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# Perovskites: An *E*merging *T*echnology in *S*olar *S*pace

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## ABSTRACT

The extent of interest which Perovsite technology is generating in solar research space is unprecedented. And there is a genuine rationale behind that. In the last one decade, the progress in efficiencies exhibited by Perovskite Solar Cells (PSCs) has gone up manifold. This is an outcome of the intensive research being done by various research organizations on efficiency enhancement of the PSCs and the various solar companies which are trying to bring this technology closer to large scale commercialization. The wide belief is that perovskites will be less expensive compared to conventional technology. While the perovskite technology is demonstrating a sea of opportunities, there is still a journey to cover. There are multiple research gaps on the road to commercialization of the perovskite technology which need to be addressed. The more important amongst them are durability and stability, rapid degradation due to UV, dissolution issue due to water exposure, degradation through oxygen and hysteresis behaviour. Having said that, the pace of research in solar space has been much faster compared to any other technology transformations the world has seen. And global warming and climate change related studies are further necessitating this pace to accelerate further. This article gives a brief history of perovskite, its technological progression, the research gaps as they stand today and what the future holds for this technology. Looking at the progress in perovskite technology, the world may not be far away from seeing a disruption in solar space.

## Introduction

The name perovskite was given to honour the Russian mineralogist L.A. Perovski [23, 24, 25, 26] who first decoded the structure of this mineral and stated it as calcium titanium oxide (CaTiO3). Its discoverer Gustav Rose, in 1837, named this material in honour of Perovski. The chemical formula of the perovskite material is XYZ3, where X is a cation with a large radius, Y is a metal cation, and Z is an anion. It is a stable structure and exhibits flexibility to adapt to a variety of elements. Depending on the choice of material used, the desired property can be obtained. This helps researchers to achieve excellent structural properties which can support a variety of applications. Later, in 1892, the first synthesis of cesium lead halide perovskite material was done which formed the basis of the chemical composition of modern Perovskite Solar Cell (PSC). The research continued on perovskite materials but it is actually the last one decade or so that research scholars actually started believing that perovskites exhibit very unique optical and electronic properties such as an extraordinary absorption coefficient which make them suitable for utilization in the solar ecosystem, especially in solar cells architecture. These properties are so unique that they lead to increasing efficiency of solar cells, result in lesser costs of production of solar energy and thus make them strong candidates for research [1, 2, 27, 28, 29].

## Principle of Perovskites

While the perovskite structure may look simple, the strength of this family is that they exhibit a wide variety of groupings or combinations. The original composition found was a combination of calcium, titanium and oxygen, with the formula of CaTiO3. But as researchers went deeper into the perovskite model, they mentioned that anything that had the XYZ3 model can be said to be part of the perovskite family, where X, Y, and Z can represent a combination of different organic and inorganic ions. Depending on the atoms / molecules, perovskites exhibited an interesting variety of properties. Researchers noted combinations using fluorine, chlorine, hydroxides, and the list goes on. Natural perovskites are few in numbers and can be counted very easily. But what are actually making headlines today and have become a matter of great research interest are the synthetic perovskite materials. There are various combinations of these, some being metallic, organic–inorganic, based on noble gas, non-metals, and so on. As per literature, there are now around couple of hundred structures of perovskites making waves in materials space. And out of these, the lead metal halides are the ones where lot of energy is being focused as they are on the top of the efficiency table in solar cells. Researchers continue to find newer and interesting structures while focusing on improving the efficiency of solar cells and making them commercially feasible [1, 2, 27, 28, 29].

## Perovskites in Solar Cell applications

How do perovskite materials make electricity. Fundamentally all solar cells make electricity in the same way. An incoming photon knocks an electron far enough out of place such that it does not immediately fall back in, generating an electron-hole pair. The electron and the hole then travel through the electrical circuit to power our equipment or any other connected electronic device. When the sunlight photons are captured, it leads to a natural flow of electrons in the system. This process of flow of electrons is called as photovoltaic effect [40, 41]. When these electrons tend to exhibit a movement in one direction, this generates a current. The extent to which this current gets generated is proportional to the extent to which the photons are captured. When the electrons get to know about a nearby energy band, it tends to get a chance to lose energy. And in that process, electricity gets generated. When the electrons and holes reach their respective electrodes, the circuit is completed [42, 43].

