Review of an Emerging Solar Energy System: The Perovskite Solar Cells and Energy Storages

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It is extremely important to achieve maximal efficiency of an alternative energy system, as such; it provides the maximum power output. In order to be maximally efficient in utilizing the available energy, researchers will study several key factors that can enable the best sustainable energy in terms of utilizing alternative energies. They have studied several methods to design the best-distributed energy system which implements the alternative energies, energy storage, and the advanced materials for the alternative energy generation. In terms of the solar photovoltaic technologies, e.g., researchers have studied the perovskite solar cells. Perovskite solar cells are highly favored for their wide, tunable band gap and solution process ability. Stellar rise of the perovskite solar cells application partly attributed to factors like high energy efficiency. These factors include innovative design such as the tandem structure, tunable band gap, and encapsulation for each layer. At present, their single-junction efficiencies are comparable to those of multi-crystalline silicon, cadmium telluride and copper indium gallium selenide. Finally, researchers have studied an energy storage system at a capacity of 3MegaWattHour. This system can enable a maximum energy output that entails a system including such key factors as the alternative energy generation, energy storage, and an advantageous distributed energy system.

Introduction

Authors employ this article to investigate and review several insightful indicators related to the current alternative energies [AE]; AE technologies and their application have been of tremendous interest and of great importance in reducing the climate changes referring to Clark *et al.* [**1,2**]. The alternative energies have been established that is recorded firstly in the 1978s in the United States [**3**].

In response to the pressing need in the carbon economy and climate changes in recent years, AE generation and strategic commercial interests lead to significant advances over the past decades in clean technologies [**1**], also known as Clean Technology. Key resources of alternative energy generation include the following: solar, wind, hydro, tidal, and geothermal biomass, hydrogen fuel cell, thermal energy conversion, nuclear energy, and ocean energy conversion technologies, etc.

The great endeavor in research and development has been dedicated to improving the output of the distributed energies. In order to adopt these technologies, it is imperative that the power output has good stability, high efficiency, and superior energy management. This article is dedicated to these technologies.

Moreover, there are huge endeavors dedicated to wisely study the alternative energies over prior two decades; with noteworthy commercial application on a large scale. There are interesting technologies and exciting ones that have recently emerged. It is hopeful that the variable power generation, with the advent of plentiful energy storage, can be sufficiently utilized more than it has been so far [**4**].

As an example, authors will study both solar power and energy storage from the supply side in this article. Solar photovoltaic (PV) cells are promising for clean energy sources as demonstrated in the NREL database [**5**]. The solar energy may have significant power output and efficiency, but it must be managed with the load-leveling so that its output is suited to the demand profiles. The energy output, a modeling database (library), and data analysis can be consequently fed into a smart grid. The smart grid may respond to demand request employing various conditions including energy storage, sources, and electrical reliability [**1**].

The top-three prevailing types of solar cells for the commercialized solar cells are based on polysilicon, single crystalline silicon, and amorphous silicon (thin film). The impacts of the first-generation PVs are as follows:

1. Polysilicon is the most popular; its efficiency ranges from 13% and up in the field to 18% in the lab;
2. Single crystalline silicon solar cells have higher efficiency, that is from 14% and up in the field to 24% in the lab;
3. Amorphous silicon (thin film) is cheap; the efficiency is low. That is from 5% and up in the field to 13% in the lab.

The current state of the perovskite solar cells demonstrates as a rising star in solar cell applications which can be a potential technology disruptor. Researchers have discovered that the material advance in the perovskite solar cells are extremely exciting [**5**]. This advance can lower the cost in the solar power generation and has a promise future to accelerate the achievement of the grid parity for the energy distribution when the cost to utilize the clean technology is the same as the electric bill to use the grid power that is traditionally powered by the fossil-based fuel(s). The authors believe that the materials advancement in the near future can achieve the significant stability, the manufacturing capability, and lower cost than the present solar PV to meet the expectation on the solar renewable energy. The single-junction efficiencies of these perovskite solar cells are comparable to those of multi-crystalline silicon, cadmium telluride and copper indium gallium selenide. In this article, the authors will focus on their studies as follows: efficiency is high, stability is being addressed, and the manufacturing cost is projected to be easier thus the cost to be much lower.

