Solar Photovoltaic Materials Present Efficiencies and Future Challenges Incorporating Indian Knowledge System

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Abstract: Solar photovoltaic (PV) technology has become one of the major players in the global transition to renewable energy sources. While solar PV materials have improved in efficiency, lingering issues connected to the cost of materials, energy conversion, sustainability, and integration to existing energy infrastructure remain. This paper discusses the current efficiencies of solar photovoltaic materials, looking at some of the different types of materials that are used in PV such as silicon-based, thin film, organic and perovskite materials. It therefore goes on to critically analyse the efficiency rates of these materials and explore the technological advances that have resulted in higher efficiency solar energy harvesting.

While important progress has been made, at least six barriers remain for the widespread adoption of solar PV technology, including manufacturing limitations, economics, recycling issues, and the challenge of energy storage. To overcome these challenges, Indian Knowledge Systems (IKS), which encompass indigenous knowledge systems and provide valuable insights into sustainability, energy conservation, and enlisting natural materials, can be integrated into modern architecture and design. Based on ancient Indian science and tradition, the paper emphasizes the role of IKS in improving the efficiency and sustainability of PV technologies to close the gap between science and tradition.

The combination of IKS with the latest in solar PV technologies will enable the country to increase its potential in harnessing solar energy while giving rise to ecologically sustainable solutions that would be suited for Indian soil. The paper ends by a note on prospects of solar PV materials, where they highlight that the future of solar energy needs to engage all branches of science and technology and prove partnership between traditional knowledge and modern innovations.

Keywords: *High Efficiency Solar Photovoltaic Materials, Ancient Knowledge Systems (IKS), Sustainable Materials, Renewable Energy.*

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I. INTRODUCTION

Solar energy is one of the most promising sources of renewable energy obtained indirectly from sunlight energy emitted by the sun. It is large, sustainable, and clean, making it a core player in the world energy crisis and the battle between climate change. Key pillar of renewable energy infrastructure are solar photovoltaic (PV) materials as they play a vital role in converting solar energy into electricity. PV technology is a key player in the global energy transition away from fossil fuels and towards cleaner energy solutions.

Solar PV energy materials have a particular efficiency, which is a measure of how much sunlight can be converted into usable electrical energy. Solid-state battery research and development has made considerable progress over the past decade, with bulk material-type efficiencies ranging from single digit percentages to those in the mid-teens as a result. Silicon-based PV materials account for most of the market, as they are relatively very efficient and stable material, but more recent technologies such as the perovskite and organic PV materials are being explored as options to achieve higher efficiencies at the lower cost. Gains in solar PV efficiency globally are pushing R&D on next-generation materials and

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technology that could make solar energy access more achievable and affordable for large-scale deployment.

Indian Knowledge Systems (IKS) is a treasure trove of ancient wisdom regarding sustainability, conservation, and ecological balance. These traditional knowledge systems provide insights into the use of natural materials and energy-efficient practices that align with sustainable development, which is particularly relevant in modern contexts. We have the tools from IKS to get these sustainable practices adopted and create an immediate reduction in solar energy usage. Integrating traditional knowledge for developing solar PV materials will make India-focused solutions more sustainable to meet the specific requirements of the country.

In this paper, we will explore the current efficiencies of solar PV materials and the issues facing the solar energy sector. It further investigates the contemporary application of Indian Knowledge Systems and its unique integration with modern technology to develop solar energy technological innovations which will be more sustainable, efficient as well as culturally relevant here. The study aims to by exploring this gap, indirectly contribute to the advancement of solar PV technology and provide a better foundation to tackle future global energy issues.

