Future Prospects of Photovoltaics

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ABSTRACT

The global solar cell market is growing substantially every year. The annual energy production of solar cells in 2015 was reported to be 51 GW, with a cumulative installed capacity of 234 GW. Research and development of solar cells using various types of semiconductor materials is underway, but currently more than 90% of the solar cells in practical use are Si solar cells. Other solar cells being produced are thin-film solar cells, such as CdTe and Cu(InGa)Se₂ solar cells. Si solar cells will certainly continue to be widely used in the future. According to a survey of trends in the solar cell industry, the cumulative installed capacity of Si solar cells is expected to reach 850 GW in 2024. Meanwhile, solar cell research and development aimed at achieving future targets for electricity generation costs is underway in many countries. This paper describes initiatives in Japan aimed at 2020 and 2030. Perovskite solar cells are an innovative solar cell technology, and there is currently a great deal of research and development being done in this area. Also, although many problems remain, it is hoped that low-cost, highperformance thin-film solar cells can be realized. Finally, this paper outlines a vision of solar cells anticipated by 2050, and touches on the need for energy management.

INTRODUCTION

At COP21 (Conference of the Parties to the United Nations Framework Convention on Climate Change), held in Paris from November 30 to December 11, 2015, the Paris Agreement, involving all 196 countries, was adopted as the new framework after the Kyoto Protocol expires in 2020.

In response to this, countries are currently carrying out R&D and implementing policies for introducing new technologies aimed at achieving targets for reducing greenhouse gases (CO₂, etc.). Japan has pledged to cut greenhouse gases by 26% from 2013 levels by 2030. In a statement issued on the acceptance of the COP21 Agreement, Prime Minister Abe declared that his Cabinet will make working toward the target of a 26% cut in greenhouse gases a task of the highest priority. In order to achieve the target for CO₂ emissions reduction, it is necessary to introduce numerous technologies that can help reduce CO₂, such as renewable energies and energysaving technologies. Among these numerous technologies, large-scale introduction of photovoltaics shows promise because its potential installed capacity is large, it can be installed within a short time frame, and it can be installed anywhere in the world.

In addition to solar cells that convert sunlight into electricity, photovoltaic systems require power electronic equipment such as inverters that convert direct currents to alternating currents, and controllers for connecting to a utility grid. This paper looks at forecasts for the installation of photovoltaic systems, and the future of solar cell technology development for making those forecasts a reality.

PRESENT STATUS OF SOLAR CELL INDUSTRY AND TECHNOLOGY

Production of solar cells continues to increase year after year. In 2015, global production reached 51 GW. Looking at production by country, China and Taiwan account

Solar cell material	Present status and advantages*	Future prospects		
Crystal Si	η=26.3% (180cm ²) η=16-20% (large area module in production) Market share > 90%	Efficiency limit: 27-28% Cost prospect: 0.33\$/W (2024)		
(c-Si)	Annual production: ~ 50GW/y(2015) Price: 0.58 \$/W *High efficiency & high reliability	Si tandem solar cells (III-V/Si, perovskite/Si etc.)		
III-V compound (multi-junction)	η=45%, concentration of sunlight (several 100 suns) *Space applications	η=50-60% Four-junction solar cells		
Si thin-film	η=12-13%(small area) Production: < 1GW/y *Consumer application	Large area module with several m ² Amorphous Si/µc Si multi-junction		
Cu(InGa)Se ₂ (CIGS)	η=22%(small area) η=16-18%(modules) Production: ~ 1GW/y *Low cost manufacturing	Release from resource constraints(In) CZTS(Cu, Zn, Sn, Se)		
CdTe	η=22%(small area) η=16-18%(modules) Production: 2.5GW/y *Low cost manufacturing	Release from resource constraints(Te)		
Organic semiconductor	η=11%(small area) Under development	Establish high efficiency & long-term reliability		
Dye sensitized	η=12%(small area) Under development	Establish high efficiency & long-term reliability		
Perovskite	η=22%(small area) Under development	Establish long-term reliability & module production		

 Table 1: Present status and future prospects of solar cells

 n: energy conversion efficiency

for more than 60% of global production. Currently, the solar cells produced for power applications are bulk Si solar cells and thin-film solar cells (CdTe, Cu(InGa)Se₂, Si thin-film), with bulk Si solar cells making up more than 90% of the production. Production of super-high efficiency III-V compound multi-junction solar cells is still low, and does not yet appear in worldwide production statistics.