The advancement of PSC is emerging as a promising leader of the next generation photovoltaic technology; that has achieved very high efficiency [**6-10**] and rapidly improved its stabilities in some case that, for example, has organic-inorganic perovskite interfaces [**8, 11-12**].

PSC advantages also include their widely tunable bandgaps [of the material]. The optimized bandgap of the perovskite-perovskite tandem photovoltaics has benefited the advancement of the efficient PSC in tandem structure [**13**] and interface engineering techniques [**11,14**].

One of the limitations for solar energy is that sometimes the sun is not shining enough or that there is no sunlight. To tackle the intermittent issues or unstable generation of the solar PV power generation, the solar PV power can be stored through one of the energy storage solutions.

In order to accomplish the smooth power output, a number of the energy storage technologies are available. Among various energy storage solutions, the Li-ion battery [**15**] is recently becoming one of the most attractive solutions [**16-19**]. Since Yoshio [**15**] created the first commercially viable lithium ion battery, the Li-ion battery has been greatly improved in recent years and extensively commercialized. The battery has reasonable cost and reasonably long life today, for example, the life time of a Li-ion battery can last from three years or 1200-cycles whichever comes sooner.

Finally, anything that can achieve an efficiency above or at a level of 26% that is the best efficiency of single crystal silicon solar cells [**6-10**] with sufficiently long life [**8**].

It may be very appealing success in the field of solar energy technology [**20,21**].

Methods and Results

Perovskite solar cell efficiency

The application of perovskite materials in photovoltaics can be traced back to the first discovery of photocurrent in $BaTiO_3$ in 1956 [**22**]. Subsequently, the photovoltaic effect in $LiNbO_3$ and other materials was also reported, which was mainly ascribed to the electric field formed on the surface of crystals [**23**]. However, the efficiency reported in those early studies was very low, usually below 1%. By 2012, photoelectric conversion efficiencies of 9.7% and 10.9% were achieved in perovskite solar cells based on $CH_3NH_3PbI_3$ and $CH_3NH_3PbI_3$-XClX [**24,25**], respectively, opening a new chapter in this type of third generation PV. In early 2013, a further enhancement in efficiency exceeding 12.3% was attained in low-temperature processed perovskite-based meso-superstructured solar cells [**24-26**]. Later that year, a sequential deposition method was reported for the fabrication of perovskite-sensitized mesoscopic solar cells, which enabled excellent photovoltaic performance up to a higher efficiency of 15% [**27**]. In the same year, the efficiency was further improved to 15.4% by incorporating vapor-deposited perovskite as the absorbing layer in a planar heterojunction thin-film architecture [**28**]. In early 2014, the efficiency was further increased to 16.7% using spiro-OMeTAD derivatives as hole-transporting materials [**29**]. Doping the TiO_2 electron transport channel layer to enhance the charge carrier concentration, and modifying the ITO electrode to reduce its work function, allowed higher efficiencies up to 17.9% [**30**]. By 2015, an efficiency reaching 20.2% was realized *via* deposition of high-quality $FAPbI_3$ films, involving $FAPbI_3$ crystallization by direct intramolecular exchange of dimethylsulfoxide (DMSO) molecules intercalated in PbI_2 with formamidinium iodide [**31**]. In 2017, the introduction of additional iodide ions into the organic cation solution was reported, to form perovskite layers through a process of intramolecular exchange which decreases the concentration of deep-level defects; this allowed a certified power conversion efficiency of 22.1% [**32**]. Furthermore, by utilizing a fluorene-terminated hole-transport material with a finely-tuned energy level [**33-40**], Jeon *et al.* [**33**] fabricated high-efficiency perovskite solar cells with a state-of-the-art maximum efficiency of 23.2% (under reverse scanning) and a steady-state efficiency of 22.9% for small-area devices (~0.094 cm^2) and 21.7% for large-area devices (~1 cm^2). Eventually, certified efficiencies of 22.6% (small-area cells, ~0.094 cm^2) and 20.9% (large-area cells, ~1 cm^2) have been established [**33**]. Thus far, one of the record efficiency of 23.3% was held by the National Renewable Energy Laboratory (NREL) [**5**], as shown in **Fig. 1** Perovskite solar cells can achieve widely tunable bandgap energies. One of the strategically tunable bandgap optimization methods is to modify the bond distance and/or angle of X-Pb-X where X is a halide element [**23,25,29**]. Extensive efforts are dedicated to enhancing the optical absorption by the modification of a bandgap of the perovskite MAPbI3 layer.