And Perovskite technology is no different. They have various minerals in the crystals which conduct charge when they are hit by light. These solar cells can also take liquid form and at the same time conduct electricity. This is the precise property which is drawing the attention of researchers worldwide for solar applications [44, 45].

## Perovskites Compared to Conventional Technology

The largest number of solar panels today are made of silicon. However, their efficiency by & large does not surpass 25% even in case of the best of the panels [1]. There is also a challenge in terms of cost of such panels. The process to remove impurities from silicon needs high temperatures which make the process difficult. These are some of the reasons why the industry is seeking alternatives for silicon. The table below gives a comparison on how perovskite technology fares in comparison with silicon as they stand today.

| Parameter | Crystalline Si | Perovskite |
|---|---|---|
| **Cost** | Higher | **Economical** compared to crystalline Si. And the reason here is their edge in capturing photons and producing more solar energy [2, 3]. |
| **Weight** | Higher | **Lighter** [30]**.** |
| **Durability** | Higher | **Lower as it stands now** [4, 5, 6, 7, 8, 30]. |
| **Flexibility** | Less | **More flexible** [30].<br>It is this property which is now being explored. The band gap of silicon based solar cell structures can be increased by the use of perovskites. A thin film of perovskites is inserted in silicon based cells which makes it easy to absorb higher number of photons. |

| Parameter | Crystalline Si | Perovskite |
|---|---|---|
| **Efficiency** | General range between 20-25% | **Improving day by day.** Trend on efficiencies is given in tables on following pages. Perovskites may soon become much more competitive compared to conventional cells [1]**.** |
| **Strength** | More | **Weaker** [30].<br>Their slender crystalline structure has a direct bearing on their robustness. |
| **Invasive** | Bulky Silicon Panels | **Less invasive.** Fits all shapes. |
| **Large scale deployment and Operating Experience** | Proven Technology | **Emerging Technology.** Commercial deployment yet to be evidenced on large scale. |
| **Shelf life** | Long | **Shorter shelf life.**<br>A big challenge in these cases is how to retain their stability, even under normal environment. Perovskites have an affinity for water and dissolve. Silicon is much more heat-resistant and temperatures in solar environment is bound to be high. More details are given in the paper. |
| **Aesthetics** | Bulkier and clearly stand out. | **Aesthetic.** |
| **High-Temperature Tolerance** | Yes | **Needs improvement and research.**<br>In a solar environment and burning sun, temperatures are bound to shoot up. At times, the temperatures can even reach 80+ degrees Celsius. Here, the situations start deteriorating. |
| **Environmental Issues** | No | **Moderate.** Use of lead in perovskite cells is a cause of worry. Issues need resolution before commercialization. [31, 34, 35] |
| **Method of preparation** | Silicon needs to be refined in high temperature furnaces. The objective here is to remove quartz impurities and make the material robust. | Compared to Silicon, the perovskite preparation techniques are relatively easy, possible at moderate temperatures. And of all, they are comparatively inexpensive as they need much less energy. Only low cost salt solutions are needed for manufacture [36, 37, 38, 39]. |

## Power Conversion Efficiency Trends- Perovskites

NREL data was tabulated to study the progress on efficiency front by perovskite based technologies vis-à-vis conventional solar cells [46]. It can be noted that while perovskite technologies are relatively young, the pace of improvement shown by researchers in Perovskite technologies has been noticeable. The last decade especially has seen a rapid rise in the reported efficiencies of Perovskite Technologies, and they are now reaching the efficiency levels of conventional technologies. And the way research is evolving, they may soon march ahead of conventional Si cell efficiencies.

