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A Comparative Study of Current Status & Challenges in Commercial Manufacturing of Perovskite Solar Cells

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Abstract

In recent years, the increasing prices of fossil fuels, imminent depletion of conventional energy sources and concerns about the environmental consequences of greenhouse gas emissions have renewed the interest in the development of alternative energy resources. In this regard, different policies could be applied to reducing carbon emissions, such as enhancing renewable energy deployment and encouraging technological innovations. Two main solutions may be implemented to reduce CO_2 emissions and overcome the problem of climate change: replacing fossil fuels with renewable energy sources as much as possible and the advancement of renewable energy technologies. Third- generation photovoltaic technologies, such as Dye-Sensitized Solar Cells (DSSCs), Organic Solar Cells (OSCs), and Perovskite Solar Cells (PSCs), are being developed as alternatives to silicon solar cells. Further research is required for making these technologies affordable and suitable for large-scale commercialization. In this paper, we discuss Perovskite Solar Cells and challenges to make it affordable and highly efficient.

(1) Introduction

Most renewable energy is derived directly or indirectly from the sun. Uneven solar heating of the Earth's surface causes wind whose energy is captured with turbines. Plants also rely on the sun to grow and their stored energy can be utilized for bio-energy. Geothermal energy utilizes the Earth's internal heat, tidal energy relies on the gravitational pull of the moon and hydropower relies on the flow of water. While renewable energy systems are better for the environment and produce less emission than conventional energy sources, many of these sources still face difficulties in being deployed at a large scale including technological barriers, high start-up capital costs, and intermittency challenges.

Solar energy, among other renewable sources of energy, is a promising and freely available energy source for managing long term issues in energy crisis. India is endowed with vast solar energy potential. About 5,000 trillion kWh per year energy is incident over India's land area with most parts receiving 4-7 kWh per sq. m per day. Solar photovoltaics power can effectively be harnessed providing huge scalability in India. Solar also provides the ability to generate power on a distributed basis and enables rapid capacity addition with short lead times. Off-grid decentralized and low-temperature applications will be advantageous from a rural electrification perspective and meeting other energy needs for power and heating and cooling in both rural and urban areas. From an energy security perspective, solar is the most secure of all sources, since it is abundantly available. Theoretically, a small fraction of the total incident solar energy (if captured effectively) can meet the entire country's power requirements. Total solar power installed capacity in India as of 28 Feb 2021 was 38.79 GW and set a target of 100 GW by 2022.

India is the world's third largest producer and consumer of electricity. India has seen an exponential growth in its renewable energy (RE) sector in the past five years. As of 31 March 2021, 36.8 % of India's installed electricity generation capacity is from renewable sources (140.6 GW out of 382.15 GW). In 2015, the government made its intentions to transition to a lower-emission electricity system clear by declaring an ambitious target of 175 GW from renewables by 2022 which includes 100 GW from solar, 60 GW from wind, 10 GW from bio-power and 5 GW from small hydro-power. Government of India has also set a target for installation of Rooftop Solar Projects (RTP) of 40 GW by 2022 including installation on rooftop of houses under 'rent a roof' policy.

The photovoltaic market has experienced a rapid growth over the past two decades, and so far, it has been largely dominated by silicon-based solar cells. The cost of Si-based photovoltaic cells however is high, and large-scale industrial production of this technology requires extensive processing. Third-generation photovoltaic technologies such as dye- sensitized solar cells (DSSCs), organic solar cells (OSCs), and perovskite solar cells (PSCs) are being developed as alter- natives to silicon solar cells. In recent years, there has been increasing scientific interest in the development of these emerging photovoltaic technologies and their power conversion efficiencies (PCEs) have increased considerably.

The successful commercialization of emerging solar cell technologies however cannot be based solely on achieving high power conversion efficiencies (PCEs). These technologies need also to become cost-competitive with conventional power generation. The cost effective deployment of photovoltaic (PV) systems is based on minimum system cost, maximum initial performance and minimum loss of performance over time as the key requirements. These emerging photovoltaic technologies, although promising for sustainable solar energy applications, have not yet achieved large-scale commercialization.