- *Solar Photovoltaic Material State-of-the-Art Efficiencies*

Solar photovoltaic materials cover a wide range of types, each with unique properties and applications. Silicon-based PV cells are by far the most widely used and are either monocrystalline, polycrystalline or amorphous silicon. These materials have formed the backbone of solar energy technology for decades, because of their relatively high efficiency and durability. Other than flexibility and low cost, thin-film PV materials, including cadmium telluride (Cadet), copper indium gallium selenide (CIGS), and amorphous silicon, tend to show lower efficiencies than silicon-based cells. Organic photovoltaic (OPV) materials, based on organic semiconductors, and perovskite solar cells have been introduced as promising alternatives owing to their high efficiency at low production costs. These materials are not yet for sale, but their development offers the potential for some exciting breakthroughs in solar technology.

Solar PV materials vary in their efficiency, depending on the type of material. Monocrystalline silicon solar cells are the most efficient ones, achieving efficiencies of 18-22%, while polycrystalline silicon solar cells have slightly lower efficiencies between 15-17%, but at lower costs. The efficiency of thin film solar cells is typically low, ranging from 10-15%, but CIGS cells have been shown to achieve up to 20% under optimal conditions. Prototype organic and perovskite solar cells are also experimental with efficiencies of between 10% and 25%, depending on the material and production method. The efficiency of these PV materials is greatly related to their material properties, including bandgap, absorption spectra, and charge carrier mobility, which directly determine the ability of the material in the collector of sunlight and conversion to electricity.

The solar PV efficiency improvements continue to be driven by technological innovations. One breakthrough is the construction of tandem solar cells, which stack several layers of different materials to capture a wider spectrum of sunlight than most conventional single-junction cells can achieve alone, resulting in efficiencies well above single-junction cell levels. Even the ever-fractious perovskite solar cells have seen extraordinary advances, with researchers achieving efficiencies exceeding 25% in lab settings. Light-trapping, anti-reflective, and bifacial solar panels—which capture sunlight on both sides of the panel—are developing as well, leading to improved energy conversion efficiencies. Technological improvements are making solar energy much more affordable than traditional energy and opening the door for wider adoption in the future.

II. CHALLENGES IN SOLAR PHOTOVOLTAIC MATERIALS

- *Material Limitations*

One of the biggest problems affecting the solar photovoltaic (PV) technology comes from the limited availability of most PV materials. Even though Silicon-based PV cells are highly efficient, they have major concerns such as being high cost, low durability, and not being eco-friendly. The energy-intensive process of making monocrystalline and polycrystalline silicon also requires the mining of raw materials, notably quartz, which contributes to environmental degradation. Silicon cells are also relatively inflexible and degrade in the presence of environmental factors over time, leading to a significant loss in efficiency and performance. Thin-films and organic PV materials are more flexible and cheaper to manufacture but generally come with lower efficiency and shorter lifespan.

- *Efficiency vs. Cost*

Until now, the efficiency-cost trade-off has always been a core topic in solar PV field. More efficient solar cells, like monocrystalline silicon, typically come at a higher price due to the complex manufacturing process. This leads to a cost of per watt, meaning that these cells are less affordable to facilitate larger adoption, especially in developing areas. Conversely, thin-film and organic PV cells, while cheaper, tend to suffer from the trade-off of lower efficiency. Finding the sweet spot between maximizing efficiency and minimizing production costs is a primary challenge for the long-term expansion and competitiveness of solar energy.

- *Recycling and Sustainability*

Recycling and disposal of the PV materials themselves at their end of life is a concern and presents significant challenges to solar energy lifecycle environmental concerns. Solar panels have a lifespan of approximately 25 to 30 years and can become waste if not recycled properly. Solar panels, particularly silicon-based ones, are complicated to recycle and expensive, and most of the material does not lend itself to reuse. Recycling of PV materials will contribute to their environmental footprint and solar energy will maintain its sustainability.

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- *The problems of Manufacturing and Scalability*

Scaling up production without sacrificing the quality or efficiency of the PV cells is another challenge. Building and maintaining such facilities for mass production of advanced solar panels demands substantial resources and infrastructure investment. Increased production gives rise to the continuous challenge of consistency, defects and low cost.

