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Advancements in Solar Energy Materials for Sustainable Development and Environmental Justice

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ABSTRACT

The rising need for eco-friendly energy has boosted research into cutting-edge solar materials that can solve the world's energy problems while minimizing harm to the ecosystem. Due to their capacity to transform plentiful sunlight into clean electric power while releasing low amounts of harmful gases, solar energy technologies have become one of the most suitable renewable energy options. Notable progress has been made in the area of photovoltaic materials by introducing crystalline silicon, cadmium telluride, copper indium gallium selenide, perovskites, organic semiconductors, quantum dots and tandem solar cells leading to an increase of their efficiency, stability, and cost-effectiveness. Apart from technological advancements, sustainable progress requires environmentally aware production, rational use of resources, and good waste management within the lifecycle of solar products. As a result, current research emphasizes “green” synthesis, recyclable materials, circular economy principles, and life-cycle assessment of solar technologies. At the same time, environmental justice appears to be one of the key aspects of renewable energy policy that guarantees access of everyone to the clean energy and creates minimum differences from environmental and social points of view. In this literature review, modern findings in solar energy materials and devices, their characteristics, methods of production, efficiency, sustainability, and prospects are considered. The link between modern solar materials and sustainable development objectives is also studied with a focus on affordable clean energy, climate change issues and responsible resource management.

Introduction

The constantly increasing world population, quick industrialization, urbanization, and technological progress have caused the worldwide energy consumption to become higher and higher. Throughout history, people relied on traditional fossil fuels coal, petroleum, and natural gas as their main sources of energy. But too much dependence on fossil fuels has caused some problems, such as, greenhouse gas emissions, global warming, air pollution, and other environmental problems. Due to these issues, countries, companies, and scientists have started seeking renewable energy resources that can meet future energy needs without harming the environment.

Of all kinds of renewable energy, solar energy is one of the most abundant, clean, and accessible forms of energy in existence. The amount of solar energy that the Earth gets in one hour is much larger than the total energy that is consumed worldwide within a year. The effective usage of solar energy became possible due to technological developments in photovoltaic (PV) technologies and semiconductors. Over the years, solar cells efficiency, manufacturing process improvement, characteristics, and production price have helped the technology of solar energy become one of the most rapidly developing renewable energy technologies in the world. The photovoltaic systems utilize photovoltaic effect which allows creating energy from sunlight by using semiconductor materials. The effectiveness of photovoltaic devices depends on the physical, chemical, and electrical characteristics of the active materials. Therefore, material science has been the An extensive amount of work has gone into creating new types of photovoltaic materials with better absorption of light, optimal charge transport, minimized losses due to recombination, higher thermal stability, and

opportune lifetime. Silicon has been, and remains, the most widely used photovoltaics material due to its effective conversion efficiency, high strength, and developed technology. At same time, new types of materials, such as perovskites, cadmium telluride (CdTe), copper indium gallium selenide (CIGS), organic semiconductors, dye-sensitized solar cells, and quantum dots, have been developed and are under research as they demonstrate great characteristics and potential for lower production costs. These new materials enable the construction of flexible solar panels, lightweight solar cells, transparent photovoltaics, and high-efficient tandem systems that can overcome the limitations of conventional silicon solar cells. Apart from the research on power efficiency, sustainability is one of the main goals with sustainable photovoltaic technologies being in demand currently. Modern researches have to be eco-friendly and focus on finding ways to reduce toxic usage, create recyclable designs, and achieve responsible life cycle design. New sustainable technologies contribute to reduction of emissions, energy security, preservation of natural resources, and environment protection.

Environmental justice is one of the important areas of renewable energy development. Solar energy is environmentally friendly, but its unequal access and distribution across regions and socio-economic groups exist. Thus, sustainable solar energy implementation should consider providing equal access to cheap electricity, using the critical minerals in the right way, and ensuring fair benefits from the solar production process.

Innovations in nanotechnology help to discover the new generation of photovoltaic. Thus, contemporary technologies allow rapid predictions of materials' properties, optimization of solar systems, reduce costs and raise the efficiency of photovoltaic resources and

systems .