(2) Current Challenges for Perovskite Solar Cells

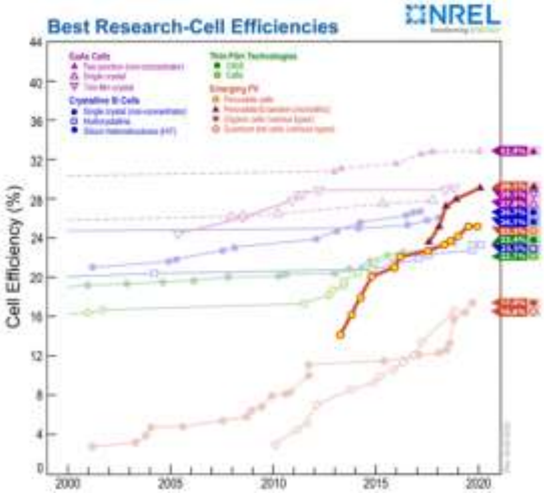
Perovskites are a family of materials with a specific crystal structure, named after the mineral with that structure. When used to create solar cells, they have shown potential for high performance and low production costs. Perovskite solar cells have shown remarkable progress in recent years with rapid increases in conversion efficiency, from reports of about 3% in 2006 to over 25% today. While perovskite solar cells have become highly efficient in a very short time, a number of challenges remain before they can become a competitive commercial technology. Much of the recent work on Perovskite solar cells has been dominated by absorber materials based on methylammonium lead halide. Although perovskite materials have been studied for more than a century, initial studies on methylammonium lead halides for semiconductor applications started in the past two decades. Initial applications of perovskite absorbers in solar cells occurred in 2006 and were published in 2009. However, these cells were not very efficient (less than 4%) and were not stable, since they relied on a corrosive liquid phase that slowly disrupted other layers within the device. By 2012 the liquid-phase components had been replaced with solid-state contacts and the efficiency was improved to 10%. Subsequent improvements in performance and stability have come through continued investigation of new materials, new device architectures, and improved fabrication processes, leading to a reported 20% cell efficiency in 2014. The Solar Energy Technologies Office (SETO) has identified four primary challenges that must be simultaneously addressed for perovskite technologies to be commercially successful. Each challenge represents a unique set of barriers and requires specific technical and commercial targets to be achieved.

The basic challenge framework is shown below, including examples of prior and current project efforts that address each challenge.

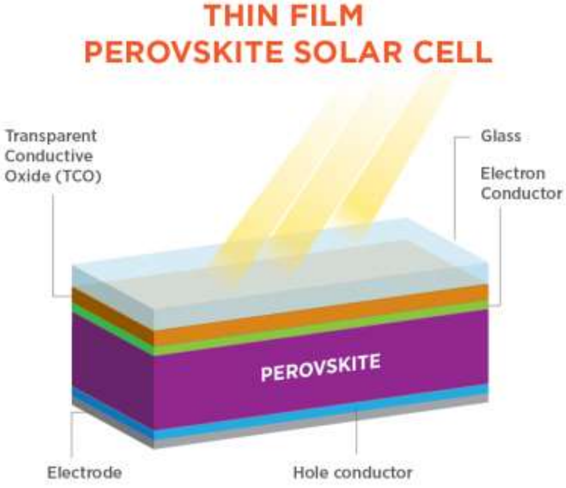
(2.1) Power Conversion Efficiency

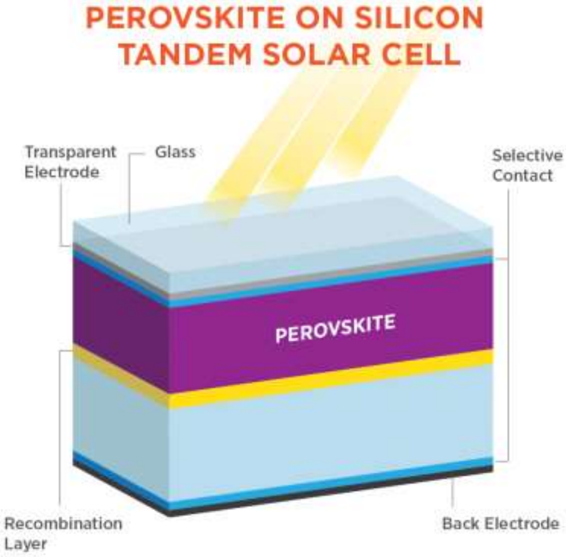
Perovskite devices have exceeded all thin-film technologies, except III-V technologies, in power conversion efficiency, showing rapid improvements over the past five years. However, high-efficiency devices have not necessarily been paired with viable stability and fabrication characteristics. For large-scale terrestrial deployment of perovskites, maintaining these high efficiencies while achieving stability and scaling will be necessary. In the meantime, continued improvement in efficiency by itself could be valuable for mobile, disaster response, or operational energy markets where lightweight, high-power devices are critical.