The energy conversion efficiency of solar cells improves every year. The latest energy conversion efficiency data is published regularly in the form of "solar cell efficiency tables" in the journal *Progress in Photovoltaics*[1]. Also, since November 2016, similar latest data has been published in the *IEEE Spectrum* magazine[2]. Based on data from these two sources, Table 1 summarizes the latest energy conversion efficiencies, the present status of production, and future trends.

Currently, perovskite solar cells are attracting the most attention in terms of research and development. Development on perovskite solar cells began on the basis of pioneering research by Miyasaka *et al.*, [3] and is now being conducted enthusiastically worldwide. It was in 2013 that this material type showed high promise as the basis for materials. At the time, very few people were aware of the magnitude of the potential of perovskite for solar cells. Perovskite solar cells have been steadily showing their strength since 2013, and have now reached 20-21% energy conversion efficiency, albeit for small surface areas.

Various types of solar cells are now commercially available, but their performance measured under standard test conditions (AM 1.5, 1 kW/m², 25 °C) is not always consistent with their performance in the real world. This is because solar cell conversion efficiency varies with operating temperature and the angle of the sun from the zenith. Also, annual power generation is highly dependent on sunlight conditions at the installation site. It is therefore necessary to measure power generation throughout one full year, and estimate the electricity generation cost based on that result. Also, as the installed capacity of photovoltaic systems increases, it becomes necessary to develop grid connection technologies. In such contexts, research is underway on the characteristics of outdoor power generation in different areas of Japan.



Fig. 1: 2 MW photovoltaic system installed in Hokuto City, Yamanashi Prefecture

Figure 1 shows a photovoltaic system installed in Hokuto City, Yamanashi Prefecture. Twenty-seven types of solar cell modules were acquired from nine different countries worldwide and installed at this site, where research such as comparative studies of power generation characteristics and studies on long-term stability of solar cells is being conducted.

INSTALLED CAPACITY OF PV SYSTEMS, AND OUTLOOK FOR SI SOLAR CELL TECHNOLOGIES

Forecasts for installed capacity of photovoltaic systems have been published by various organizations, but this section describes forecasts based on ITRPV-2016 (International Technology Roadmap for Photovoltaic) [4], created primarily by PV-related companies. Figure 2 shows



Fig. 2: The world solar cell market is expected to reach 250GW in 2030. At that point, the replacement of modules that will reach the end of their lifespan will begin. Cumulative capacity is expected to reach 4500GW.

forecasts for global cumulative installed capacity and annual production of solar cells. As shown in the figure, the world solar cell market is expected to reach 250 GW in 2030. At that point, the replacement of modules that reach the end of their lifespan will begin. Cumulative capacity is expected to reach 4500 GW by 2050. Given that the current global cumulative installed capacity of solar cells is approximately 200 GW, an installed capacity more than 20 times the current capacity can be expected. Also, the predicted annual production of 250 GW is approximately 5 times the current production. These forecasts clearly show that photovoltaics is an industry that will grow substantially up to 2050.

The most important technological issue in realizing the installed capacities predicted in ITRPV-2016 is how far the cost of solar cells can be reduced. As shown in Table 2, ITRPV-2016 predicts that the cost of Si solar cells will fall to 0.33 US\$/W by 2024. To express these numbers in a way that is easy to understand, let us calculate the cost of a 1 m square Si solar cell module. Assuming that the energy conversion efficiency of the module in 2024 is 25%, the module's output will be 250 W. Therefore, the cost of the 1 m square module will be 82.5 US\$. This is extremely cheap. Furthermore, the module will be operational for 25–30 years. Currently, solar cell manufacturers are providing various types of quality guarantees (system guarantees, module guarantees), and many guarantee the module itself for about 25 years.

	12/ 2015	12/ 2016	12/ 2018	12/ 2021	12/ 2024
Cum. module shipments(GW)	234				
Price at the end of period(US\$/W)	0.58				
Predict. cum. module shipments (GW)		320	440	630	850
Avg. W increase (period to period)		3%	4%	5%	5%
Cost reduction (period to period)		8%	10%	10%	10%
ITRPV 5th editon cost trend (US\$/W)		0.52	0.45	0.38	0.33

Table 2: From "International Technology Roadmap for Photovoltaic (ITRPV)" March 2016. Global market price of modules over time. Cost has been falling beyond expectations, and currently stands at 0.6\$/W. Expected to drop to 0.33\$/W by 2024.

