Chapter 3

Efficient Low-Cost Materials for Solar Energy Applications: Roles of Nanotechnology

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Additional information is available at the end of the chapter

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Abstract

The generation of energy to meet the increasing global demand should not compromise the environment and the future. Therefore, renewable energies have been identified as potential alternatives to fossil fuels that are associated with CO_2 emissions. Subsequently, photovoltaic (PV) solar system is seen as the most versatile and the largest source of electricity for the future globally. Nanotechnology is a facilitating tool that offers a wide range of resources to resolve material challenges in different application areas. This studies X-rays, energy trilemma, potential nanotechnology-based materials for low-cost PV solar cell fabrication, and atomic layer deposition (ALD). In pursuance of improved performance, PV solar-cell technologies have revolutionized from first-generation PV solar cells to third-generation PV solar cells. The efficiency (19%) of second-generation PV cells is higher than the efficiency (15%) of first-generation cells. The second-generation PV cell technologies include a-Si, CdTe and $Cu(In,Ga)Se_2$), $Cu(In,Ga)Se_2$ (CIGS) cells. The third-generation PV cells are organic-inorganic hybrid assemblies, nanostructured semiconductors, and molecular assemblies. This nanocomposite-based technology aims at developing low-cost high efficiency PV solar cells. The nanotechnology manufacturing technique, ALD, is seen as the future technology of PV solar cell production.

Keywords: photovoltaic cell low-cost materials, photovoltaic solar technologies, energy trilemma, CO_2 emission, greenhouse gas emission

1. Introduction

The available energy resources are becoming significantly more interesting due to the transition of the world's energy systems. This transition is orchestrated by the falling technology costs and the improved energy conversion and storage efficiency, coupled with the world stands on greenhouse gas emissions. These trends are expected to continue, with renewables playing a key role. Policymakers and regulatory frameworks of many countries must respond quickly and appropriately to catch up with technology alternatives and unstable energy demands. In a survey, over 50% of energy leaders predicted

Disruptors	**Need trend**
African economic growth	Demand generation
	Growing commercial & industrial sector
	Emerging middle class
	Access to electricity
Shifting the energy mix	New capital
	Wind, solar, biomass
	Gas to power
	Nuclear
	Coal
	Hydro
Changing role of customers	Customer shift
	Consumer to producer
	Self-generation
	Demand managers
	Every company is an energy company
Renewable technology	Renewable technology
	Affordability of new technologies
	Solar PV, storage
	Off-grid solutions
Smart grids, smarter utilities	Smart utilities
	Smarter utility management
	Analytics
	Smart grids
	Smart metering
Changing market structures and dynamics	Market restructure
	Consumer to producer
	Self-generation
	Demand managers
	Every company is an energy company

Table 1. Trends of power disruption in SSA [5].

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that in 2025 the share of installed distributed generation capacity will increased by 15% or higher [1]. Basden et al. simply put the estimate as 'a business or a home in North America and Europe goes solar every two minutes' [2]. In 2002, United Nations Development Programme estimated the amount of energy that strikes the earth from the sun per year is 1575–49,837 exajoules (EJ). This is by far more than the world's annual energy consumption of about 559.8 EJ [3]. It was posited in Gratzel study in 2001 that covering 0.1% of the earth's surface with PV panels of 10% efficiency will generate the world's total energy need [4]. And yet the developing countries of Africa and other regions are wallowing in energy poverty leading to high unemployment, abject poverty and terrifying standard of living. Till date the energy generated from the sun is less than 0.1% of the current global energy need.

The energy generated from the sun is limited by certain factors which include cost of producing solar cells and the PV cell converting efficiency. To raise the conversion efficiency of solar materials has attracted a lot of interest. Previous attempts reduce the effects of these factors yielded successes and studies are still on going to break more grounds. The attempts have been multi-criteria improvement approach, which has led to the three categories of PV cell materials today – first, second and third generations of PV materials. However, the world's quest to replaced fossil fuels with alternative energy sources has further stretched study on solar materials and system. Several interventions to alter the present power situation in most developing regions, especially in sub-Saharan Africa and Asia (South India), have not yielded the expected results. The impacts of the interventions have been engulfed by challenges arising from global technologies landscape changes, which led to several disruptions in the industry. These disruptors have caused a paradigm shift in the industry in SSA and other developing countries, and have been classified into six by Deloitte as presented in **Table 1** [6]. Therefore, a fresh and systematic power infrastructure investment will be needed to meet the current and future energy demand in developing countries. Solar energy is seen as the best option for alternative energy source because of its abundance, and environmental friendliness. This chapter aims to analyze the global energy trends in terms of achievements, challenges and outlooks. The study X-rays global energy accessibility and the role of PV solar cell system in achieving global supply of energy with modern energy attributes. Further, the significance of nanotechnology in enhancing the efficiency of PV solar materials was discussed.