Large area perovskite solar cells

Another direction in perovskite research is to develop technologies to fabricate high-efficiency solar cells with large areas. Kim *et al.* [**3**] achieved a large-area (16 cm^2) single perovskite solar cell with an independently certified efficiency of 12.1%. An antisolvent spraying step realized a homogeneous and densely-packed perovskite film over a large area, and a metal grid was incorporated to remove the series resistance in the transparent conductor.

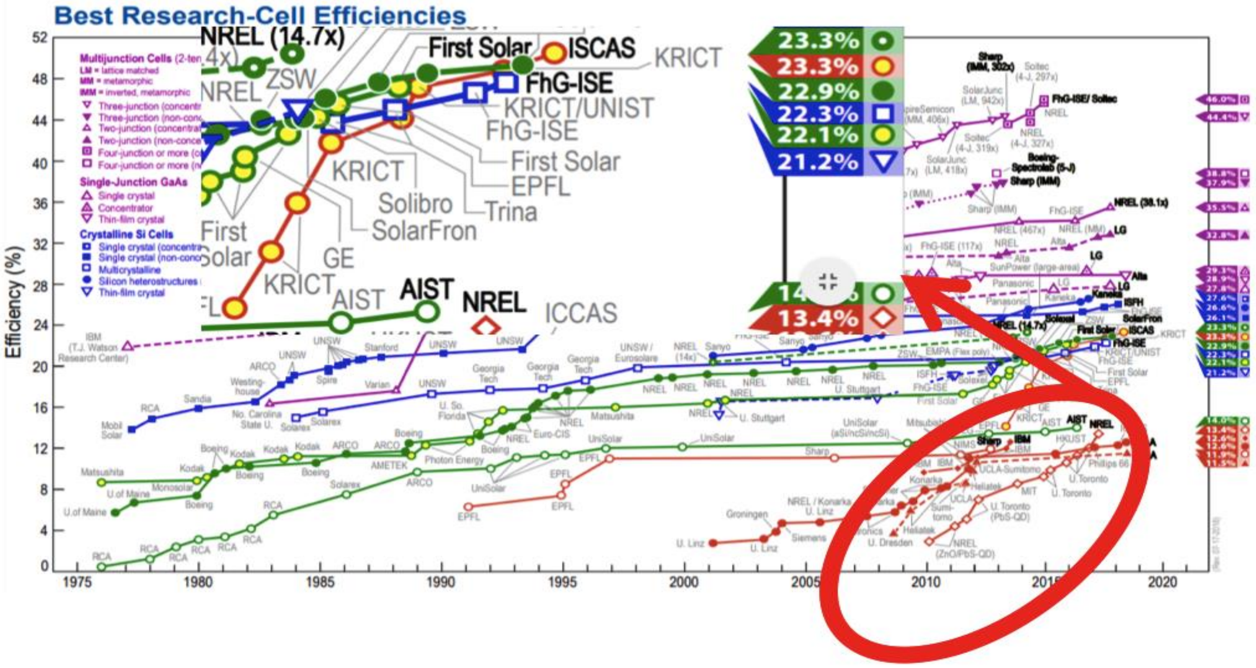

Fig. 1. Best research cell efficiencies from the National Renewable Energy Laboratory (NREL) database [5] a plot of compiled values of highest confirmed conversion efficiencies for research cells, from 1976 to the present, for a range of photovoltaic technologies. Authors acknowledge the courtesy permit from NREL.

