-4>.
- 5 Jothivenkatachalam, K., Kavinkumar, V., and Moscow, S. (2023). Metal-metal oxide based nanocomposites for the photovoltaic applications. In: *Reference Module in Earth Systems and Environmental Sciences*, 775–788. Elsevier. <https://doi.org/10.1016/b978-0-323-93940-9.00152-3>.
- 6 Al-Ezzi, A.S. and Ansari, M.N.M. (2022). Photovoltaic solar cells: a review. *Applied System Innovation* 5 (4): 67. <https://doi.org/10.3390/asi5040067>.
- 7 Pastuszak, J. and Wegierek, P. (2022). Photovoltaic cell generations and current research directions for their development. *Materials* 15 (16): 5542. <https://doi.org/10.3390/ma15165542>.
- 8 Iqbal, M.A., Malik, M., Shahid, W. et al. (2022). Materials for photovoltaics: Overview, generations, recent advancements and future prospects. In: *Thin films photovoltaics* (ed. B. Zaidi and C. Shekhar), 775–788. IntechOpen: <https://doi.org/10.5772/intechopen.101449>.
- 9 Yang, Y., Hoang, M.T., Bhardwaj, A. et al. (2022). Perovskite solar cells based self-charging power packs: fundamentals, applications and challenges. *Nano Energy* 94: 106910. <https://doi.org/10.1016/j.nanoen.2021.106910>.
- 10 Shwetharani, R., Ravikumar, C.H., Jyothi, M.S., and Balakrishna, R.G. (2022). Application of quantum dots in solar cells. In: *Quantum dots: Fundamentals, synthesis and applications* (ed. R. Ameta, J.P. Bhatt, and S.C. Ameta), 277–311. Elsevier. <https://doi.org/10.1016/b978-0-12-824153-0.00012-4>.
- 11 Cai, W., Gong, X., and Cao, Y. (2009). Polymer solar cells: recent development and possible routes for improvement in the performance. *Solar Energy Materials and Solar Cells* 94 (2): 114–127. <https://doi.org/10.1016/j.solmat.2009.10.005>.
- 12 Shukla, A.K., Sudhakar, K., and Baredar, P. (2016b). A comprehensive review on design of building integrated photovoltaic system. *Energy and Buildings* 128: 99–110. <https://doi.org/10.1016/j.enbuild.2016.06.077>.
- 13 Rahman, M.F., Hasan, M.K., Chowdhury, M. et al. (2023). A qualitative design and optimization of CIGS-based Solar cells with Sn₂S₃ back surface field: a plan

- for achieving 21.83% efficiency. *Heliyon* 9 (12): e22866. <https://doi.org/10.1016/j.heliyon.2023.e22866>.
- 14 Ouyang, J. (2019). Applications of carbon nanotubes and graphene for third-generation solar cells and fuel cells. *Nano Materials Science* 1 (2): 77–90. <https://doi.org/10.1016/j.nanoms.2019.03.004>.
 - 15 Bej, S., Ghosh, P., Majumdar, G. et al. (2019). Design and synthesis of new ruthenium coordination complex as efficient dye in DSSC like alternative energy resources with a bird's eye view on strategies towards GHGs mitigation. In: *Reference Module in Materials Science and Materials Engineering* (ed. Z. Dughaish), 395–410. Elsevier Inc. <https://doi.org/10.1016/b978-0-12-803581-8.11672-8>.
 - 16 Aftab, S., Iqbal, M.Z., Hussain, S. et al. (2023). Transition metal dichalcogenides solar cells and integration with perovskites. *Nano Energy* 108: 108249. <https://doi.org/10.1016/j.nanoen.2023.108249>.
 - 17 Guerrero-Lemus, R., Vega, R., Kim, T. et al. (2016). Bifacial solar photovoltaics – a technology review. *Renewable and Sustainable Energy Reviews* 60: 1533–1549. <https://doi.org/10.1016/j.rser.2016.03.041>.