2. Global energy challenges

2.1. Access to electricity in developing economies

Developing countries across the regions of the world, especially, sub-Saharan Africa (SSA) and Asia experience a high percentage of inadequate, costly and epileptic power supply

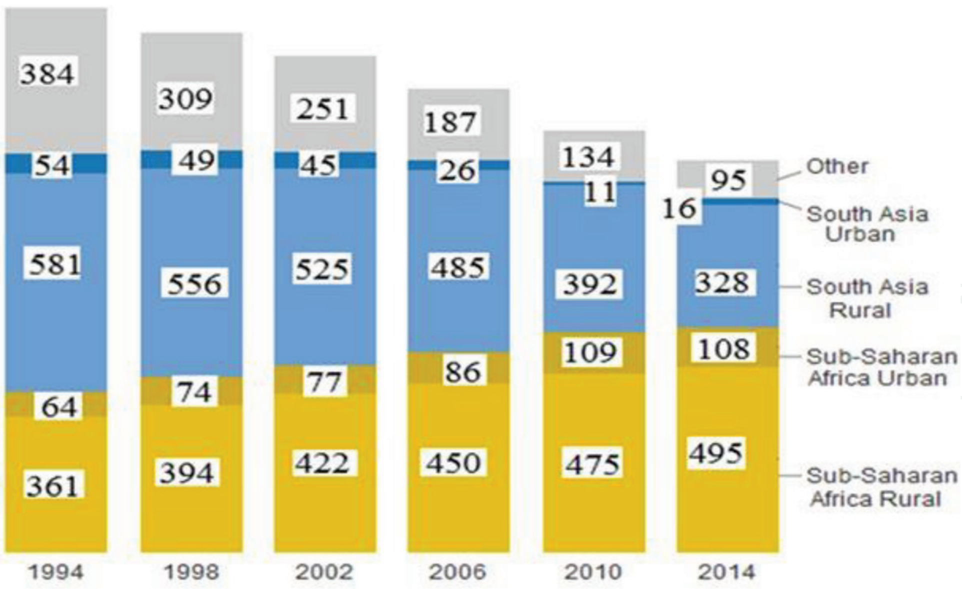

Figure 1. People without electricity access in millions in 2014 [9].

[7, 8], as depicted in **Figure 1**. In 2014, the International Energy Agency (IEA) reported that two-thirds of SSA population has no access to electricity and other modern energy services [10]. Large populations have no access to modern energy in many rural and remote areas of developing countries. It has been predicted that the population without access to electricity in rural areas of SSA would increase from 585 million in 2009 to 645 million in 2030 [11]. The concerted efforts and interventions from both domestic and international arenas to change this scenario have not yielded the expected results.

2.2. Environment sustainability: fossil fuel global environmental challenges

The world's energy demand from fossil fuels accounts for the upward trend in CO_2 emissions, as shown in **Figure 2**. The fossil fuels for power generation are characterized by climate change, greenhouse gases (GHG) emission, and global warming. In 2012, power and transport sectors generated two-thirds of the global CO_2 emission with each emitting about 42% and 23% respectively [13]. For decades, fossil fuels, such as diesel, petrol, coal, and natural gas have proved to be efficient economic development drivers but with health and environmental consequences. Fossil fuels environmental challenges include climate change, global warming, and CO_2 emissions. These negative fallouts have not deterred man from fossil fuel usage because of energy significance to human existence and industrialization. The world's oil consumption annual growth rate of 1.6%, and gas annual growth rate of 1.5% were reported in 2016 [14].

The amount of GHG emission is vastly different amongst countries but is associated with industrialization. The annual CO_2 emissions from fossil fuels combustion have abruptly risen since the Industrial Revolution from near zero to more than 33 $GtCO_2$ in 2015. The highly industrialized countries contribute most to CO_2 emission. The International Energy Agency in 2015 estimated the CO_2 emission from industrial waste and non-renewable municipal waste and the combustion of natural gas, oil, coal and other fuels [15]. **Figure 3** shows 20 of the different countries examined.

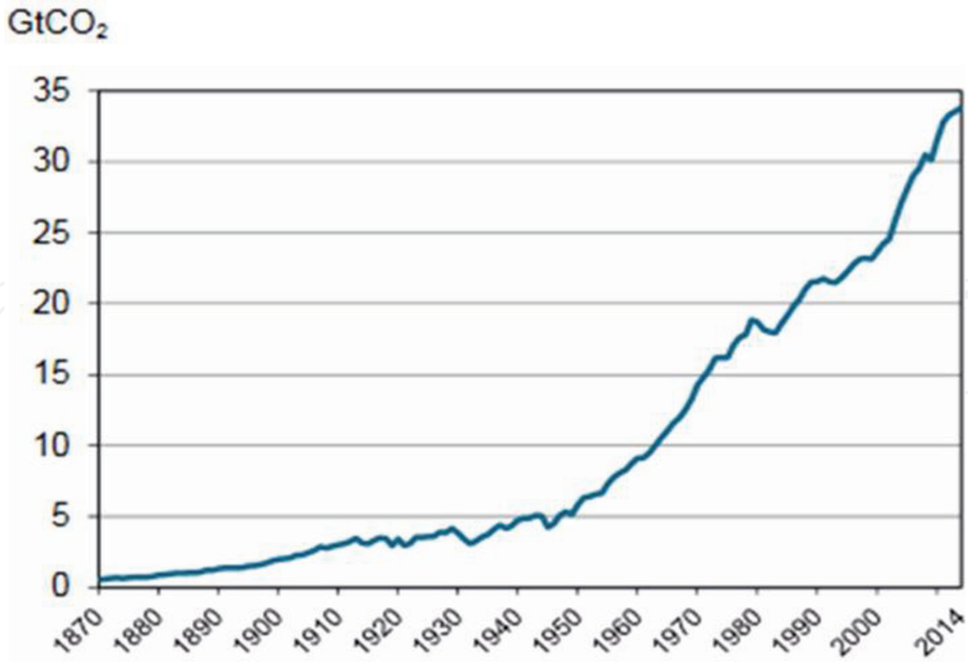

Figure 2. The trend of CO_2 emissions from fossil fuel combustion from 1870 to 2014 [12].