Researchers have studied the impact of parametric conditions in the perovskite MAPbI3 film deposition and observed very interesting phenomena [**27**]. For example, the precursor temperature preceding the deposition can alter the bandgap for perovskite solar cells; they have found in this study that a film with a precursor temperature of 70°C shows an optimal band gap value (1.516eV) for solar cell applications. Moreover, when various processes are tuning by design, the reflectance data have demonstrated that varied fabrication techniques change the bandgaps [**28**] and that is studied in terms of the dielectric functions, optical bandgap, and optical absorption of the perovskite MAPbI3 films. The above variation has included such factors, for instance, differed spinning, evaporation, and various-solvent bathing. According to researchers, they have employed different deposition methods and processing techniques in the experimental design; the bandgap is studied to vary from 1.591 eV to 1.501 eV that is attributed to mechanisms such as different Pb-I orbital hybridization and spin-orbit coupling.

Han *et al.* [**41**]. employed a triple layer mesoporous TiO_2/ZrO_2/carbon as a scaffold on a halide perovskite $(5\text{-AVA})_x(MA)_{1-x}PbI_3$, which allowed a 10.4%-efficiency on an active area of 49 cm^2, within a module consisting of 10 serially connected cells (10×10 cm^2). Moreover, a soft-cover deposition (SCD) method was used to successfully fabricate a perovskite solar cell with a total device area of 51 cm^2; continuous processing in ambient air allowed a material utilization ratio up to ~80%, and a 17.6%-efficiency was verified using a 1-cm^2 aperture by Han [**42**], Stolterfoht *et al.* [**43**] applied PFN-P_2 and LiF as interfacial layers at the PTAA/perovskite and perovskite/C_{60} interfaces, respectively, to suppress recombination losses by 65 meV and 35 meV, respectively; hence the best efficiency of 20%, and a certified efficiency of 19.83% for 1-cm^2 cells is achieved. Lu *et al.* [**44**] modified the perovskite with cyano-substituted benzenethiol to enhance charge extraction and reduce charge recombination, thus increasing the efficiency from 19.0% (18.5%) to 20.2% (19.6%) with a 0.16-cm^2 (1.00-cm^2) aperture.

Stability enhancement of perovskite solar cells

Any stability issues in perovskite solar cells arise from the material properties on which they are based, which are affected greatly by humidity, temperature, and light. Their thermal and environmental stability can be significantly enhanced when mixed-cations are used in perovskite solar cells. Saliba *et al.* [**44**] introduced rubidium cations into perovskite solar cells to improve their reliability and photovoltaic performance; a 21.6% -efficiency was achieved in a 0.5-cm^2 cell area, and 95% of this efficiency was retained under exposure to standard light for 500 hours. Certified efficiencies reached 20.1% and 19.5% for 0.049-cm^2 and 1-cm^2 cell sizes, respectively, after Tan *et al.* [**45**] reduced the interface recombination and contact resistance via excellent passivation achieved on chlorine-coated titanium oxide colloidal nanocrystals. The solar cell also demonstrated good stability, with 90% of the initial efficiency retained under light irradiation for 500 h. Lee *et al.* [**46**] applied a customized thin-film encapsulation comprising a multilayer stack of organic/ inorganic layers deposited using chemical vapor deposition and atomic layer deposition; 97% of its original efficiency was retained under accelerated conditions of 50 C and 50% relative humidity for 300 h [**8**]. Saidaminov *et al.* [**47**] incorporated cadmium into a mixed perovskite lattice, thus releasing the remaining lattice strain, and further increasing the energetic penalty associated with vacancy formation (**Fig. 2A**). Significantly extended stability is exhibited in unencapsulated perovskite solar cells, maintaining > 90% of their initial efficiency after 30 days of storage in ambient air at a relative humidity of 50% (**Fig. 2B**). Better improvement has been attained on the life performance since then [**14**].