 - 18 Pillai, D.S., Shabunko, V., and Krishna, A. (2022). A comprehensive review on building integrated photovoltaic systems: emphasis to technological advancements, outdoor testing, and predictive maintenance. *Renewable and Sustainable Energy Reviews* 156: 111946. <https://doi.org/10.1016/j.rser.2021.111946>.
 - 19 Faes, A., Virtuani, A., Quest, H. et al. (2025). Building-integrated photovoltaics. *Nature Reviews Clean Technology* 1: 333–350. <https://doi.org/10.1038/s44359-025-00059-9>.
 - 20 Liu, C., Xiao, C., Xie, C., and Li, W. (2021). Flexible organic solar cells: materials, large-area fabrication techniques and potential applications. *Nano Energy* 89: 106399. <https://doi.org/10.1016/j.nanoen.2021.106399>.
 - 21 Alami, A.H., Olabi, A., Mdallal, A. et al. (2023). Concentrating solar power (CSP) technologies: status and analysis. *International Journal of Thermofluids* 18: 100340. <https://doi.org/10.1016/j.ijft.2023.100340>.
 - 22 Yadav, A.K., Kumar, A., and Sinha, S. (2024). A review of concentrated solar power status and challenges in India. *Solar Compass* 12: 100079. <https://doi.org/10.1016/j.solcom.2024.100079>.
 - 23 Bennagi, A., AlHousrya, O., Cotfas, D.T., and Cotfas, P.A. (2024). Comprehensive study of the artificial intelligence applied in renewable energy. *Energy Strategy Reviews* 54: 101446. <https://doi.org/10.1016/j.esr.2024.101446>.
 - 24 Khare, V., Khare, C., Nema, S., and Baredar, P. (2022). Fundamental and basic principles. In: *Decision science and operations management of solar energy systems*, 1–33. Academic Press. <https://doi.org/10.1016/b978-0-323-85761-1.00005-6>.
 - 25 Barber, D.A. (2023). Solar architecture and the sufficiency imperative. *Renewable and Sustainable Energy Transition* 4: 100066. <https://doi.org/10.1016/j.rset.2023.100066>.
 - 26 Duffie, J.A. (1981). Active solar systems. In: *Solar energy conversion II* (ed. A.F. Janzen and R.K. Swartman), 93–108. Pergamon Press. <https://doi.org/10.1016/b978-0-08-025388-6.50020-9>.

- 27 Esfandeh, S., Esfe, M.H., and Kamyab, M.H. (2022). Applications of nanofluids in solar energy collectors focusing on solar stills. In: *Advances in nanofluid heat transfer* (ed. H.M. Ali), 341–373. Elsevier. <https://doi.org/10.1016/b978-0-323-88656-7.00010-6>.
- 28 Vasant, L.G. and Pawar, V.R. (2017). Solar-wind hybrid energy system using MPPT. 2017 International Conference on Intelligent Computing and Control Systems (ICICCS), 595–597. <https://doi.org/10.1109/ICCONS.2017.8250531>.
- 29 Widmer, J., Christ, B., Grenz, J., and Norgrove, L. (2024). Agrivoltaics, a promising new tool for electricity and food production: a systematic review. *Renewable and Sustainable Energy Reviews* 192: 114277. <https://doi.org/10.1016/j.rser.2023.114277>.
- 30 Trommsdorff, M., Dhal, I.S., Özdemir, Ö.E. et al. (2022). Agrivoltaics: Solar power generation and food production. In: *Solar energy advancements in agriculture and food production systems* (ed. S. Gorjian and P.E. Campana), 159–210. Elsevier. <https://doi.org/10.1016/b978-0-323-89866-9.00012-2>.
- 31 Amer, A., Attar, H., Asad, S. et al. (2023). Floating photovoltaics: assessing the potential, advantages, and challenges of harnessing solar energy on water bodies. *Journal of Ecological Engineering* 24 (10): 324–339. <https://doi.org/10.12911/22998993/170917>.