The objectives of the review are:

- To compare established and new technologies of solar energy.
- To evaluate sustainability of advanced technologies of solar manufacturing.
- To analyze role of the environmental justice in renewable energy development.

The review focuses on breakthroughs in solar energy manufacturing and how photovoltaic technologies support sustainable development.

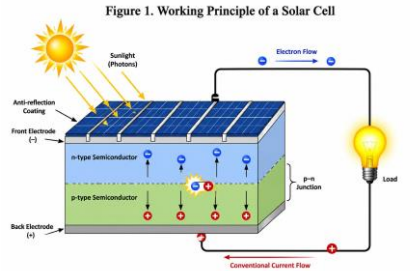


Figure 1. Working Principle of a Solar Cell

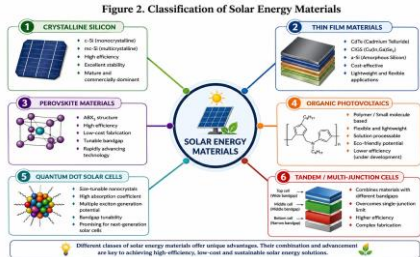


Figure 2. Classification of Solar Energy Materials

Literature Review

Evolution of Solar Energy Materials-Since the introduction of the first efficient silicon solar cell in 1954, solar energy technology has progressed tremendously. The first solar panels had low efficiency and could only be used in space due to their high costs. Since then, the technology has been getting better due to ongoing developments in semiconductor processing, crystallization methods, surface treatment, and engineering of devices. In recent years, solar energy has become one of the fastest-growing renewable energy technologies globally and plays an important role in the global transition to renewable energy systems. Today, crystalline silicon is still the most popular photovoltaic substance used to make most solar panels. The popularity of crystalline silicon can be explained by its great electrical properties, durability, reliability, and well-established production chain. Ongoing developments in both monocrystalline and polycrystalline silicon technology led to increased commercial efficiency while decreasing costs.

Crystalline Silicon Solar Cells-Silicon-based photovoltaic technology is still primarily used in the global solar industry, because of its remarkable efficiency, good durability, and developed production processes. Today's solar cells with the use of the passivated emitter and rear contact (PERC), the tunnel oxide passivated contact (TOPCon), and the heterojunction technology (HJT) exhibit the energy conversion efficiency that far exceeds the efficiency of traditional silicon-based cells. Some recent research proves that innovative silicon devices operate by reducing losses related to the recombination of charge carriers, improving light absorption, and enhancing the voltage in open circuit mode. The development of technologies has made it possible to receive efficiency in laboratory conditions of over 26%, which proves that crystalline silicon is one of the most effective materials for photovoltaic electricity production. However, in spite of the benefits stated above, silicon production process involves the use of high temperature and significant energy consumption, due to which the scientists continue searching for eco-friendly production methods that can minimize carbon emissions and improve the recycling process.

Perovskite Solar Cells

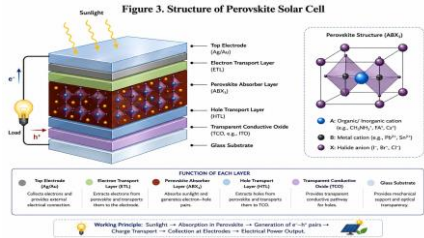


Figure 3. Structure of Perovskite Solar Cell

Perovskite solar cells are among the greatest achievements in the field of photovoltaic devices in the past ten years. The materials have great optical absorption, adjustable band gaps, high carrier mobility, and easy manufacturing processes. One of the main benefits of using the novel perovskite materials is that the increase in the power conversion efficiency is rapid – it has already become remarkable in a relatively short time. Their compatibility with flexible substrates and tandem solar cells makes them even more commercially viable. Nevertheless, there are still some problems with the long-term stability, moisture sensitivity, ultraviolet radiation damage, thermal stability, and environmental safety of the piloted lead-containing materials. Thus, the main spheres of research today are targeted at lead-free perovskites, better encapsulation practicalities, interfacing, and environment-friendly technologies of synthesis.