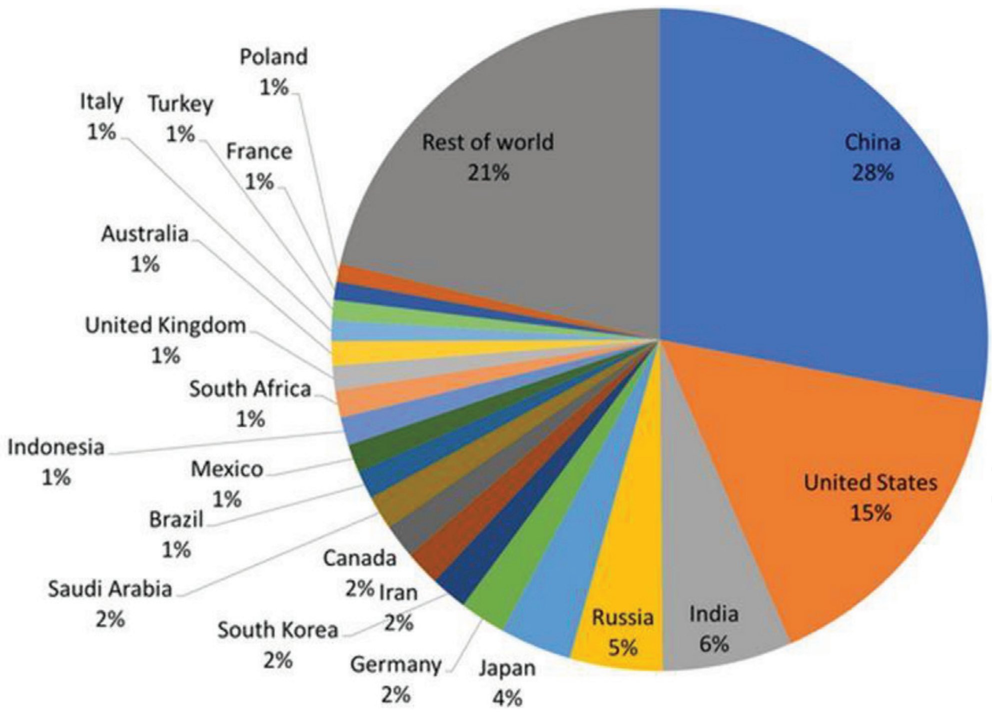

Figure 3. Estimated CO_2 emission of 20 different countries [15].

2.3. Energy trilemma

Apart from the need for adequate, and affordable power supply, the global dynamics in the transformation of electricity sector are these three reinforcing trends–digitization, de-carbonization and decentralization. Also, there is an emergence of authorized energy consumers with new choices in how they utilize and manage their energy usage. The governance and

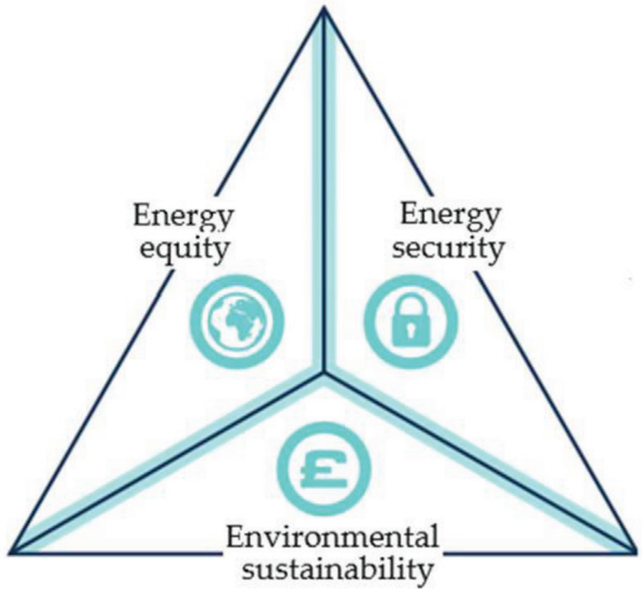

Figure 4. The energy trilemma [16].

management of this complex global energy dynamic is challenging and critical to energy security, climate change mitigation and energy poverty. The interconnectivity between energy security, energy equity and environmental sustainability energy poverty, as shown in **Figure 4**, is termed energy trilemma. Energy sustainability was defined by the World Energy Council based on energy security, energy equity, and environmental sustainability [17–19]. Balancing these three dimensions constitutes what is known as energy trilemma and is the foundation for the individual countries' success and competitiveness [16].

The challenge of balancing energy affordability, energy security, and environmental sustainability could promote the understanding of the framework of the disruptions and opportunities of increased decentralization in the energy system. **Table 2** presents opportunities and challenges associated with trilemma.

Components of trilemma	Opportunities	Challenges
Energy security	Energy supply shocks due to improved system resilience can be cushioned by diversification and decentralization of energy sources.	Challenges to system management and the possibility of system failure are promoted by the increased system complexity and technology needs.
Energy equity	Rural electrification and energy democratization can be improved by the range of models of energy supply.	Costs increase may be occurred for system and structure establishment to accommodate the increased system complexity and technology needs.
Environmental sustainability	Alterations in the energy mix have the potential to contribute towards environmental degradation reduction, de-carbonization, and reduce lifecycle impacts known with certain energy sources.	Changes to the energy mix have the potential to increase carbon emissions and create life cycle impacts associated with certain energy sources.

Table 2. Trilemma opportunities and challenge.