- *Storage and Integration the with the Grid*

The intermitted and variable nature of solar energy pose challenges to energy storage and grid integration. Time-of-day difference as well as weather conditions makes solar energy generation inconsistent, often leading to supply-side issues. Batteries are a critical component of effective energy storage systems, allowing for the storage of excess energy for use on cloudy days or at night, but the technology is expensive and limited in capacity. Moreover, tapping large-scale solar energy into the grid will necessitate infrastructure upgrades to manage variable inputs and maintain a consistent power output. To unlock the potential of solar energy in the energy ecosystem, solutions need to be developed to overcome these challenges.

- *Integration of Solar PV Technologies with Indian Knowledge Systems*

Mahatma Gandhi envisioned India to be a rich, independent country free from oppression where the rich man, with his wealth, would not be able to rob someone of their dignity.

IKS has since time immemorial, emphasised sustainability, energy conservation, living in harmony with nature etc. Traditional Indian ideas like using natural resources for building, traditional way of managing water and agricultural methods show us a profound understanding of conserving resources. IKS understands energy as more than a commodity; it is a critical part of the environment, interrelated with natural processes. Local communities living in sync with nature where sustainable practices such as rainwater harvesting, passive cooling in architecture and building homes with locally available, renewable materials are examples of sustainable living in Indian traditions. This holistic perspective on sustainability paints a vivid picture of the process of "living in harmony with nature," which can provide incredible inspiration for us re-paradigm around sustainable technology today.

- *Sustainable Technologies from a Vedic Perspective*

The entire spectrum of Vedic knowledge, from Rigveda to Upanishads, speaks about everything being interconnected words of wisdom to live a life in harmony with the environment. These writings show us the need to save natural energies, and we must recognize the life-giving cosmic energy is present in everything. Vital practices of sustainability through minimal environmental impact on technology draw from roots in ancient Indian principles of Ahimsa (non-violence) and Prakriti (nature). It also can motivate current solar PV to follow the same approach of energy efficiency and sustainable manufacturing in tandem with traditional wisdom.

- *Indigenous Materials, Solar Energy*

In India, the use of indigenous materials for energy conservation is a practice that dates back thousands of years, especially in architecture. Also, the traditional "Jutras" (solar temples) and the use of courtyards to optimize sunlight have been integral to passive solar heating and cooling systems. Conducting a thorough investigation of these materials for compatibility with solar energy technologies can facilitate more sustainable and effective solar panels. A few natural resources like bamboo, clay, stone, etc., which are thermal insulator, can be possible innovative solution for improving the energy efficiency of PV systems. Case studies of energy-efficient buildings such as stepwells and traditional solar-heated dwellings highlight critical passive solar energy use principles.

- *Integration of Integrated Knowledge Systems and Modern Science in the Development of Solar PV Technologies*

The synthesis of traditional knowledge systems and scientific innovations of solar PV technology has substantial potential. There is also room for principles of passive solar heating to come into play when it comes to designing solar panels to maximize their efficiency. Indigenous knowledge of materials and energy conservation can collaborate with global knowledge systems to innovate eco-friendly, cost-effective solar technologies appropriate to the local environmental and socio-economic context. Integrating IKS with modern scientific approaches can help build solar PV through energy solutions that are technically viable and culturally relevant, economically feasible, and environmentally sustainable.

III. OUTLOOK OF SOLAR PHOTOVOLTAICS MATERIALS

- *Novel Solar PV Materials: Emerging Technologies*

Emerging Technologies and Ongoing Research on Solar Photovoltaic Rack Materials Perovskite solar cells have attracted much interest because they can reach high efficiencies at a lower cost than conventional silicon-based materials. These cells, however, utilize a distinct crystal configuration that enables them to absorb a wider spectrum of sunlight and be generated more effectively in a laboratory setting. There is also a Tilt towards organic photovoltaics (OPVs) to provide flexible, lightweight, potentially low-cost manufacturing. While OPVs are still less efficient than silicon-based cells, their performance is increasing quickly, and they could find a place in several niche applications. And tandem solar cells, which layer multiple different materials on top of one another to capture a broader spectrum of light, are breaking the efficiency record. Unquestionably, these innovations will greatly optimize solar power harvesting and reduce the cost per watt making solar power a more feasible energy alternative for the masses.