Thin-Film Photovoltaic Materials-Thin-film PV technologies are superior to conventional silicon-based technologies in various aspects. Thin-film technologies consume little material, are light and flexible, thus making the manufacturing cheaper.

- Important thin-film materials include:
- Cadmium Telluride (CdTe)
- Copper Indium Gallium Selenide (CIGS)
- Amorphous Silicon (a-Si)

Thin-film technologies are a good choice for building-integrated photovoltaics, portable gadgets, and flexible solar modules. Development of deposition techniques, optimization of interfaces, and defect engineering has been beneficial for the effectiveness of these technologies. However, the problem of availability of certain elements and toxicity of cadmium leads to the search for less harmful alternatives.

Organic Photovoltaic Materials-The technology of organic photovoltaics (OPVs) proved to be a wonderful substitute because it is a lightweight, flexible technology that can be processed at low temperatures and suited for the roll-to-roll production method. Organic semiconductors are made of conjugated polymers and small organic materials, which are able to absorb visible light and induce the generation of electrical energy through exciton dissociation. Due to these properties, organic semiconductors are able to produce transparent and flexible solar panels suitable for future solar energy applications. Nevertheless, organic solar cells have lower efficiencies as well as shorter life spans than those of inorganic photovoltaic technologies. Therefore, current studies concentrate on molecular engineering, donor-acceptor optimization, and inventing new methods of encapsulation in order to enhance the performance of devices.

Nanotechnology and Quantum Dot Solar Cells-Nanotechnology has opened up entirely new horizons for photovoltaic studies due to technologies like quantum dots, graphene, carbon nanotubes, semiconductor nanowires, and plasmonic nanostructures. Quantum dots have size-dependent properties that make them efficient in absorbing light in different spectrum ranges. They can also use tunable band gap technology to achieve better results with regards to light harvesting and reduce energy losses in the form of heat.

Graphene has gained amazing popularity thanks to its superior conductivity, transparency, and flexibility, while carbon nanotubes improved charge transport and conductivity as well. These technologies are still in the research stage, but they have a great potential of creating photovoltaic products that are extremely efficient.

Tandem Solar Cells-Tandem solar photovoltaics involve the combining of various semiconductors which possess a different bandgap. Using the silicon-perovskite type of photovoltaic cells has enabled the increase in the efficiency of conversion of sunlight into electricity through maximum application of the efficiency of photons' usage and thermalization losses. Nevertheless, studies are being conducted regarding the improvement of tandem solar panels which deal with the problems regarding compatibility of materials, stability

at the interface, affordable production in mass scale, and durability of efficiency.

Sustainability and Environmental Justice-The latest scientific publications have been written with the understanding that photovoltaic development concerns not only improvements in functionality of solar systems but also sustainability and social accountability. Analysis of specific life-cycle assessments shows that solar technology has much lower greenhouse gases emissions during its entire operational life than thermal generation from fossil fuels. New solutions concerning recycling the modules, circular economy practices, and environmentally friendly manufacturing are helping to decrease the ecological footprint of solar technologies.

Environmental justice is now treated on the same level as environmental protection. Scientists now focus on equal access to sustainable electric power, responsible mining of key minerals, ethical employment practices, community participations, and recycling of the end-of-life components of solar technology.

Research Gap-Despite significant achievements in photovoltaics, numerous critical research challenges still exist. Among them are improvements in stability over time of perovskite substances, production of photovoltaic absorbers free of lead, cutting down manufacturing costs, increasing efficiency in recycling, lessening the need for limited crucial minerals, and combining photovoltaic technologies with advanced energy storage methods.

The future research should also focus on manufacturing that is sustainable, the use of circular economy principles, the application of artificial intelligence to discover new materials, and the implementation of laws that promote environmental justice. If these research gaps are settled, it will lead to the creation of highly effective, low-cost, eco-friendly, and socially fair photovoltaic technologies.