Authors should remark that the inorganic perovskite PSC has had rapid advancement in a few years and has played an extremely interesting role [**48-54**]. Solar cell efficiencies of devices using these materials have increased from 3.8% in 2009 to 25.2% in 2019 in single-junction architectures, and in silicon-based tandem cells, to 30% [**55**]. Several organic-inorganic-based perovskite materials have recently been developed with standard wet chemistry techniques which is done in a traditional wet lab. The hybrid perovskite, i.e., methylammonium and formamidinium lead trihalides, has been fabricated employing solvent techniques, such as spin coating, slot-die coating, blade coating, spray coating, inkjet printing, and screen printing, electrodeposition, and vapor deposition techniques. The afore-mentioned solvent techniques have the potential to be scaled up with relative good feasibility. Interested readers are referred to recent literatures on the interesting inorganic and Pb-free PSC [**49-54**]. The author's focus has been investigating a system via a typical systematic configuration and limiting this article with references to many excellent literatures for details.

Tandem perovskite silicon solar cell

The best efficiency of the single-junction perovskite solar cell is as high as 23.3%, but less than that of crystalline silicon (26.67%), meaning that it is difficult for the former to compete effectively with silicon-based solar cells in the mainstream PV market. Perovskite/silicon tandem solar cells have very high efficiencies as they are an attractive route to break the Shockley–Queisser limit of single-junction solar cells. In fact, Bailie group from Stanford University reported in 2015 [**56**] the use of a simple "mechanical stacking" approach to obtain a dual-junction

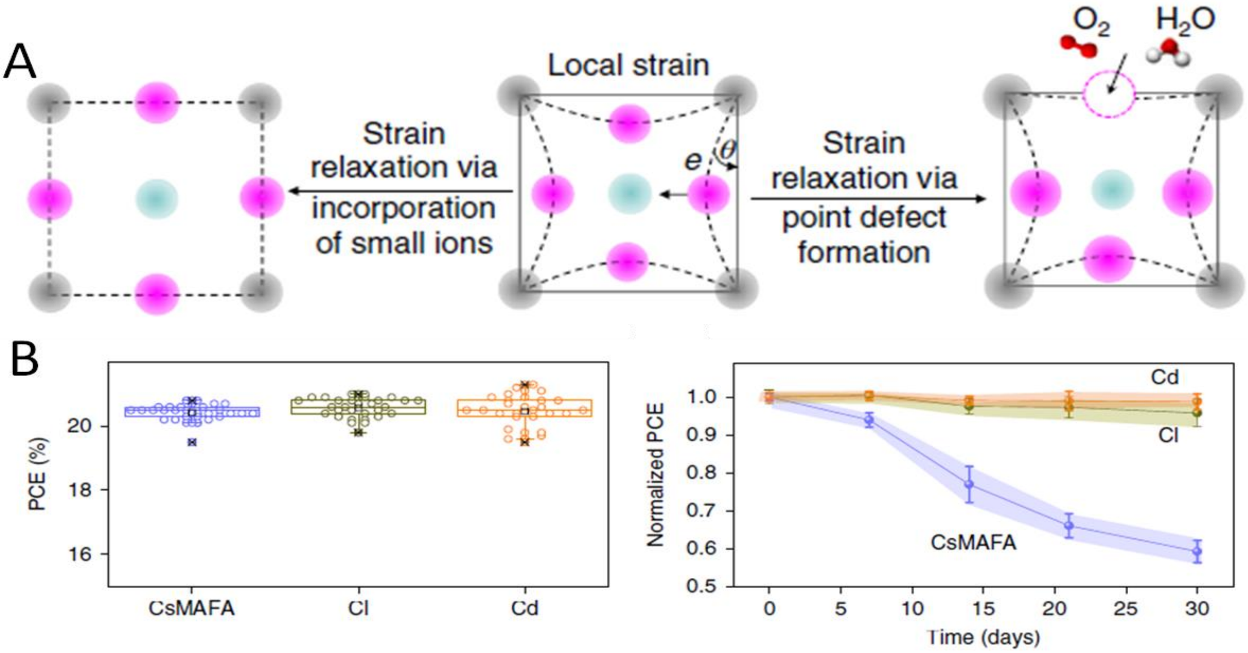

Fig. 2. (A) Mechanisms of lattice relaxation. (B) Power conversion efficiency performance of perovskite solar cell with and without dopants. Figure revised from the literature [48]. Authors acknowledge a permit from its Copyright Clearance Center.