Perovskites can be tuned to respond to different colors in the solar spectrum by changing the material composition, and a variety of formulations have demonstrated high performance. This band gap flexibility opens up another useful application for perovskite solar cells in high-performance tandem device architectures, with potential power conversion efficiencies over 30%.



In these structures, perovskites are combined with another, differently tuned absorber material to deliver more power. Perovskite solar cells of certain compositions can convert ultraviolet and visible light into electricity very efficiently, meaning they might be excellent hybrid-tandem partners for absorber materials such as crystalline silicon that efficiently convert infrared light. It is also possible to combine two perovskite solar cells of different composition together to produce a perovskite-only tandem. Doing so could lead to even higher efficiency and more cost-effective tandem photovoltaic (PV) applications. Perovskite-only tandems could be particularly competitive in the mobile, disaster response, and defense operational energy areas, as they can be produced on flexible substrates with high power-to-weight ratios.





(2.2) Stability and Degradation

Perovskite solar cells have demonstrated competitive efficiencies with potential for higher performance, but their stability is quite limited compared with that of leading PV technologies: They don't stand up well to moisture, oxygen, extended periods of light, or high heat. To increase stability, researchers are studying degradation in both the perovskite materials and the contact layers. Improved cell durability is paramount for the development of commercial perovskite solar products.

Despite significant progress in understanding the stability and degradation of perovskite solar cells, current operational lifetimes are not commercially viable. Mobile markets may tolerate a shorter operational life, but stability during storage (prior to use) is still a key performance criterion for this sector. For mainstream solar power generation, technologies that cannot operate for more than two decades are unlikely to be viable regardless of other benefits.

Early perovskite devices degraded rapidly. A few years ago, typical perovskite devices would degrade within minutes or hours to non-functional states. Now multiple groups have demonstrated lifetimes of several months of operation. For commercial, grid-level electricity production, SETO is targeting an operational lifetime of at least 20 years, and preferably more than 30 years.

The perovskite PV R&D community is heavily focused on operational lifetime and is considering multiple approaches to understand and improve intrinsic and extrinsic stability and degradation. Efforts include improved surface passivation of absorber layers; alternative materials and formulations for absorber layers, charge transport layers, and electrodes; and advanced encapsulation materials and approaches that mitigate degradation sources during fabrication and operation.

One issue with assessing degradation in perovskites relates to developing consistent testing and validation methodologies. Research groups frequently report performance results based on varied test conditions, including variability in encapsulation approaches, atmospheric composition, illumination, electrical bias, and other parameters. While such varied test conditions can provide insights and valuable data, the lack of standardization makes it challenging to directly compare results and difficult to predict field performance from test results. This affects the entire perovskite research and development (R&D) community, independent of any specific research area, material set, or stability improvement approach.

(2.3) Manufacturability

Scaling up perovskite manufacturing is required to enable production of perovskite solar cells. Making the processes scalable and reproducible could increase manufacturing and allow perovskite PV modules to meet and potentially exceed the office's levelized cost of electricity targets.

The cells are thin-film devices built with layers of materials, either printed or coated from liquid inks or vacuum-deposited. Producing uniform, high-performance perovskite material in a large-scale manufacturing environment is difficult and there is a substantial difference in performance between small-area cell efficiency and large-area module performance. The future of perovskite manufacturing will depend on solving this challenge, which remains an active area of work within the PV research community.

Various methods have been used to produce lab-scale perovskite devices. Many of these methods are not easily scalable, but there are significant efforts to apply highly scalable approaches to perovskite fabrication. For thin-film technologies, these can be split into two major types of production line:

Sheet-to-Sheet: Device layers are deposited on a rigid substrate, which typically acts as the front surface of the completed solar module. This approach is commonly used in the cadmium telluride thin-film industry.

Roll-to-Roll: Device layers are deposited on a flexible substrate, which can then be used as either an interior or exterior portion of the completed module. Researchers have tried this approach for other PV technologies, but it did not gain significant commercial traction owing to barriers to obtaining high solar conversion efficiency (independent of the fabrication approach). It is, however, widely used to produce photographic and chemical film and paper products, such as newspapers.

The scalability of these fabrication approaches gives perovskites the potential to enable faster capacity expansion relative to silicon photovoltaics. The processes under consideration are well established in the film and display industry, making the knowledge and supply chains around the tooling and components easily leveraged to further reduce scaling costs and risk.

Additional barriers to commercialization are the potential environmental impacts related to the perovskite absorber, which is lead-based. As such, alternative materials are being studied to evaluate, reduce, mitigate, and potentially eliminate toxicity and environmental concerns.