- 32 Zander, K.K., Mathur, D., Mathew, S., and Garnett, S.T. (2024). Public views about the world's largest proposed solar farm in remote Australia. *Energy Policy* 191: 114197. <https://doi.org/10.1016/j.enpol.2024.114197>.
- 33 Ko, D., Chae, S., Moon, H. et al. (2023). Agrivoltaic farming insights: a case study on the cultivation and quality of kimchi cabbage and garlic. *Agronomy* 13 (10): 2625. <https://doi.org/10.3390/agronomy13102625>.
- 34 Fernández-Solas, Á., Fernández-Ocaña, A.M., Almonacid, F., and Fernández, E.F. (2023). Potential of agrivoltaics systems into olive groves in the Mediterranean region. *Applied Energy* 352: 121988. <https://doi.org/10.1016/j.apenergy.2023.121988>.
- 35 Mellit, A. and Kalogirou, S. (2021). Artificial intelligence and internet of things to improve efficacy of diagnosis and remote sensing of solar photovoltaic systems: challenges, recommendations and future directions. *Renewable and Sustainable Energy Reviews* 143: 110889. <https://doi.org/10.1016/j.rser.2021.110889>.
- 36 Marangis, D., Livera, A., Tziolis, G. et al. (2024). Trend-based predictive maintenance and fault detection analytics for photovoltaic power plants. *Solar RRL* 8 (24): 2400473. <https://doi.org/10.1002/solr.202400473>.
- 37 Ramos, A.A., Cheung, M.C.M., Chifu, I., and Gafeira, R. (2023). Machine learning in solar physics. *Living Reviews in Solar Physics* 20 (1): 4. <https://doi.org/10.1007/s41116-023-00038-x>.
- 38 Wang, P., Ma, Z., Shao, M. et al. (2022). Data-driven energy management in residential areas leveraging demand response. *Energy and Buildings* 269: 112235. <https://doi.org/10.1016/j.enbuild.2022.112235>.

- 39 Rani, D.P., Suresh, D., Kapula, P.R. et al. (2023). IoT based smart solar energy monitoring systems. *Materials Today Proceedings* 80: 3540–3545. <https://doi.org/10.1016/j.matpr.2021.07.293>.
- 40 Jothikrishna, K., Rithika, S.M., Swetha, S.V., and Kavitha, K. (2023). Solar power remote monitoring and controlling using IoT. 2023 2nd International Conference on Advancements in Electrical, Electronics, Communication, Computing and Automation (ICAECA), 1–5. <https://doi.org/10.1109/ICAECA56562.2023.10200775>
- 41 Jelle, B.P. and Breivik, C. (2012). State-of-the-art building integrated photo-voltaics. *Energy Procedia* 20: 68–77. <https://doi.org/10.1016/j.egypro.2012.03.009>.
- 42 Martín Chivelet, N., Kapsis, C., & Frontini, F. (Eds.). (2024). *Building-integrated photovoltaics: A technical guidebook*. Routledge. <https://doi.org/10.1201/9781003432241>
- 43 Vartiainen, E., Peippo, K., and Lund, P. (2000). Daylight optimization of multi-functional solar facades. *Solar Energy* 68 (3): 223–235. [https://doi.org/10.1016/s0038-092x\(99\)00072-9](https://doi.org/10.1016/s0038-092x(99)00072-9).
- 44 Benemann, J. (1994). Multifunctional solar facades—a new challenge for photo-voltaic. *Proceedings of 1994 IEEE 1st World Conference on Photovoltaic Energy Conversion – WCPEC (A Joint Conference of PVSC, PVSEC and PSEC)*, 1, 784–787. <https://doi.org/10.1109/WCPEC.1994.520077>.
- 45 Peterson, K.W., Balaras, C.A., Crawley, D.B. et al. (2022). *ASHRAE position document on building decarbonization*. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). <https://doi.org/10.13140/RG.2.2.32640.71689>.