Methodology

This research work presents a narrative review using systematic methodology to highlight current progress in solar energy material development and its relation to environmental justice and sustainable development. Unlike traditional experiments conducted within laboratories, the research relied on review and synthesis of scientific literature. The methodology chosen during the current research enabled collecting, filtering, analyzing, and interpreting available data in an effective and straightforward manner.

Research Design-The methodology of qualitative reviews was used to collect information on various advanced photovoltaic materials. The investigation aimed to spot innovations, contrast properties of various solar energy materials, and find out their environmental and sustainability consequences. The focus of the review is on scientific evidence mentioned in peer-reviewed works rather than on collecting primary experimental data. The relevant literature was acquired by making thorough searches of various journals enjoyed by the scientific community, such as ScienceDirect, SpringerLink, Wiley Online Library and others. Searches were concentrated primarily on works issued over the last ten years, i.e. mostly recent scientific achievements, while landmark studies did not remain without attention. The search consisted of many keywords covering the issues referring to solar technologies, semiconductors, sustainability and environmental justice, such as solar energy materials, photovoltaic cells, crystalline silicon, perovskite solar cells, thin film photovoltaics, organic solar cells, quantum dots, renewable energy, and environmental justice. Various combinations of these terms ensured obtaining relevant literature.

Study Selection-The evaluation process was based upon defined selection criteria. The highest preference was given to peer-reviewed articles containing original research, updated studies or general reviews of solar photovoltaic techniques and sustainable energy technologies. Those publications which provided insufficient scientific backing, duplicated records, were written in languages other than English, editorials, and those not relevant to the topic of this study were eliminated from analysis.

Data Extraction-From each chosen publication, relevant scientific information was extracted systematically. The information includes the kind of photovoltaic material, fabrication method, photovoltaic performance, conversion efficiency, aquitability, environmental impact, recyclability, economic feasibility, and mentioned pros or cons. Also, the information regarding sustainability indicators was recorded, whenever available.

Comparative Analysis-The chosen studies underwent scrutiny

through comparative analysis in order to discover parallels as well as discrepancies and advancements in technology, along with areas which have not been researched among different photovoltaic materials. The comparative evaluation included various parameters including the energy conversion efficiency of the material, accessibility of the material, the requirements for its manufacturing, its performance in use, environmental compatibility, ability to be recycled, and possibilities for its commercialization.

Sustainability and Environmental Assessment-The analysis of the sustainability characteristics of solar materials was done by looking at the literature on life cycle assessment, carbon emissions, resource use, waste management techniques, and recycling of the materials after their lifetime. The study also highlighted the already existing trends in the field of green production, circular economy programs, and environmentally friendly material choice.

Environmental Justice Perspective-The role of modern solar energy materials has also been reviewed with regard to environmental justice. Studies have been reviewed on responsible extraction of raw materials, equitable access to renewable electricity, participation of communities, rural electrification, and reduction of inequalities. This insight allowed to understand the connection between technological advancements and socially inclusive sustainable development.

Scope and Limitations-The conclusions presented in the review are based only on the published scientific literature and do not consider the observations from the collected primary data. Although there are a lot of attempts made to carry out quality research, the results are still affected by the availability of previous research. The utilization of peer-reviewed articles published in internationally-recognized journals helps increase the credibility of the review.

Quality Assessment of the Selected Literature-In order to bolster the scientific validity of this review, we evaluated the quality of reviewed articles prior to their inclusion in the final analysis. More emphasis is given to articles appearing in peer-reviewed international journals with precise research objectives, sound methodology, transparency in presenting data and scientifically valid conclusions. Preference is given to paper presenting photovoltaic efficiency, material stability and environmental performance indicators with the use of standardized methodology. Papers presenting contradictory findings or lacking details on methodology were examined before making a decision for comparative analysis. Such quality assessment resulted in making sure that the discussion presented in this review is based on highly reliable and scientifically justified evidence.