- *Innovative Solar Technologies: What Role of the IKS?*

An IKS approach therefore has the potential to define the solar technologies of the future. Traditional wisdom, especially in the areas of resource sustainability and energy

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conservation, can also help guide the integration of PV technologies with human systems. Such as Indian Ancient Techniques in architectural passive solar heating, the use of natural materials such as clay and bamboo, and water conservation techniques to develop more efficient eco-friendly solar panels. Drawing on IKS tradition — which emphasizes balance with nature and minimal environmental impact — could inspire the design of solar technologies that are not only technologically advanced, but also in harmony with the principles for a sustainable life.

➢ *Tools for Greater Efficiency and Sustainability*

These advancements are to be coupled with significant integration, IKS both around materials science and relevant high impact resource use improvements that increases the functionality of solar PV technologies, On the other hand, for solar PV technologies to be more efficient and sustainable, we need innovations both in materials science and IKS integration. From a materials science perspective, the emergence of hybrid solar cells integrating the best features of organic, inorganic, and perovskite materials will lead to higher performances and lower costs. 3D printing of solar cells and other advanced manufacturing techniques provide an opportunity to reduce production costs and maintain quality. Incorporating IKS principles, such as employing renewable, locally sourced materials and passive solar designs, may make solar technologies more available and environmentally sustainable. The future use of solar PV materials can be aligned with these crucial environmental targets by using both conventional traditions and modern-day scientific advancements that will lead to energy challenges while sustaining our fragile ecology and promoting energy independence.

IV. CONCLUSION

➢ *Summary of Findings*

In this paper, we have examined the current trends in solar photovoltaic (PV) materials by presenting the efficiencies of different types of solar cells which include silicon-based cells, thin-film cells, organic cells, and perovskite cells. There have been great strides of learning to make this more efficient, yet there remain challenges in material constraints, cost/efficiency trade-offs, recalcitrance of materials in terms of recycle-impact analysis, and scalability. Indian Knowledge Systems (IKS) integration is emerging to tackle at least some of these challenges. Ancient wisdom of sustainability, energy conservation and natural materials, as contained in traditional Indian practices can complement more efficient and eco-friendly solar PV technologies. Through bridging the gap between ancient wisdom and modern science, IKS could be utilized to develop solar technologies that are more harmonious with nature, or locally adaptive or cost-effective.

➢ *Recommendations for Future Research*

Research in the future would ideally explore whether there are such synergies possible between advanced solar PV technologies and traditional systems of knowledge. For example, studies could explore how IKS could inform the design of solar panels using indigenous materials and energy-efficient architectural principles. Materials scientists should continue to innovate in both new and hybrid materials, like perovskites and organic photovoltaics, as well as work on maximizing their efficacy, considering durability and scalability. Furthermore, if you were to introduce interdisciplinary strategies that incorporate materials science, engineering, and sustainability studies as core subjects, this might contribute towards greater innovation in solutions to maximize performance while minimizing environmental and social impact.

➢ *Could it have Ramifications for India's Plans for Renewable Energy?*

The integration of IKS into solar PV technologies can deliver a significant leap in the renewable energy future of the country. Solar energy offers a huge opportunity for a country like India which has a vast amount of sunlight resources. Integrating IKS in this domain could help India address challenges in association with existing energy sources, for instance, increased production cost and environmental threats, as well as promote sustainable energy patterns. This integration may help divert the country towards its renewable energy targets and put India on the global map for sustainable solar energy solutions. Now, the inclusion of IKS in the new NEP supports India’s objective of protecting environment and addressing climate change in the longer run.

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