**Table 1: Efficiency trends of solar cells [Source NREL] [1, 46]**

| Year | Cystalline Si | Perovskite Cells | Perovskite / SI Tandem [Monolithic] | Perovskite / CIGS Tandem [Monolithic] |
|---|---|---|---|---|
| 1977 | 14 | | | |
| 1980 | 16 | | | |
| 1985 | 20 | | | |
| 2000 | 21 | | | |
| 2005 | 22 | | | |
| 2010 | 24 | | | |
| 2011 | 24 | | | |
| 2012 | 24.7 | | | |
| 2013 | | 14.1 | | |
| 2014 | 25.6 | 20.1 | | |
| 2015 | 25.1 | 15.6 | | |
| 2016 | 26.6 | 22.1 | 23.6 | |
| 2017 | 26.1 | 22.7 | | |
| 2018 | | 23.7 | 28 | 22.4 |
| 2019 | 26 | 25.2 | 29.5 | 23.3 |
| 2020 | | 25.8 | 29.5 | 24.2 |
| 2021 | | | 29.8 | |
| 2022 | 26.8 | | 32.5 | |
| 2023 | | | 33.2 | |

Quantum Dot Cells are also gradually using perovskites to enhance efficiencies. Details of the reported data based on this technology is also given below. Here as well, we can see a jump in the efficiencies in last few years.

**Table 2: Efficiency trends of Quantum dot cells (QDC) [Source NREL] [1, 46]**

| Year | Cell Type | Detailed description | Efficiency [%] |
|---|---|---|---|
| 2017 | QDC | lead halide perovskite quantum dot films | 13.4 |
| 2018 | QDC | mixed caesium and formamidinium lead tri-iodide perovskite system [Cs1−xFAxPbI3] | 16.6 |
| 2020 | QDC | Perovskite based on the BHT Additive | 18.1 |

Perovskite based technologies are yet to be fully commercialized and there is hardly any official data available on this.

## Levelised cost of Energy (LCOE)

The LCOE gives an indicative assessment of the net present value of unit-cost of power for the full life of the power-generating asset i.e. over the total power output [65, 66]. Since the Perovskite technology is not yet fully evidenced on large commercial scale, there are various research reports which are predicting the cost of LCOE of perovskite technology compared to that of conventional technology. While these reports are in various geographies, it still gives us an indication of the relative magnitude of costs where perovskite stands compared to conventional technologies.

1. *Cai, M et al* in their paper have compared LCOE based on coal, natural gas, hydropower with that of Perovskite technology. They designed module structures for PSCs in order to build a cost comparative. The paper gives an edge to perovskites compared to other solar PV technologies. And increase of efficiencies could reduce module cost further. Reference was also drawn to conventional energy costs reported in Annual Energy Outlook 2015 by United States Energy Information Administration. As per the paper, the LCOE of PSC would fall in the range of 30-45 USD / MWH while that of nuclear power was over USD 90 / MWH and coal in the range of USD 90-120/MWH. [2]

2. Solar Square mentions that the price of a polycrystalline silicon solar cell in India will be nearer to Rs. 25.5/watt, and the price of a monocrystalline cell will tend to be around Rs. 31/watt. As against that, the price of a Perovskite cell could be in the range of Rs. 12-13 per watt and with further advancements in research, the prices may go down further [47].

3. *Kajal, P et al* has described about LCOE of carbon-based perovskite modules in their paper. As per their calculations, the LCOE in case of PSC technology varies from US$ 0.034 to 0.016 $kWh^{-1}$ for module. They go on to state that these numbers are comparable to the conventional silicon panels [48].

While all these are indicative analysis, it can be inferred that the solar persovskite technology LCOE will gradually develop a favourable edge over conventional solar technology. And as the efficiency improves further, the gap will widen even further, thus giving PSCs a substantial commercial edge.

## Discussion: Challenges in commercialization of Perovskite Technologies

While scientists and academics are deliberating on Perovskite technology for some time now, the last decade has seen significant interest in this space [49]. The important element here are the inexpensive materials that they use, which are available in plenty [50]. Despite the improvement in efficiency evidenced, there are still some challenges which need to be resolved [44, 45].

Following are some of the challenges that need to be addressed for perovskite technologies so that they can move towards large scale commercialisation.

### Lead Pollution

These cells use a lead-based absorber. Efficiency improves due to lead [31,32, 33, 34]. However if lead finds its way to the surrounding environment, this may cause harm. In case there is a device failure, it may get washed into the soil and can go into the food chain [32, 33, 34] which can have serious repercussions. The options to stop seepages in case of glitches in solar cells are not full-proof. The risk of lead pollution exists. This is becoming a major obstacle to commercialization of the PSC technology.