3. Response to global energy and environmental challenges

To appropriately respond to these global challenges, the need to generate more energy without compromising the future becomes a clarion call. This implies the use of fossil fuel should be limited or eliminated. To effectively do this, clean, reliable and renewable energy sources of energy with low or no GHG emissions must be available. To significantly contribute to the realization of global energy trilemma, both developed and developing countries should incorporate the following into their national infrastructure planning:

- Increasing share of renewables
- Electrification of vehicles and process heat by renewable energy sources
- Robust policy framework and consumer sensitization agenda on energy efficiency to reduce GHG emission, costs and risks
- Strengthening the interdependency and complexity of power systems
- Vibrant consumers' awareness program of new energy alternatives
- Greater accessibility and reliable power supply because of growing dependency on electricity
- The rising threat of cyber-attacks should be met with increased energy infrastructure automation
- The introduction of more disruptive technologies, such as energy storage, PV solar, electric vehicles, and power electronics that might substantially change the energy space as the cost of technology drops.

3.1. Alternative energies-clean energies

Renewable energies have been identified as potential alternatives to fossil fuels. This is due to the notable environment benefits the renewable energies offer, such as reduced CO_2 emission and their off grid utilization. Subsequently, the renewable energy technologies are receiving immense attention. The building of renewable technologies infrastructure to increase the portion of electricity generated from renewable energy has commenced in many countries. Policies and framework have been formulated by different countries to guide the use, the growth and the constitutionality of renewable energy. For example, a bill requiring all the electricity retail sellers to serve 33% of their load with renewable energy by 2020 was signed by the governor of California in 2011 [20].

The available alternatives to the fossil fuels are solar, geothermal, tidal, biofuels, hydro, and wind. A huge capacity of the required electricity can be derived from nuclear energy. However, many countries are skeptical about the use of nuclear energy because of the perceived side effects. They consider the use of nuclear energy for electricity as a risky venture. In Singapore for instance, studies by independent analysts and government agencies have described the existing nuclear plants as too risky for Singapore's small size and dense population [21]. Amongst these natural resources sun (solar), small hydropower, and wind are the most established and are considered better alternatives for environment and cheaper electricity sources in the long term. The exploitability of the solar resource in urbanization is more versatile than other renewable energy sources.

3.1.1. Solar energy: photovoltaic solar cell

Criticisms have trailed renewable energy technology due to their low energy densities, intermittency and region-based resources, making them less suitable for urban applications. Solar is the most common renewable energy whose potential is highly region-dependent. However, the annual direct solar irradiation in some regions exceeds 300 W/m^2. Interestingly, several of the regions that are likely to experience the maximum increase in urbanization are in solar-rich regions. Subsequently, a lot of studies and technical advances have been focused on solar efficiency, structure and cost. This resulted in a drastic drop of solar energy installed price by about 50% since 2010 [22]. Despite this achievement, the efficiency of multi-crystalline silicon photovoltaic cell, which is the widely installed panels, is hovering around 10–17% [23]. However, recent studies have shown PV laboratory efficiency over 40%, using concentrated multijunction cells [24]. This means that the photovoltaics power density could surpass 120 W/m^2 under optimal conditions. For instance, Singapore has an annual average of solar irradiance of 1580 kWh/m^2/year and about 50% more solar radiation than temperate countries. This makes solar photovoltaic (PV) generation as the greatest potential for wider utilization in Singapore. In 2014, Singapore planned to raise solar power from 19 MWp installed capacity to 350 MWp by 2020 and this is 5% of the projected peak electricity demand [25].

The world solar heat collectors' thermal power density average is 67 Wt/m^2 [23, 26] and the use of domestic solar hot-water heaters is on the increase because it is low-cost and compact. Up to 84% of urban households installed solar hot-water heaters on their rooftops [27] and five Australian cities saving approximately 17% energy, using a Trombe wall. Trombe is a technique of collecting and storing of solar thermal energy in the summer for heating in the winter. About 91% of the total energy required in a large residential building in Richmond, VA, is provided from this technology [28].

3.2. Sustainable integrated policies and technologies for urbanization

Sustainable development challenges come with a rise in global urbanization in the dense cities especially in the lower-middle-income countries where the growth of urbanization is rapid. Urban sustainable solutions in the form of integrated policies and technologies are needed globally to lower GHG emissions, reduce the cost of clean energy and guarantee safe energy. The common clean energy challenges in urban are energy intermittency and reliability, cost of installation and low power density. Renewable energies such as wind, hydro and solar have common intermittency and reliability challenges. It is not always windy, sunny and the water level in the source is not always the same. This limits the level of providing a constant power supply to users. There are several approaches that are ongoing in tackling these challenges and these include: the combination of renewable energy sources in a hybrid system; and development of low-cost and efficient renewable energy generation and storage materials.

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3.3. Hybrid renewable energy systems

The goal of the combined systems is to cushion the inconsistency supply by a power bolster, either a diesel generator or pumped storage hydroelectric. The bolster runs at low output during low peak hours' demand and increases to full output at peak hours' demands. The combination of renewable energy sources, such as solar, hydro, wind, diesel generator and energy storage units, have been studied extensively in recent years. This combination is often called hybrid renewable energy systems (HRES). Hybrid renewable energy system is a response to challenges of scarce supply of a single renewable resource and intermittent generation challenges. The study on HRES involves modeling, managing and optimizing the different energy systems from design to operation, as shown in **Figure 5** [30–34]. It is vital to consider the system design and operation from a range of time scales because HRES has various stages of life cycle. Irrespective of life cycle (whole life or daily), real-time optimization offers a significant opportunity to handle HRES systematically [29].