(2.4) Technology Validation and Bankability

Validation, performance verification, and bankability—ensuring the willingness of financial institutions to finance a project or proposal at reasonable interest rates—are essential to the commercialization of perovskite technologies. Variability in testing protocols and minimal field data have limited the ability to compare performance across perovskite devices and to develop confidence in long-term operational behavior.

Current testing protocols for solar PV devices were developed for the existing mainstream PV technologies. These use indoor testing using protocols validated based on decades of correlation to outdoor performance. They may not be good predictors of the long-term outdoor performance of new PV technologies. Objective, trusted validation using test protocols that can adequately predict long-term outdoor performance is critical to obtaining sufficient confidence in perovskite technologies to enable investment in production scale-up and deployment. The rapidly changing material and device compositions of perovskite solar cells make this standardized validation particularly challenging and important.

(3) Benchmarks and Targets

To monitor progress in the R&D and manufacturing SETO communities and engages with potential interested entities, investors, financiers, and end users to create benchmarks and targets for the commercial deployment of perovskite photovoltaics for the bulk-power generation market. These benchmarks and targets will likely evolve with increased understanding of what will enable the manufacture and deployment of perovskite photovoltaics at the gigawatt scale.

Various materials, device structures, and manufacturing techniques are being pursued, and it is unclear which of these approaches is the most promising. The targets for single-junction perovskite cells and modules will be different than those for hybrid perovskite tandems and all-perovskite tandems. What follows are some generalized early-stage targets relevant to spurring perovskite PV commercialization. Later-stage targets are under development and will be published in the future.

As perovskite PV is commercialized, there must be balance among demonstrating high power conversion efficiency and high stability, utilizing scalable manufacturing processes, and scaling from individual cells to multi-cell modules with larger active areas. The targets provided here are for modules rather than cells. Some loss in active-area efficiency is inherent in scaling up from cells to modules. For perovskite PV technology to move toward commercial viability, power conversion efficiency targets between 18% and 25% are necessary at the early stages, demonstrated with multi-cell modules that range from tens of square centimeters to square meters. More than half the layers (including the perovskite layer) in the device stack should be deposited with scalable deposition techniques at relevant throughputs or deposition speeds for high-volume manufacturing. Initially these modules should be able to demonstrate operational stability, retaining 80% to 95% of their original output after 1,000 hours of accelerated testing. These figures will need to further improve in the future to be representative of the desired decadal operational lifetime. In the meantime, these targets provide a useful metric to help the perovskite community to increase reliability.

(4) Conclusions

As per the research study put forth by Finland University of Technology, India has great potential to move into a fully renewable electricity system by 2050. This is possible if we can employ sophisticated technologies. Renewable energy’s development in India looks bright as around 293 global and domestic companies have committed to generate 266 GW of solar, wind, mini hydel and biomass-based power in India over the next decade.

In such a scenario, a bright and sustainable future beckons both for sustainable energy growth and employability. The renewable energy sector creates a lot of jobs at all levels, especially in rural India. India has limitless renewable energy to bridge the gap between demand and supply so we must persistently put in efforts to harness various forms of renewable energy sources by employing newer technologies to form a clean and safe place for generations to come.

Rising global demands for energy, combined with the rapid depletion of fossil fuels, has led to increased interest in renewable energy sources over the past decades. From a purely economic standpoint however, silicon solar cells are not yet competitive with fossil fuel sources. Further reduction in the cost of solar energy is required to increase the market share of this technology. This reduction in the cost of solar energy can be achieved through the development of new solar cell materials and device concepts. A number of alternatives to silicon-based cells are being investigated, aiming at the development of photovoltaic devices with relatively high conversion efficiency at lower costs.

Perovskite solar cells are widely considered the most promising new solar cell technology. Their PCEs can rival those of silicon-based solar cells, at considerably lower cost, and they are suitable for numerous sustainable solar energy applications. They can also be used in tandem with other solar cell technologies, such as Si or CIGS, resulting in high-efficiency, cost-effective solar cell devices.

These emerging solar cell technologies however are still not commercially available in large volumes. Disadvantages such as the relatively low efficiency and stability of these cells compared to silicon-based solar cells pose a hindrance to their commercialization. Current research efforts are focused on overcoming these obstacles through the development of novel materials, processing techniques, and device architectures. The outcome of these research efforts are expected to unlock the potential of emerging solar cell technologies and lead to their future commercialization.

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