- 46 Karamoozian, M. and Zhang, H. (2025). Obstacles to green building accreditation during operating phases: identifying challenges and solutions for sustainable development. *Journal of Asian Architecture and Building Engineering* 24: 350–366. <https://doi.org/10.1080/13467581.2023.2280697>.
- 47 Peterson, E.A. and Ulferts, G.W. (2014). Perspectives on the LEED (Leadership in Energy and Environmental Design) system as a green certification standard. *Journal of Sustainability Management (JSM)* 2 (2): 51–58. <https://doi.org/10.19030/jsm.v2i2.8981>.
- 48 Ildiri, N., Bazille, H., Lou, Y. et al. (2022). Impact of WELL certification on occupant satisfaction and perceived health, well-being, and productivity: a multi-office pre- versus post-occupancy evaluation. *Building and Environment* 224: 109539. <https://doi.org/10.1016/j.buildenv.2022.109539>.
- 49 Pham, H.C., Pham, V.H.S., and Than, T.K. (2024). Adoption of green mark criteria toward construction management sustainability. *Buildings* 14 (5): 1242. <https://doi.org/10.3390/buildings14051242>.
- 50 Isimbi, D. and Park, J. (2022). The analysis of the EDGE certification system on residential complexes to improve sustainability and affordability. *Buildings* 12 (10): 1729. <https://doi.org/10.3390/buildings12101729>.
- 51 Shuvo, S.S. and Yilmaz, Y. (2022). Home Energy Recommendation System (HERS): a deep reinforcement learning method based on residents' feedback

- and activity. *IEEE Transactions on Smart Grid* 13 (4): 2812–2821. <https://doi.org/10.1109/tsg.2022.3158814>.
- 52 Liu, T., Chen, L., Yang, M. et al. (2022). Sustainability considerations of green buildings: a detailed overview on current advancements and future considerations. *Sustainability* 14 (21): 14393. <https://doi.org/10.3390/su142114393>.
 - 53 Akrofi, M. and Okitasari, M. (2022). Integrating solar energy considerations into urban planning for low carbon cities: a systematic review of the state-of-the-art. *Urban Governance* 2 (1): 157–172. <https://doi.org/10.1016/j.ugj.2022.04.002>.
 - 54 Adil, A.M. and Ko, Y. (2016). Socio-technical evolution of decentralized energy systems: a critical review and implications for urban planning and policy. *Renewable and Sustainable Energy Reviews* 57: 1025–1037. <https://doi.org/10.1016/j.rser.2015.12.079>.
 - 55 Akella, A., Saini, R., and Sharma, M. (2008). Social, economical and environmental impacts of renewable energy systems. *Renewable Energy* 34 (2): 390–396. <https://doi.org/10.1016/j.renene.2008.05.002>.
 - 56 Mehedi, T.H., Gemechu, E., and Kumar, A. (2022). Life cycle greenhouse gas emissions and energy footprints of utility-scale solar energy systems. *Applied Energy* 314: 118918. <https://doi.org/10.1016/j.apenergy.2022.118918>.
 - 57 Krauter, S. and Rüther, R. (2004). Considerations for the calculation of greenhouse gas reduction by photovoltaic solar energy. *Renewable Energy* 29 (3): 345–355. [https://doi.org/10.1016/s0960-1481\(03\)00251-9](https://doi.org/10.1016/s0960-1481(03)00251-9).
 - 58 Hernandez, R., Easter, S., Murphy-Mariscal, M. et al. (2013). Environmental impacts of utility-scale solar energy. *Renewable and Sustainable Energy Reviews* 29: 766–779. <https://doi.org/10.1016/j.rser.2013.08.041>.
 - 59 Kaya, O., Klepacka, A.M., and Florkowski, W.J. (2019). Achieving renewable energy, climate, and air quality policy goals: rural residential investment in solar panel. *Journal of Environmental Management* 248: 109309. <https://doi.org/10.1016/j.jenvman.2019.109309>.