The attainment of clean energy based urbanization, large depends on the advances in renewable energy generation technologies, in terms of low cost and efficiency. For a faster, more secure transition from fossil fuels, high efficient and low-cost renewable energy generation and storage materials need to be developed.

3.4. Photovoltaic solar systems

The photovoltaic solar system is composed of different supporting components in addition to PV solar modules. This supporting equipment, often referred to as balance of system (BOS), serves to balance the system and to sustain the operation. The BOS components include controllers, energy storage devices, wiring, grid connections, trackers, mounting hardware, and inverters. However, these components vary from one system to another depending on the scale and application. The different types of PV configurations that work for both Grid-connected and Stand-alone applications are shown in **Figure 6**.

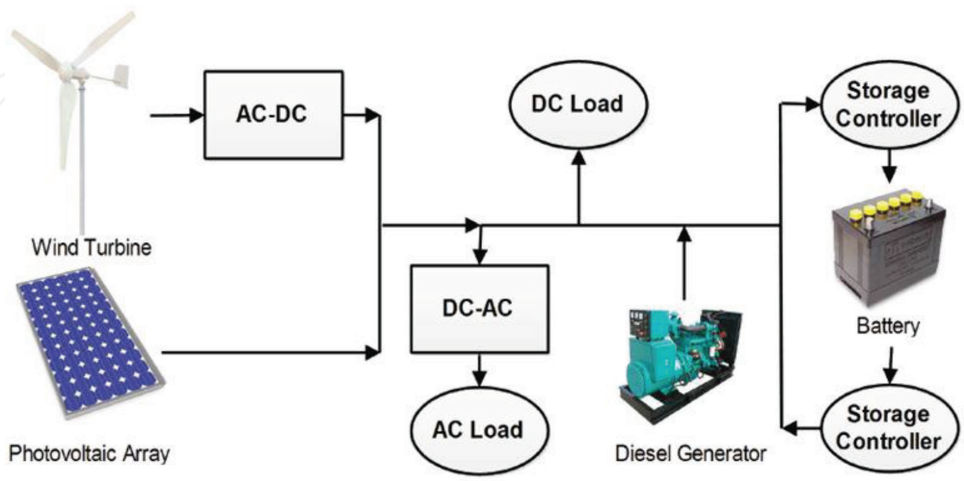

Figure 5. Hybrid renewable energy system (HRES) schematic [29].

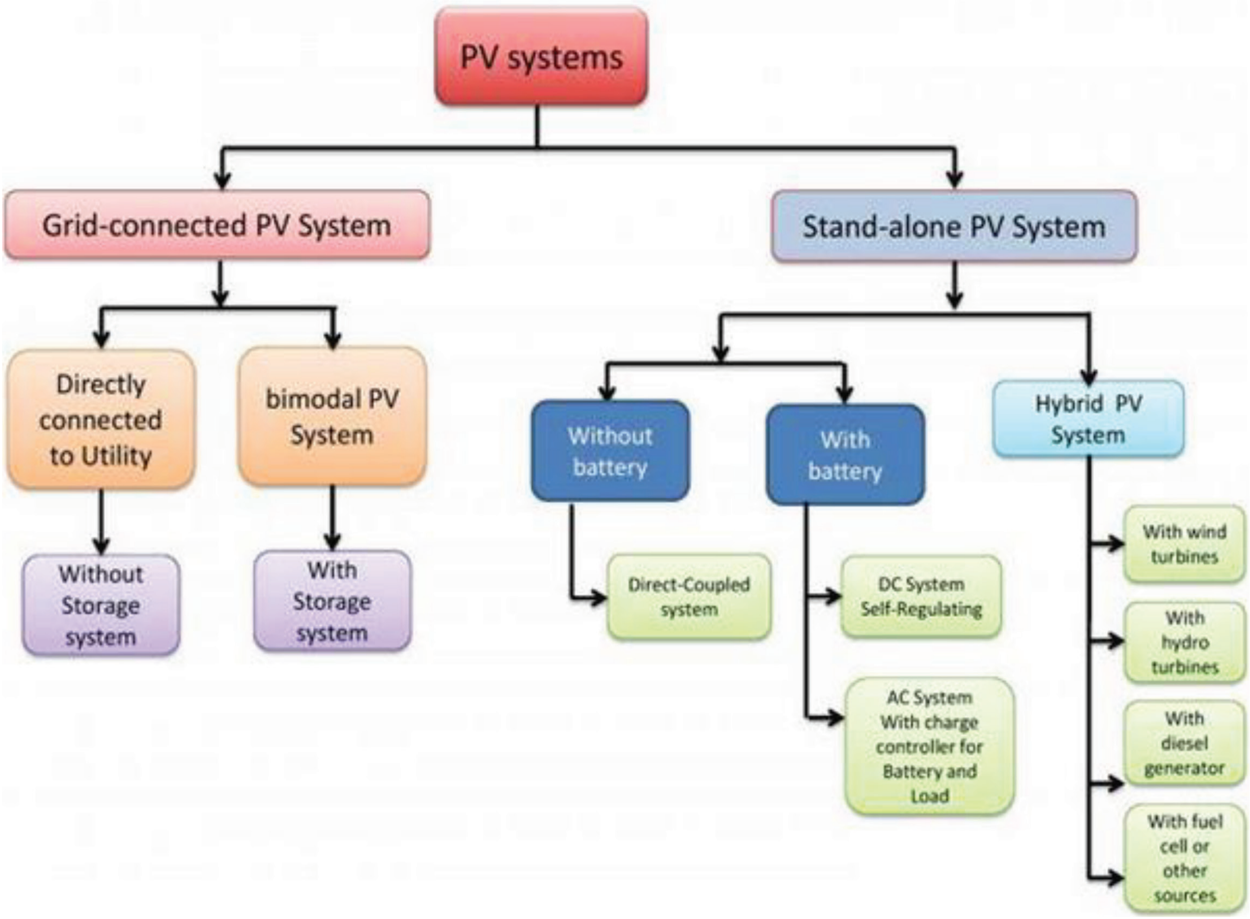

Figure 6. The different types of PV configurations [35].