tandem perovskite/silicon solar cell. By stacking a perovskite top cell of 12.7%-efficiency atop a low-quality crystalline bottom cell with an efficiency of only 11.4%, the solar cell conversion efficiency can be increased to 17%. The following year, Bush *et al.* [**57**] successfully fabricated a four-terminal perovskite/silicon solar cell with an inversion structured top cell, yielding an efficiency of 18%. Albrecht *et al.* [**58**] reported an integrated perovskite/silicon heterojunction tandem cell by cryogenic treatment, allowing a maximum efficiency of 18.1%. Furthermore, Chen *et al.* [**59**] reported stacking a record-high 16.5-% efficiency semi-transparent perovskite top cell incorporating ultrathin metal electrodes, atop a 6.5-% efficiency silicon heterojunction bottom cell, yielding an overall efficiency of 23.0%. Werner *et al.* [**60**] demonstrated that when a NIR transparent perovskite top cell (16.4% efficiency) was mechanically stacked on a silicon sub-cell, the four-terminal and two-terminal efficiencies reached 25.2% and 20.6%, respectively.

The successful development of perovskite/silicon tandem solar cells in Hong Kong Polytechnic University [**61**] yielded an efficiency as high as 25.5%. This tandem cell was fabricated *via* three innovative approaches: 1) a chemical process/low-temperature annealing process in dry oxygen to reduce defect-related losses in the perovskite; 2) a tri-layer of molybdenum trioxide/gold/ molybdenum trioxide with optimized constituent layer thicknesses to allow light penetration from the perovskite top layer into the silicon bottom layer; 3) a haze film that mimics the surface morphology of rose petals was applied as the top layer to trap more light. Werner *et al.* [**62**] successfully fabricated a monolithic perovskite/silicon solar cell using a low-temperature processing method after thickness optimization of the perovskite layer, producing efficiencies of 19.2% (for 1.22 cm^2) and 21.2% (for 0.17 cm^2). Bush *et al.* [**10**]. increased the efficiency of monolithic, two-terminal, 1-cm^2 perovskite/silicon tandems to 23.6% by combining an infrared-tuned silicon heterojunction bottom cell with the recently developed caesium formamidinium lead halide perovskite. Furthermore, Sahli *et al.* [**63**] achieved conformal growth of multiple compounds with controlled optoelectronic properties directly on micron-sized pyramids of textured monocrystalline silicon. Tandem devices have yielded a certified steady-state efficiency, 27.3% [**20**] by Osborne's group. These successive layers are combined in a series in the tandem perovskite to stop some substrate structure. In this series, as the solar radiation light incident upon the first perovskite layer, layer No.1; the light energy out of the layer No.2 is the light into the layer No.2. The efficiency of the tandem device structure as a combined system, is the total energy output in series divided by the energy supplied to the first layer. Theoretically, a tandem structure that connects in series of n-layers [i = 1, 2… n] can achieve the following system efficiency:

$$1\text{-}\eta_{series} = \prod_{i}(1-\eta_i) \qquad (1)$$

Energy storage

When it is connected to the grid, the variable power output from a large amount of renewable energy (e.g. photovoltaic or wind energy) may lead to huge power fluctuations. The fluctuations can range from a few seconds to tens of minutes, thus affecting the grid frequency and causing grid instability. As a result, power demand leveling by energy storage becomes increasingly important.