Data Synthesis and Interpretation-Once the information from the identified studies was collected and analyzed, the obtained material was synthesized using thematic analysis. The results of the studies were categorized according to the type of photovoltaic material, technical progress, efficiency of energy transformation, environmental characteristics, and sustainability parameters as well as possible future applications. Various studies were compared to determine the present trends in research and identify the gaps in knowledge. The analyzed data were interpreted taking into consideration the concepts of sustainable development and environmental justice in such a way that the technological advancement achieved in the field was analyzed along with the environmental problems posed by these technologies.

Results and Discussion

Comparative Performance of Advanced Solar Energy Materials

Table 1. Comparison of Different Solar Energy Materials						
Material Category	Typical Examples	Structure / Composition	Bandgap (eV)	Typical Efficiency (%)	Key Advantages	Key Limitations
Crystalline Silicon (c-Si)	c-Si (mono) mc-Si (multi)	Crystalline silicon lattice (diamond structure)	1.10 - 1.12	18 - 26	✓ High efficiency ✓ Excellent stability and durability ✓ Mature technology ✓ Abundant and non-toxic	✗ High temperature processing ✗ High energy consumption ✗ Rigid and heavy
Thin Film Materials	CdTe CdS a-Si (Deposited in some cases)	Thin semiconductor layers (nm range) on substrate	1.1 - 1.6 (material dependent)	10 - 18	✓ Low material usage ✓ Lightweight & flexible ✓ Low cost ✓ Better performance in low light	✗ Lower efficiency than c-Si ✗ Stability issues over time ✗ Toxicity (Cd in CdTe)
Perovskite Materials	CH ₃ NH ₃ PbI ₃ (and other ABX ₃ perovskites)	Perovskite structure (ABX ₃) A: organic/inorganic cation B: metal cation X: halide	1.50 - 1.60 (tunable)	25 - 26+ (record > 26%)	✓ Very high efficiency potential ✓ Lightweight & flexible ✓ Solution processable ✓ Tunable bandgap ✓ Low cost	✗ Stability issues (moisture, heat, UV) ✗ Lead toxicity ✗ Scale-up challenges
Organic Photovoltaics (OPV)	P3HT:PCBM and other conjugated polymers	Carbon-based conjugated polymers or small molecules	1.5 - 2.0 (tunable)	8 - 15	✓ Lightweight & flexible ✓ Solution processable ✓ Tunable bandgap ✓ Low cost ✓ Semi-transparent options	✗ Low efficiency compared to inorganic PV ✗ Shorter lifetime ✗ Sensitive to oxygen and moisture
Quantum Dot Solar Cells (QDSC)	CdSe, PbS, PbSe, InP Quantum Dots	Nanoscale semiconductor particles (2-10 nm)	Tunable (1.0 - 2.2)	10 - 20 (potential > 20%)	✓ Tunable bandgap ✓ Multiple exciton generation ✓ High absorption coefficient ✓ Low material usage	✗ Complex synthesis ✗ Surface recombination ✗ Toxicity issues

Table 1. Comparison of Different Solar Energy Materials
Through the analysis of the selected studies, it is clear that tremendous developments have been achieved in the field of photovoltaic materials during the last decade. Continuous developments in semiconductor technology, device architecture and structure, interface engineering, and nanotechnology have