During repairs, the BOS components can be removed or added to the plant without significant disruption to the infrastructure due to the modular nature of PV solar system. The balance of system components and their functions are presented in **Table 3**. The quality of the BOS is crucial for providing efficient and lasting operation, as the industry aim is to offer PV systems with minimum operational lifetime of 25 years [36, 37]. **Figure 7** shows photovoltaic solar system.

There are three basic processes of photovoltaic effect and they are:

i. Production of charge carriers because of the absorption of photons in the materials that make a junction.

ii. The resulting parting of the photo-generated charge carriers in the junction.

iii. Collection of the photo-generated charge carriers at the terminals of the junction.

The solar cells working principle is based on the production of a potential difference at the junction of two different materials in response to electromagnetic radiation photovoltaic, as shown in **Figure 8**. This occurrence is generally termed photovoltaic effect and is similar to photoelectric effect, which is the emission of electrons from materials that absorb light at a frequency that exceeds the material-dependent threshold frequency. Albert Einstein in 1905 explained this effect has energy and assumed that the light has well-defined energy quanta, called photon, given as Eq. (1):

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$$E = hv \qquad (1)$$

The absorption of photon by a semiconductor with a bandgap, E_G, is shown in **Figure 8**. The photon with energy $E_{ph} = h_v$ excites an electron from E_i to E_f. At E a hole is created. If $E_{ph} > E_g$ a part of the energy is thermalized.

where h is Planck's constant and v is the light frequency.

Component	Functions
Battery	The electrical power harvested by PV solar panels can be stored in batteries. Solar systems are often built with a battery backup to be used at night or dull days. The batteries are usually deep circle batteries because of their robustness and discharging endurance.
Battery charge controllers	The battery charge controller is similar to automotive battery charger in function. It ensures that a consistent amount of power is sent to the batteries to avoid over charged, and to prevent the backup battery from discharging back through the system at night.
Inverter—solar power converter	It converts the solar panels generated DC power into AC power using electronic switching techniques since home runs on AC power.
Trackers	A device for concentrating a solar reflector, orienting a solar panel or lens towards the sun for optimization of solar energy conversion into electricity.
Mounting hardware	The solar panels are placed on mounting hardware.
Main panel	This is where all electric loads in the building are connected, and protected with circuit breakers.
System power meter	Is enhances the system to gain maximum efficiency from solar installation and estimates the amount of money being saved by the solar system.
Power conditioning unit	It offers protection against electric faults, such as short line-to-ground faults or circuits.
DC and AC disconnect	Solar systems are usually provided with manual disconnection devices for safety reasons. They are used to cut off the power during maintenance and emergency.

Table 3. Functions of photovoltaic solar system components.

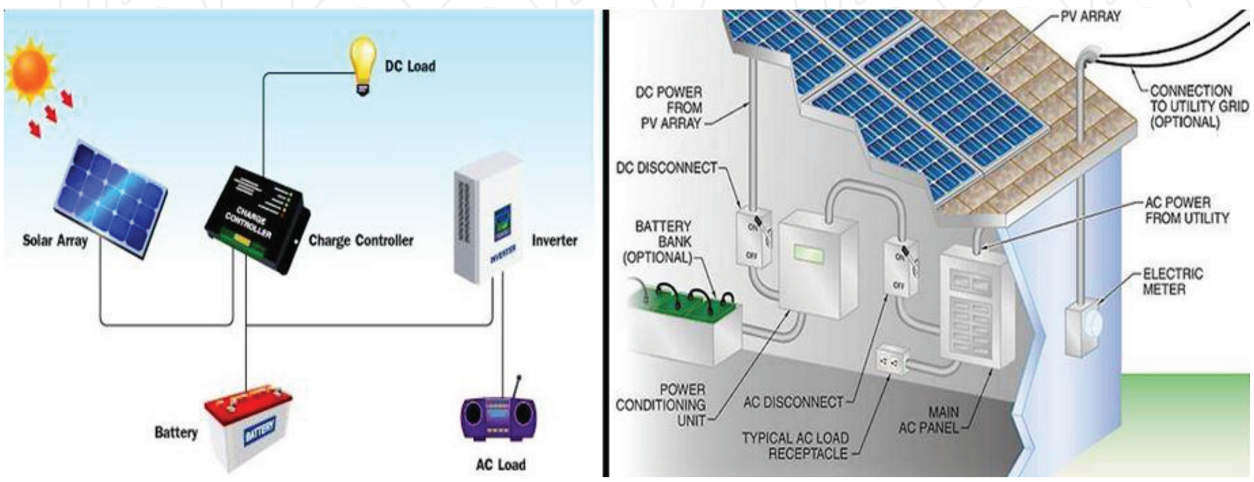

Figure 7. The photovoltaic solar system [38, 39].