Researchers have successfully constructed storage banks cargo by Liu, *et al.* [**16**], and a bank of the energy storage systems by Kittner, *et al.* [**4**]. The energy storage is a cargo container with battery in banks stacking racks as shown in **Fig. 3**. They are pretty innovative and have earned a noteworthy top innovation-2017 awarded in its field [**16**]. This construction is a solution from the supply-side strategies with storage capability of 3MWh that is contained in a cargo of battery stacking racks for the energy storage. Both the current energy storage design and system development is based on lithium-ion batteries, car batteries or lead-acid batteries; there is a huge opportunity for new and great innovation in the storage technology area to date. A storage cargo container typically includes the battery bank, the stacking rack(s), electrical wiring/connection/ harness for both global and local wiring, sensors and video monitors, air conditioning, and fire safety system. The energy storage system is connected to the national grid and has been tested for an extended period of time.

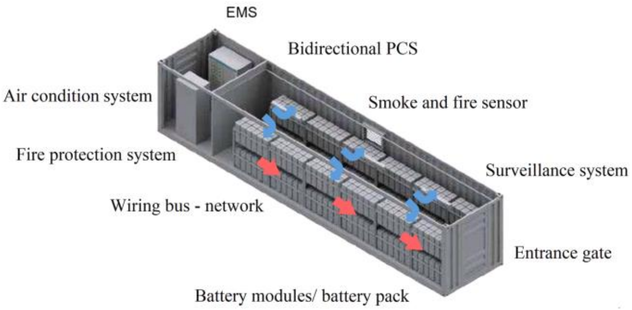

Fig. 3. Illustrated is the interior of an energy storage. Its energy management system is located atop for the operator's interface.

The method that resolves the imbalance of the need and supply between a consumer who is in need of power and a prosumer who can either produce or consume energy, abides by a simple principle as follows. The surplus energy production in day time is stored in the energy storage devices; and this energy is extracted for use when it is needed later or deemed convenient.

Furthermore, the energy storage system has a designed-in battery management system to ensure that every battery cells are integrated optimally and are operating in the safe operation window via both charge and discharge processes.

A good energy management system is critical so that it has significantly improved the battery efficiency and the battery capacity. The illustration in **Fig. 3** is a design of an integrated energy storage system. It has operated in 3MWh capacity [**16**]. A typical energy storage system includes the following: battery modules, wiring bus, fire protection system, air conditioning system, bidirectional power conversion via smart grid, smoke and fire sensor, surveillance system, and entrance for the engineering works.

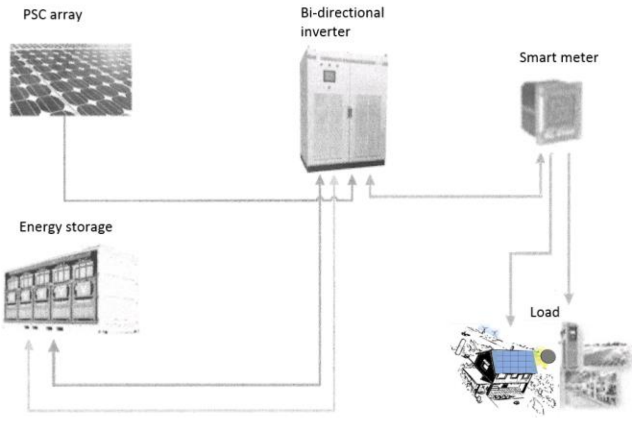

Fig. 4. The design schematics illustrates a large-scale solar power generation system.

Fig. 4 shows a design schematics of an integrated solar PV power generation system that is designed and built for the local power generation. The utility companies often offer a gateway for the local power generation to be connected to a power grid through a smart meter that can transfer electric energy either to or from the power grid; this power transfer can meet the requirement the peak and valley hours' use of electricity. The gateway is connected to a smart meter; the smart meter can have the necessary energy exchange that is available in connection to the power grid and that provides power to a consumer load.

Finally, a strategy is employed to smooth the peak power both from the supply-side and in the demand-side of the power. This strategy is imperative for the power dispatch; this strategy can help the good transmission in order to resolve field issues during the power dispatch uptime. The improvement in the uptime will be beneficial for the clean energy from resources like the perovskite solar energy power. The energy efficiency needs to be stable by balancing supply and demand. With the improved design of energy storage systems, the transmitted values of the outputs from renewable energy sources are believed to improve significantly and to become more stable on a large time scale.