significantly improved the efficiency, durability, and marketability of solar systems. The analysis demonstrates that there is no universal photovoltaic material, as every technology has its own advantages and disadvantages, depending on the nature of the application, manufacturing techniques, environmental side effects, and cost-effectiveness of the technology. Crystalline silicon is still the benchmark photovoltaic material as it has optimal operability, high conversion efficiency, and well-established manufacturing infrastructure. Commercial silicon modules are known to have more than twenty-five years of operational service life with negligible degradation in performance. These factors have made silicon photovoltaic technologies prevail on the global solar market. Nevertheless, the production of silicon wafers requires high-temperature process and high energy consumption, which results in the search for alternative materials with lower production costs and ecological footprint. Thin-film photovoltaic technologies, such as CdTe and CIGS technology, have shown a lot of promise with respect to light-weight and flexible solar devices. Their lower material use and compatibility with large-area deposition techniques enable lower production costs. Nevertheless, considering the dependence on rare resources such as indium and tellurium, as well as the hazards of cadmium, the material use is an important challenge in terms of sustainable utilization and recycling. Among all the new photovoltaic technologies, perovskite solar cells are one of the most important scientific inventions. The rapid increase in energy conversion efficiency demonstrates the enormous potential of perovskite materials for commercialization in the future. The advantages of materials, like high optical absorption coefficient, long carrier diffusion length, possibility to adjust band gap, and the use of solution-based manufacturing methods, make perovskites very promising for upcoming solar technologies. Despite all the advantages of perovskites, the analysis reveals that the limited long-term stability of perovskite solar cells is still a key barrier on the way to their wide commercialization. Exposure to moisture, oxygen, ultraviolet radiation, and high temperatures leads to the wearing out of materials and losses in effectiveness. Besides, the presence of lead in many perovskite formulations raises ecological concerns regarding toxicity and waste disposal. Therefore, there is an ongoing search for lead-free perovskites, as well as for improved encapsulation and safe production technologies.

Technological Advancements in Photovoltaic Materials

Table 2. Comparison of Conventional and Emerging Photovoltaic Technologies						
Parameter	Crystalline Silicon (C-Si) / CIGS / a-Si	Thin-Film (CdTe / CIGS / a-Si)	Perovskite Solar Cells (OPV)	Organic Photovoltaics (OPV)	Quantum Dot Solar Cells (QDSC)	Tandem / Multi-junction Solar Cells
Technology Type	First Generation (Conventional)	Second Generation (Emerging)	Third Generation (Emerging)	Third Generation (Emerging)	Third Generation (Emerging)	Advanced / Next-Gen (Emerging)
Typical Efficiency (2024 Value)	18 – 24 % (commercial)	10 – 18 % (commercial)	25 – 26%+ (record ~ 26%)	8 – 15 %	10 – 20 % (potential > 20%)	30 – 47 % (laboratory record)
Theoretical Efficiency Limit	~29.4 % (Single junction)	~22 % (Single junction)	~33 % (Single junction)	~20 % (Single junction)	~30 – 40 % (Depending on QDs)	~ 50 % (Multi-junction limit ~ 60%)
Active Material	Crystalline Silicon (mono / multi)	CdTe, CIGS, Amorphous Si	Hybrid Organic-Inorganic Perovskites (ABX ₃)	Conjugated Polymers / Small Molecules	Quantum Dots (CdSe, PbS, etc.)	Combination of Materials with different bandgaps
Manufacturing Cost	High	Low to Moderate	Low to Moderate	Low	Moderate to High	High
Key Advantages	• High efficiency • Long lifetime • Excellent stability • Mature technology	• Low material usage • Lightweight • Flexible options • Low cost	• Very high efficiency (potential) • Low temperature processing • Solution processable • Scalable • Tunable bandgap	• Lightweight & flexible • Solution processable • Low-temperature processing • Printable	• Tunable bandgap • Multiple excitation generation • High absorption coefficient	• Very high efficiency potential • Diverse material combinations • Better performance
Key Limitations	• High temperature processing • Rigid and heavy • High energy consumption	• Lower efficiency (mono-junction) • Stability issues (long-term) • Toxicity (Cd in CdTe)	• Stability issues (moisture, heat, UV) • Lead toxicity • Scale-up challenges	• Low efficiency • Shorter lifetime • Sensitive to oxygen and moisture	• Complex synthesis • Environmental concerns (toxic materials) • Stability issues	• Complex fabrication • Environmental concerns (heavy metal) • Thermal mismatch issues
Commercial Maturity	★★★★★ (Very High)	★★★☆☆ (High)	★★★☆☆ (High)	★☆☆☆☆ (Low)	★★★☆☆ (High)	★★★☆☆ (High)
Typical Applications	• Rooftop PV systems • Utility scale plants • On-grid systems	• Large scale PV plants • Building integrated PV • Portable devices	• Next-generation PV • Tandem solar cells • Flexible / Lightweight applications	• Wearable electronics • Indoor / Low light applications • Building integrated PV	• Next-generation PV • Photocatalysis • Quantum device	• Space applications • High-efficiency PV • Concentrator solar systems