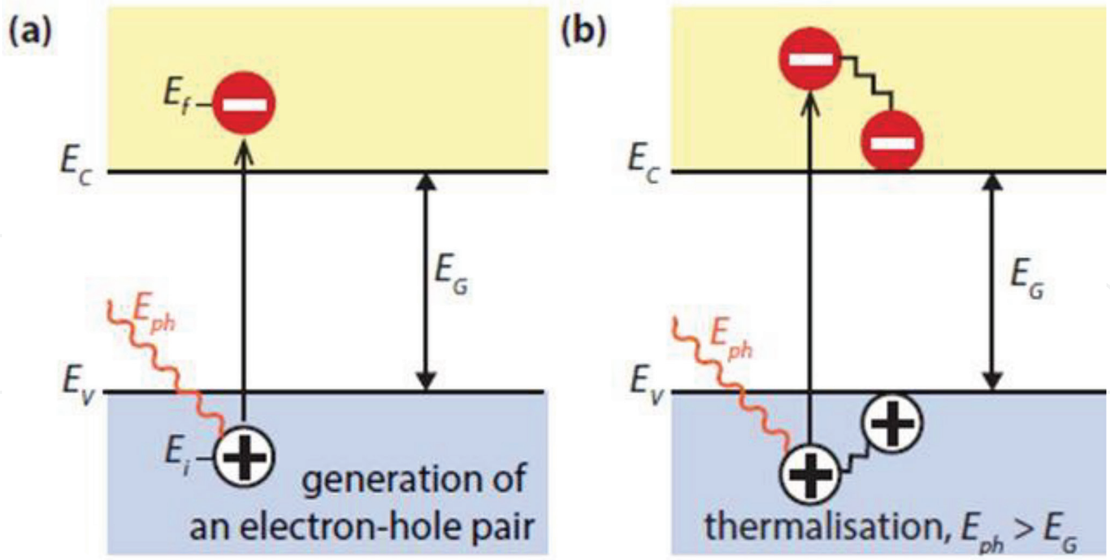

Figure 8. (a) Depicts semiconductor absorption of a photon with bandgap E_G. (b) If $E_{ph} > E_g$ a part of the energy is thermalized.

4. The development of low-cost and efficient renewable energy generation and storage materials

There has been an intense study on the development of low-cost and efficient renewable energy generation and storage materials, but the scope of work only covers PV cell materials. The application of photovoltaic (PV) technology to harness the huge amounts of energy that the sun releases to the earth is one of the most promising alternatives. Thin-film or crystalline silicon are the most widely used materials for industrial production of PV cells [40]. However, the rigidity form of Si PV modules limits their economic incorporation into commercial and residential buildings, while thin film PV cells are more appropriate in terms of cost, ease of fabrication and installation [41]. The thin film PV is receiving more attention and is being considered for large scale power generation and for building integrated photovoltaic (BIPV) applications [42].

4.1. Encapsulation of thin film PV cells

Photovoltaic modules are desirable to provide cheap power for more than 20 years at <10% power degradation outputs at an affordable production cost [43]; and survive 1000 hours at ambient conditions of 85°C and 85% relative humidity in accordance with IEC61646 international standard [44]. Providing thin layer barriers to protect thin film CIGS and DSSC to satisfy these requirements has been challenging. This is because both cells degrade under the ambient conditions if they are not properly protected from moisture ingress.

The requirement for efficient methods to module encapsulation, is a serious challenge facing thin film PV modules producers. The quest to develop appropriate approach for thin film cells encapsulation started around 2002 and is still ongoing. Hence, new low-cost methods of module encapsulation are required to meet this desire. Present developments in the PV cells industry have affected the initial barrier coatings. DSSC and CIGS on flexible substrates are now being considered for flat plate modules with glass-to-glass and BIPV as well as for flat plate module applications, respectively.

4.2. Photovoltaic module materials

Copper indium gallium selenide (CIGS) – one of the most recent developed materials in the renewable energy space, are copper indium gallium selenide, $CuIn_{1-x}Ga_xSe_{2,}$ (CIGS) materials, used for flexible thin-film photovoltaic (PV) modules. Their efficiency levels are beyond that of Si-based rigid PV modules and the films offer substantial advantages in the mass and building integrated photovoltaic (BIPV) applications. However, they are greatly susceptible to environmental degradation in the long term due to water vapor transmission to the active (absorber) layer via the protective encapsulation layer. To prevent the permeability of water vapor to the absorber, a barrier layer of a few nanometres thickness is provided to encapsulate the PV. Roll-to-roll (R2R) atomic layer deposition (ALD) methods are used to deposit amorphous aluminum oxide (Al_2O_3) material on a planarized polyethylene naphthalate (PEN) substrate. Howbeit, water vapor still permeates the barrier because of micro and nano-scale defects present, generated by the deposition process. This occurrence reduces the cell efficiency unit longevity, and ultimately, causes failure [45]. Roll-to-roll technology is used to manufacture flexible devices by repeatedly depositing and patterning of thin layer materials on polymer films substrates [46]. The thickness of the flexible thin layer prior to final encapsulation is about 3 μm [47].

In the solar community, apart from CIGS, dye-sensitized solar cells (DSSCs) have attracted interest and are being given considerable attention due to these attributes: ease of production, comparatively low fabrication cost; and reasonable solar-to-electrical efficiency. Subsequently, they have been regarded as potential materials to replace traditional Si-based solar cells in specialized applications [48]. However, there is a limitation on the absorption coefficient due to standard DSSC employment of a Ru-based dye, which possesses moderate molar absorption [49, 50]. The DSSC system therefore, requires a high surface area substrate for the dye, nanoparticulate TiO_{2}, and to attain good light harvesting efficiency (LHE). Further, a slow redox shuttle usually I-/I3 is needed since electron transport is reasonably slow in nanoparticulate TiO_2 [51].