To address this issue, various engineering solutions are being discussed on how to stop lead from penetrating the surroundings in case of a malfunction. Methods like Phytoremediation, Bioremediation, Gravity Setting Chambers, etc. can help trap small lead quantities, if discharged [52].

*Horvath et al* are working on a method of using phosphate salts to mitigate the risk of lead discharge [53]. These salts react with lead and form an insoluble compound. The advantageous optoelectronic properties of the device are also not impacted and the compound does not go to the surroundings mitigating the risks and helping achieve commercialization [54, 55, 56].

## Hysteresis behaviour in Perovskites

Hysteresis behaviour which has been impacting perovskites commercialization severely [4, 5, 17]. This is a sign of steadiness of electrical output. This in turn selects suitability of a material as a source of electricity. If the J-V curves obtained during forward voltage scan differ significantly from the reverse one, then this behaviour represents a challenge for researchers, especially on power conversion efficiency front [66]. Researchers have been working on this issue for some years now [57].

As per various papers, some of the factors which are impacting the hysteresis behaviour are device architecture, type of interface charge-transporting layers, the structure of perovskite layer [4, 5]. One more aspect which impacts is electrical bias [58]. MAPbI3 devices is one emerging option which is being developed by researchers to address this issue. It uses the all-organic transport layers and as per researchers, the hysteresis behaviour related issues are getting somewhat addressed [18, 19, 58]. There is still a knowledge gap to be bridged on hysteresis behaviour in perovskites which needs to be addressed to move forward to commercialization.

## Stability in Perovskites

Researchers are trying to address the stability aspect of Perovskites in solar cells. Some of the aspects which they are working on include structural modifications, new ingredients and new manufacture methods [5]. Operating tenure under normal environmental conditions also is another area to be addressed [4, 6]. Soft nature of perovskite materials could be the reason behind this issue. The weak Van der Waal forces and weak hydrogen bonds make things a bit unstable [18]. Factors such as moisture, oxygen entry, UV light, thermal treatment, and light also impact stability [4]. Degradation happens even under normal conditions. As per *Bass et al.,* perovskite crystallization may be controlled by addressing the humidity issue [7, 8]. UV frequencies are also known to cause degradation, though there has been some improvement on this front [9]. Pure oxygen is another area of concern. They remove hydrogen atoms from the perovskite organic components, especially at higher temperatures.

While research has led to some increase on stability front, a lot more is yet to be desired. It is believed that stability should be at least 10 years. Aspects like structural strategy, use of different ingredients, different electrode materials and encapsulation procedures are being looked at to address the issue [4, 10, 11, 13].

Researchers have found out that oxygen can help address some of the shortcomings in perovskite crystals. This is done through the process of passivation. This process also helps to improve performance by addressing some of the shortcomings. Degradation issue is also addressed in this process [4, 14, 15, 16].

Atmospheric moisture is another research subject to be addressed as they have affinity for water [7]. There are some benefits of moisture as well such as improvement in lifespan [4, 8, 18]. There still exists a research gap in Perovskite stability which needs resolution.

## Fabrication Processes in Perovskites

Another area to be addressed is its fabrication process. Manufacture of perovskite solar cells at a large scale under normal conditions is still an area to be addressed [69]. It is observed that deterioration happens when the devices are used under normal conditions. Research is going on to address this issue [36, 37, 38]. A similar issue is that of thermal stability of perovskite cells. High temperatures lead to degradation. Solar panels operate at extreme temperatures in the sun and get exposed to very high temperatures.

Jiang et al have worked on the process and identified a gentle gas-quench method to address some part of the issue. As per the paper, these cells were able to maintain higher efficiencies at 65°C for a sizeable timeframe [39]. However, to summarize, there still exists a gap in Perovskite fabrication process which needs resolution.