Table 2. Comparison of Conventional and Emerging Photovoltaic Technologies

The reviewed literature suggests that the recent innovations in technology have greatly developed the performance of photovoltaic devices due to improvements in materials engineering and device establishment. The surface passivation procedures minimize the losses brought about by charge carrier recombination in crystalline silicon solar cells facilitating generation of stronger open circuit voltage and higher energy conversion efficiency. The same can be said about the technology of heterojunctions and passivated contacts that also increased the electrical efficiency of commercially available photovoltaic devices while providing them with high reliability in operation. Finally, nanotechnology has become one of the main factors in the improvement of photovoltaic devices. With the help of nanostructured materials, including graphene, nanotubes of carbon, semiconductor nanowires and quantum dots, the efficiency of light absorption, conductivity and charge transportation has increased. In addition, these materials allow creating flexible solar cells appropriate for portable power systems, wearable devices and building-integrated photovoltaics. The last

achievement worth mentioning is tantalum solar energy cells. This technology allows to work with semiconductor materials possessing different band gap levels enabling tandem photovoltaic devices to use wider part of solar energy in comparison to traditional single-junction ones.

Sustainability Assessment of Solar Energy Materials

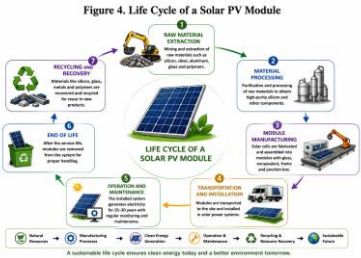


Figure 4. Life Cycle of a Solar PV Module

The comparative analysis reveals that sustainability goes beyond just the effectiveness of solar panels. Even if solar raw materials help lower harmful greenhouse emissions during the generation of electricity, it becomes clear that their actual sustainability depends on the stages of getting raw materials, production and distribution, the length of time they work, and waste disposal. Life cycle assessments indicate that energy generated by solar technologies is much cleaner than that from fossil fuels. Technological advancements helped today’s solar technologies return the energy spent to produce them in a short period of time. Current research points out that manufacturing practices should also focus on sustainability by reducing energy consumption, excluding solvents in production, using recyclable materials, and integrating the principles of the circular economy in photovoltaic technology production. Sustainability will play a key role as many solar technologies will reach their end of life in the near future. The users will have a chance to recover precious metals and other materials used in solar technologies’ manufacturing and thus minimize dependence on primary raw materials extraction.

Emerging Photovoltaic Technologies

Recent literature indicates that new photovoltaic technologies have made it possible to exploit solar energy not only for electricity generation. Organic photovoltaic (OPV) devices, quantum dot solar cells, dye-sensitized solar cells (DSSCs), and tandem photovoltaic systems are the next generation solar technologies created to address some issues associated with classical silicon technologies.

Organic photovoltaic materials have a great number of advantages because they are lightweight, flexible, and can be produced by low-temperature solution-processing. This is especially important for wearable electronics, portable energy devices, smart windows, and building-integrated photovoltaic systems. Moreover, roll-to-roll manufacturing will help to minimize production expenses and enable mass production. Nevertheless, the comparative analysis shows that organic solar cells are less effective than crystalline silicon because they have lower power conversion efficiency and shorter lifetime.

Quantum dot solar photovoltaics possess also significant scientific promise. Solar cells’ semiconductor nanoparticles have adjustable band-gap energies, which facilitate the absorption of a broader spectrum of solar radiation. The analysis of literature shows that quantum dots are capable of improving absorption of photons and decreasing heat losses. However, material stability, mass production, and environmental safety of quantum dots remain the main obstacles for practical use. Further scientific study aimed at solution of the existing problems is needed.