 - 60 Carboni, C. and Montanari, R. (2008). Solar thermal systems: advantages in domestic integration. *Renewable Energy* 33 (6): 1364–1373. <https://doi.org/10.1016/j.renene.2007.07.004>.
 - 61 Izam, N.S.M.N., Itam, Z., Sing, W.L., and Syamsir, A. (2022). Sustainable development perspectives of solar energy technologies with focus on solar photovoltaic—a review. *Energies* 15 (8): 2790. <https://doi.org/10.3390/en15082790>.
 - 62 Jenniches, S. (2018). Assessing the regional economic impacts of renewable energy sources – a literature review. *Renewable and Sustainable Energy Reviews* 93: 35–51. <https://doi.org/10.1016/j.rser.2018.05.008>.
 - 63 Timilsina, G.R., Kurdgelashvili, L., and Narbel, P.A. (2012). Solar energy: markets, economics and policies. *Renewable and Sustainable Energy Reviews* 16 (1): 449–465. <https://doi.org/10.1016/j.rser.2011.08.009>.
 - 64 Delicado, A., Figueiredo, E., and Silva, L. (2016). Community perceptions of renewable energies in Portugal: impacts on environment, landscape and local development. *Energy Research & Social Science* 13: 84–93. <https://doi.org/10.1016/j.erss.2015.12.007>.

- 65 Lugo-Laguna, D., Arcos-Vargas, A., and Nuñez-Hernandez, F. (2021). A European assessment of the solar energy cost: key factors and optimal technology. *Sustainability* 13 (6): 3238. <https://doi.org/10.3390/su13063238>.
- 66 Chapman, A., Shigetomi, Y., Ohno, H. et al. (2021). Evaluating the global impact of low-carbon energy transitions on social equity. *Environmental Innovation and Societal Transitions* 40: 332–347. <https://doi.org/10.1016/j.eist.2021.09.002>.
- 67 Zhou, S., Wang, Y., Zhou, Y. et al. (2018). Roles of wind and solar energy in China's power sector: implications of intermittency constraints. *Applied Energy* 213: 22–30. <https://doi.org/10.1016/j.apenergy.2018.01.025>.
- 68 Millison, D., George, L., Acharya, J., and Wijayatunga, P. (2022). Enabling policy and regulatory environment for solar power development: lessons in Asia-Pacific region. *Solar Compass* 2: 100023. <https://doi.org/10.1016/j.solcom.2022.100023>.
- 69 Abdullahi, D., Renukappa, S., Suresh, S., and Oloke, D. (2022). Barriers for implementing solar energy initiatives in Nigeria: an empirical study. *Smart and Sustainable Built Environment* 11 (3): 647–660. <https://doi.org/10.1108/sasbe-06-2020-0094>.
- 70 Haas, J., Palma-Behnke, R., Valencia, F. et al. (2018). Sunset or sunrise? Understanding the barriers and options for the massive deployment of solar technologies in Chile. *Energy Policy* 112: 399–414. <https://doi.org/10.1016/j.enpol.2017.10.001>.
- 71 Alsaman, M., Ahmed, V., Bahroun, Z., and Saboor, S. (2023). An economic analysis of solar energy generation policies in the UAE. *Energies* 16 (7): 3165. <https://doi.org/10.3390/en16073165>.
- 72 Luthra, S., Kumar, S., Garg, D., and Haleem, A. (2015). Barriers to renewable/sustainable energy technologies adoption: Indian perspective. *Renewable and Sustainable Energy Reviews* 41: 762–776. <https://doi.org/10.1016/j.rser.2014.08.077>.
- 73 Miskat, M.I., Sarker, P., Chowdhury, H. et al. (2023). Current scenario of solar energy applications in Bangladesh: techno-economic perspective, policy implementation, and possibility of the integration of artificial intelligence. *Energies* 16 (3): 1494. <https://doi.org/10.3390/en16031494>.
- 74 Labordena, M., Patt, A., Bazilian, M. et al. (2017). Impact of political and economic barriers for concentrating solar power in Sub-Saharan Africa. *Energy Policy* 102: 52–72. <https://doi.org/10.1016/j.enpol.2016.12.008>.