Discussion

The perovskite solar cell presents itself a very promising opportunity for the solar clean energy technology. Along with other emerging clean technologies, it exists side-by-side with a young PV industry that is highly successful and yet fragmented to date in the energy market in comparison to the traditional fossil-based energy incumbent. Both industries have great technology profiles and market potentials for the energy market. In keeping pace to become mature, they need huge growth into the traditional one. Because of their potentials, they are ranked as highly attractive as its profiled success will need more competitive advantage for both investors and consumers.

The development of perovskite solar cells has advanced favorably for their entrance into many mainstream applications. The potential of perovskite can realize far higher efficiencies, environmental and performance stability at minimal production costs. This potential will promote perovskites to be commercially mature with the benefits of high efficiency, easy to manufacture, and cost advantages. .

Authors have shown that the perovskite solar cell technology has achieved very high energy conversion efficiency. Simply put, this technology could become a huge contender in the PV industry with tremendous potential and low cost to produce if these cells could be functionally produced with a long-term stability. They demonstrated that these cells are prepared well in various topologies in the cell structure helpful for the performance improvement including but not limited to the tandem designs, encapsulation in multi-layer structure, planar architecture with new materials of varied bandgap, etc.

The tandem designs, such as perovskite cells stacked atop silicon sub-cells have achieved over 27% in efficiency and above. They can have very high efficiencies and has recently attracted a huge and dramatically increasing attention from researchers.

Perovskite solar cells have advantages for widely tunable energy bandgap via variation of the dopant concentration. The single-junction efficiencies of these perovskite solar cells are comparable to those of multi-crystalline silicon, cadmium telluride and copper indium gallium selenide. As the research and development has exhibited significant success in the energy storage technology at a mega-watt level, authors have briefly reviewed the energy storage [**4, 16]** from the supply side management. This is important for the expanding technologies in successful alternative energy generation and application.

Conclusions

The scope of this article is to study an emerging solar energy system highlighted by both advances of the perovskite solar cells and of energy storages. In conclusion, authors have provided case studies on solar technologies that there are tremendous research and important breakthrough in perovskite solar cells development. In the afore-mentioned cases, the related new technologies have potentially superior performance with promising new materials, new processing methods, and superior architecture. The perovskite solar cells have high efficiency at near or above 30% [**20,55**], and the PSC have extended life-time at or above one-year.

In the light of alternative energy technologies, authors emphasize PSC and they briefly discuss the significant milestone progress in the energy storage technology. As the exciting research and development has exhibited significant success in energy storage technology at a meg-watt hours level, a study on a distributed clean energy system is conducted.

Finally, the huge commitment and intense international collaboration among scientists have been dedicated to the perovskite stability [**8,10-12**] and have extended beyond its one-year long life-time in just a few years of development. The perovskite is apparently providing the fastest-advancing solar technology to date; authors therefore believe that may be available soon for emerging technology commercialization in scale as this technology matures in near future.

Declaration

- Ethics approval and consent to participate (Yes)
- Consent for publication (Yes)
- Availability of data and material (Yes)
- Competing interests (Not applicable)
- Funding (Yes)
- Authors' contributions (Yes, cf. below)
- Conceived plan: aj, kc, jz. Investigation: zl, zy, kc, aj. Data analysis: zl, aj, zy, kc, jz, jz. Wrote the paper: aj, zl, zy, kc.
- Authors have no competing financial interests.
- Acknowledgements (Yes)
- Authors' information (optional) (Yes, cf. below)

Abbreviation

- DMSO: dimethylsulfoxide
- ES: Energy Storage
- ITO: indium tin oxide
- MW: mega watt
- MWh: mega watt hour
- NREL: National Renewable Energy Laboratory
- PURPA: public utility regulatory policies act
- PV: photovoltaics

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Keywords

Perovskite solar cells, surface passivation, quantum efficiency, tandem cells, large-area fabrication, environmental stability, high efficiency, energy storage.

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