Environmental Justice and Sustainable Energy Transition

According to the literature the technological progress alone is not enough to attain sustainable development. In addition to that the issue of equal access to clean and cheap energy seems to be equally important. The concept of Environmental Justice states that the process of using renewable energy should be fair and should not put vulnerable communities at the environmental risk.

The development of the solar power industry due to the rapid growth of solar power has led to better access to electricity for rural areas and remote regions where there are no conventional grid systems installed. Photovoltaic systems provide electricity necessary for assuring educational and medical services as well as agricultural and industrial process leading to poverty reduction.

At the same time there exist numerous Environmental Justice problems in the sphere. For instance the extraction of important raw materials such as lithium, cobalt, indium, gallium and rare earth

elements can cause environmental problems and social tensions if it is done irresponsibly. Another factor to consider is lack of recycling of the photovoltaic in the end of its life cycle.

Future Research Perspectives

The comparison indicates that photovoltaic science has to be developed in several areas. Currently, the priority is to develop lead-free perovskite solar panels capable of functioning outdoors for a long period of time. The achievements in the material science field and optimization of interfaces should allow getting closer to the achievement of this goal. The following high-tech advancements should help find new materials for solar cells. AI and machine learning will help in predicting the properties of newly discovered materials for solar power systems and designing them, as well as in reducing the expenses on experiments significantly.

One more important aspect of the future studies is accomplishing the circular economy principles in solar module design, material production and manufacturing technology. According to the results obtained from the present study, continuous innovations in solar energy materials have changed photovoltaic technologies into one of the most promising solutions to global issues related to energy and environmental problems. While conventional crystalline silicon still dominates the market due to its reliability and long service life, new materials developed, like perovskites, quantum dots, organic semiconductors, and tandem solar cells provide new opportunities for obtaining higher efficiency and expanding their spheres of application. However, sustainable development also means that technological advancement must be achieved with responsible production, effective utilization of resources, and recycling processes in mind, as well as ensuring equal access to renewable energy sources for everyone. The combination of scientific innovations and principles of environmental justice will allow future solar energy systems to not only contribute to the reduction of greenhouse gas emissions but also help promote social justice, economic development, and sustainable environmental protection. Thus, it could be concluded that advanced solar energy materials will continue playing a significant role in shifting toward a low-carbon economy. Further interdisciplinary research, supportive state politics, international collaboration, and sustainable technologies investments are necessary for the further successful application of solar energy.

Conclusion

The fast-paced development of solar energy technologies has profoundly changed the renewable energy landscape and accelerated the worldwide process of moving towards a green low-carbon society. According to this review, continuous modifications in photovoltaic materials have managed to increase their efficiency, stability, cost-effectiveness, and feasibility, thus ensuring the promising potential of solar energy to replace fossil fuels. Out of the numerous photovoltaic technologies, crystalline silicon is still regarded as the leading commercial technology due to its reliability and durability. However, the production of innovative materials such as perovskites, thin-film semiconductors, organic photovoltaics, quantum dots, and tandem solar cells is worth noting. Despite the fact that these materials were developed very recently and received a lot of attention, further research is needed to improve their practicality and sustainability. The data presented in this review confirms that the results of any photovoltaic technology have to be evaluated not only according to their efficiency. Environmental sustainability, responsible resource consumption, recyclable module design, green production technology, and end-of-lifecycle waste management are also significant requirements in order to achieve minimum negative impact of solar energy on the environment. From the perspective of environmental justice, the expansion of solar energy can prevent energy inequalities and promote access to electricity in deprived communities. Nevertheless, the usage of renewable energy also requires proper mining practices, ethical extraction of primary materials that are produced from nature, successful recycling of photovoltaic waste, and equal distribution of benefits. To sum up, the conclusions drawn from the evidence given in the review show those innovative solar technologies will continue being the basis of sustainable energy systems of the future. Interdisciplinary studies, technological advancements, favorable government policies, and international connections are crucial in order to solve existing technical and

environmental problems. Future researches should concentrate on the creation of highly effective and reliable photovoltaic materials that are both cheap and environmentally friendly.

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