### Sandwiching ferroelectric material between paraelectric superlattice structures

*Yun Y et al* presented this novel approach of sandwiching for substantial improvement in photocurrents. This was done in a superlattice form. It led to substantial improvement in efficiency. A large dielectric permittivity and lowered band gap has also a role to play in this as per researchers [59].

A sandwiched electrode buffer also supposedly bridges the perovskite absorber to metal contact. It also passivates multiple defects including mass loss and safeguards this material from moisture. This aspect addresses various aspects pertaining to efficiency, stability and brings PSCs closer to commercialization [59]. Various scientists are working on overcoming these shortcomings and make PSCs a great success [6].

### Tandem silicon-perovskite cells

In this, the cells are set with suitable band gaps. The process of manufacture of a tandem cell contains numerous added treatments. The objective here is to lead to better efficiency as well as enhanced stability [8, 60]. Work is still going on in the field of tandem solar cells [4].

This is a convincing method for decreasing thermal loss during transformation of solar energy. In this, two absorber layers are unified. If the interconnecting layers are properly addressed, better efficiencies can be expected. Researchers mention that the efficiencies here should be around 30% and the lifespan of 16 years for these to compete with conventional technologies [4, 8].

### Interfacial engineering and modulators to prevent ion migration

In order to enhance the efficiency of PSCs, a method named interface engineering is being used as part of the antisolvent deposition process. *Wang M et al* in their research report in September 2020 mentioned about their experiment. In the experiment, they inserted a small molecule between the perovskite layer and the hole transport layer. This led to formation of a cross-linkage bridge. The molecule which they inserted was an alcohol-soluble small molecule, namely 2-mercaptoimidazole [61].

The cross-linking bridge sustained in augmenting the hole transmission. It also helped subdue interfacial recombination. It is reported that this led to formation of hysteresis-free devices with a higher efficiency of 20.68%. Performance of the devices also improved and showed better environmental stability. This research may lead to a good hope in commercialization of inverted PSCs [61].

## Emerging uses of Perovskite Technologies

Perovskite are yet to reach a large scale commercialization stage. Various research questions are yet to be addressed. But in parallel, some applications which are being looked at are listed below:

### Perovskite in IOT

Aided by solid research, perovskite layers have so far improved the ability to withstand UV. They can easily absorb visible bands [42]. And efficiencies are improving day by day [62, 63]. It is now believed that this technology will play a major part in photovoltaic devices used in the residences. LEDs are the major source of light here and halide perovskites will play the role of key differentiator in IoT. It is believed that hundreds of thousands of items will be linked by this technology in years to come. And perovskites can become a major source of energy inside homes and commercial establishments. This can provide a robust charging technique for indoor devices [70, 72]

### Light films and Solar Paints

Due to lesser mass and flexibility in thin film perovskite construction, there are major chances to deploy this technology in vehicles. Drone Integrated Photovoltaics is being pursued. This can be used in monitoring climate conditions. Battery electric vehicles are being researched [71]. Another area where the perovskite technology can be deployed are solar paints. Because of their flexibility, they can be easily deployed over houses, roads and electricity can be generated.

## Conclusion

Perovskite solar power is yet to come in the mainstream, primarily because this material is yet to be perfected. There are various research gaps which exist in this technology as of today. Several questions are yet to be answered but work is going on in various research institutions to increase stability, efficiency, and to find the winning formula. Solar space has been a unique technology. Over the last few decades, it evolved at a pace much faster than any other technology, be it cost or technology or efficiency. Not long ago, solar panels were at the same stage where perovskite technology is there today. So there is no reason to disbelieve that perovskites will soon cross all hurdles and achieve the milestone of commercial success. A lot of work has already been made in this space. And researchers are addressing this in various directions. Enclosing the perovskite in glass or plastic, newer compounds to strengthen the perovskite framework and making it more resistant to structural changes brought on by heat are some milestones in this journey which one would never have thought in the past. Perovskite will translate into increasing accessibility, affordability, and efficiency of solar energy. The inherent benefits of this technology such as being lesser expensive, easier to operate more than outweigh the shortcomings. The pace of change made by researchers in the last few years makes the belief stronger that this technology will transform the energy industry without doubt, much sooner than expected. If supported by industry and associations, perovskite will become an answer to address the climate change challenges.

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