5. Application of nano based technology in the manufacturing of energy materials

Chapin et al. at Bell laboratories developed the first generation of PV solar cells, silicon (Si) p/n in 1954 [52]. The first generation PV solar cells have high cost as a major drawback due to the quality of materials used - low defect single Si crystal, reinforced low-iron glass cover sheet, and encapsulants. The second generation solar cells were aimed at lowering cost than the first generation. Examples of the second generation cells technologies are a-Si, CdTe and Cu(In,Ga)Se2), Cu(In,Ga)Se2 (CIGS) cells. Although, this generation cells have efficiency of 19%, which is higher than the first generation PV cells efficiency, the price is considered high. They are usually use in space applications where cost is not a major drawback [53]. In pursuit of overcome the cost and efficiency challenges associated with PV solar cells, the concept of nanocomposite, which enhances device for better performance was utilized. This was exploited in the production of PV solar cells to surmount limits of single materials in solar spectrum response; reaction of holes or electrons with chemicals; transport of holes or electrons; and reduce of costs. This gave birth to the third generation devices that are based on nanocomposites, such as organic–inorganic hybrid assemblies, nanostructured semiconductors, and molecular assemblies. The third generation PV solar cells are aiming to deliver low-cost high efficiency materials nanocomposite.

5.1. Application of atomic layer deposition

Atomic layer deposition (ALD) is a vapor-phase based deposition technique used for depositing high quality, conformal and uniform thin films at comparatively low temperatures. This technique is used to control interface properties through the deposition of high-quality thin films with specific growth control, excellent uniformity over large areas and very good step coverage on non-planar surfaces [54, 55]. These striking attributes of ALD have been employed in several applications including in the fabrication of solar cells for PV modules. In this regard, ALD has benefited the surface passivation layers, buffer layers and barrier layers of crystalline silicon (c-Si), CIGS and dye-sensitized solar cells (DSSCs). Encapsulation of flexible CIGS and organic photovoltaic (OPV) cells with film layer barriers has been performed successfully with ALD. Presently, ALD has been described as the future standard of solar cell equipment manufacturing.

The application of ALD for PV cell started in the 1990s and Bedair and co-workers group reported the first application in 1994. This was followed by the reports on the use ALD to deposit boron-doped ZnO films as transparent conductive oxide (TCO) and ZnSe buffer layers for CIGS solar cells [56]. In 1998, copper indium diselenide (CIS) cells was acclaimed the most common thin film material for PV [57], while the application of a more productive, similar combination material, CIGS, was reported in 2009 [58]. Thin film PV modules are preferred to the conventional crystalline rigid Si cells mainly because of the following merits:

i. Thin film PV cells require less materials [59].

ii. Several vacuum and non-vacuum techniques are used to deposit in thin films PV cells on inexpensive substrates [60].

iii. Thin film deposition on flexible and/or curved substrates, such as polymeric sheets is achievable, forming rollable or foldable solar generators [61]. This has further increased PV cells application areas to include high altitude platforms, cars, aircraft, and various electric appliances. Flexible PV thin-film offers specific design alternatives for BIPVs [62] and the interest in flexible thin film PV cells and technologies is progressively increasing.

In a study [63], ALD was carefully used to develop CuSbS2 thin films at a low-temperature route. After 15 minutes, postprocess, annealing, was performed at 225°C. It was observed that CuSbS2 films ALD-grown, crystalline with micron-sized grains, showed a band gap of 1.6 eV, absorption coefficient of >104 cm^{-1}, and hole concentration of 1015 cm^{-3}. Further, the study demonstrated the first open-circuit voltage on par with CuSbS2/CdS heterojunction PV devices and the potential of ALD grown CuSbS2 thin films in environmentally friendly

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PVs. It concluded that CuSbS2 and Cu12Sb4S13, members of the Cu–Sb–S family that may be reproducibly synthesized by ALD were added to the short list of metal sulfide thin films.

Recently, attention has been given to new mixed metal oxide materials realized from templating strategy in combination with ALD for DSSC photoelectrodes. Hamann et al. [64] showed the feasibility of the use of TiO_2 structures as dye-sensitized electrodes by typifying their forms and photovoltaic performance. In the study, a new pseudo-one-dimensional structure for DSSC photoanodes was made from mesoporous aerogel, a low-density, high surface area, and thin films by templating. Atomic layer deposition was used to control the variable thickness of TiO_2 deposition on aerogel templates conformally. The study revealed that the cell efficiency was proportional to TiO_2 thickness deposited because of increasing charge diffusion lengths; the electrodes integrated into DSSCs showed good light harvesting and exceptional power efficiencies compared with the nanoparticle TiO_2 based DSSCs; and ALD-coated aerogel-templated photoanodes have been described as a promising candidate to move beyond nanoparticle electrodes in DSSCs due to design flexibility, materials generality, and ease of manufacturing.

6. Conclusion

The World Energy Council categorized energy sustainability into three components - energy security, energy equity, and environmental sustainability. Fossil fuels are the greatest economic drivers amongst the available fuels, but they have huge environmental threats and consequences, such as CO_2 emissions. The increasing global energy demand coupled with the complex nature of the global energy dynamic make management challenging. To effectively respond to the global energy challenges, the generation of energy to satisfy the increasing demand should be done without compromising the environment. Solar energy is a potential alternative to fossil fuel is known for CO_2 emission. As such, photovoltaic solar system is seen as the best option to fossil fuels. The exploitability of solar resource amongst renewable energy sources and the production of low-cost flexible PV cells will facilitate energy trilemma success.

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