- 75 Chanchangi, Y.N., Adu, F., Ghosh, A. et al. (2023). Nigeria's energy review: focusing on solar energy potential and penetration. *Environment Development and Sustainability* 25 (7): 5755–5796. <https://doi.org/10.1007/s10668-022-02308-4>.
- 76 Sargunanathan, S., Elango, A., and Mohideen, S.T. (2016). Performance enhancement of solar photovoltaic cells using effective cooling methods: a review. *Renewable and Sustainable Energy Reviews* 64: 382–393. <https://doi.org/10.1016/j.rser.2016.06.024>.
- 77 Nwaigwe, K., Mutabilwa, P., and Dintwa, E. (2019). An overview of solar power (PV systems) integration into electricity grids. *Materials Science for Energy Technologies* 2 (3): 629–633. <https://doi.org/10.1016/j.mset.2019.07.002>.

- 78 Bahadori, A. and Nwaoha, C. (2013). A review on solar energy utilisation in Australia. *Renewable and Sustainable Energy Reviews* 18: 1–5. <https://doi.org/10.1016/j.rser.2012.10.003>.
- 79 Rabaia, M.K.H., Abdelkareem, M.A., Sayed, E.T. et al. (2020). Environmental impacts of solar energy systems: a review. *The Science of the Total Environment* 754: 141989. <https://doi.org/10.1016/j.scitotenv.2020.141989>.
- 80 Mahmud, M. and a. P., Huda, N., Farjana, S. H., & Lang, C. (2018). Environmental impacts of solar-photovoltaic and solar-thermal systems with life-cycle assessment. *Energies* 11 (9): 2346. <https://doi.org/10.3390/en11092346>.
- 81 Albattah, M. and Attoye, D.E. (2021). A quantitative investigation on awareness of renewable energy building technology in the United Arab Emirates. *Sustainability* 13 (12): 6665. <https://doi.org/10.3390/su13126665>.
- 82 Wang, L., Teles, M.P., Arabkoohsar, A. et al. (2022). A holistic and state-of-the-art review of nanotechnology in solar cells. *Sustainable Energy Technologies and Assessments* 54: 102864. <https://doi.org/10.1016/j.seta.2022.102864>.
- 83 Hasan, M.M., Hossain, S., Mofijur, M. et al. (2023). Harnessing solar power: a review of photovoltaic innovations, solar thermal systems, and the dawn of energy storage solutions. *Energies* 16 (18): 6456. <https://doi.org/10.3390/en16186456>.
- 84 Avwioroko, A., Ibegbulam, C., Afriyie, I., and Fesomade, A.T. (2024). Smart grid integration of solar and biomass energy sources. *European Journal of Computer Science and Information Technology* 12 (3): 1–14. <https://doi.org/10.37745/ejcsit.2013/vol12n3114>.
- 85 Kaushik, S., Reddy, V.S., and Tyagi, S. (2011). Energy and exergy analyses of thermal power plants: a review. *Renewable and Sustainable Energy Reviews* 15 (4): 1857–1872. <https://doi.org/10.1016/j.rser.2010.12.007>.
- 86 Minazhova, S., Akhambayev, R., Shalabayev, T. et al. (2023). A review on solar energy policy and current status: top 5 countries and Kazakhstan. *Energies* 16 (11): 4370. <https://doi.org/10.3390/en16114370>.
- 87 Beatley, T. (2007). Envisioning solar cities: urban futures powered by sustainable energy. *Journal of Urban Technology* 14 (2): 31–46. <https://doi.org/10.1080/10630730701531682>.
- 88 Kumar, S.S., Bibin, C., Akash, K. et al. (2020). Solar powered water pumping systems for irrigation: a comprehensive review on developments and prospects towards a green energy approach. *Materials Today Proceedings* 33: 303–307. <https://doi.org/10.1016/j.matpr.2020.04.092>.