Under these circumstances, how will the structure of Si solar cells evolve? Figure 3 shows a forecast of how the market share of each Si solar cell structure will change up until 2025. As shown in the figure, the dominant type



Fig. 3: From "International Technology Roadmap for Photovoltaic (ITRPV)" March 2016. Forecast on the types of solar cells that will fill the market. Si solar cells possess over 90% of the market, and other material types are not included in this chart.

of Si solar cell structure as of 2015 is BSF (back surface field), but this gradually changes to the PERC/PERT/ PERL (passivated emitter cell series) type; and in 2025, the Si-heterojunction, back contact, and Si-based tandem types emerge.

Next, this section describes forecasts of PV system installation in Japan. Japan is aiming for a cumulative installed capacity of 64 GW by 2030 as a national target, but considering that 30 GW had already been installed by the end of 2015, this target will not be difficult to reach. Meanwhile, the Japan Photovoltaic Energy Association (JPEA), which has been formed from the solar cell industry, has drawn up and published its own "PV Outlook 2030," which sets a challenging target that exceeds the national target. According to this forecast, Japan's cumulative installed capacity will reach 100 GW by 2030. Also, the market is predicted to shift from mega-solar to residential systems as we head toward 2030. Figure 4 shows a typical mega-solar system. Its installed capacity is 70 MW.

In Japan, "smart towns" with solar cells installed on building roofs are also being constructed [5]. Figure 5 shows a photograph of a smart town built in Fujisawa City. Here, a total of 3 MW of solar cells have been installed on the roofs of 600 detached houses and 400 apartment buildings. As well as solar cells, batteries for storing electricity have been installed. With the aim of comprehensive energy savings, IT has been fully introduced so that the energy usage of each household can be easily viewed. A number of innovations have been employed to protect the safety and security of residents, and

Cumulative GW	2015	2020	2030
Residential	-	16.3	36.4
Less than 1MW	-	25.2	34.6
1MW or more	-	24.2	29.1
Total (GW)	34	65.7	100.1

Table 3: Forecast of photovoltaic system installation in Japan (JPEA).



Fig. 4: Photovoltaic system with installed capacity of 70 MW in Nanatsujima, Kagoshima Prefecture.

the smart town residents are working together to create an environmentally friendly town.

ROADMAP AIMED AT REDUCING THE GENERATION COST OF ELECTRICITY

Currently, countries throughout the world are setting their own strategic targets and conducting R&D aimed at reducing electricity generation costs. This section describes development targets set by Japan's New Energy and Industrial Technology Development Organization (NEDO) [6].



Fig. 5: Fijisawa Sustainable Smart Town (Google Earth).

Japan is conducting research and development aimed at targets it has set to be reached by 2020 and 2030. As an example, Table 4 shows development targets in the field of non-residential systems of 10 kW or above. The aim is to achieve an LCOE of PV comparative to conventional thermal power, namely, 7 yen/kWh, by 2030. Similarly, for residential applications, after adding functions, including storage of electricity and power controls such as stabilization and variation suppression, the aim is to reduce the LCOE of PV to the same level as the price of electricity for households, namely, about 21 yen/kWh.

	2013	2020	2030
System price (yen/W)	275	200	100
Operation period (years)	20	25	30
Module efficiency (%)	16	22	25
Capacity factor	13	15	15
Total (yen/kWh)	23.10	13.21	6.87

Table 4: Breakdown of levelized cost of energy target (NEDO) $[non-residential \ge 10 kW].$

In order to achieve these targets, NEDO is carrying out R&D with the themes shown below:

- High efficiency and high reliability modules 2015–2019
- High performance systems and low maintenance costs 2014–2018
- Low-cost recycling technology 2014–2018
- Low-cost installing technology in untapped fields 2013–2016
- High-value PV system technology 2014–2016

Here, Table 5 shows the targets in the "high efficiency and high reliability module" program. For c-Si solar cells, the aim is to achieve a system price of 100 JPY/W and a module efficiency of 25% by 2030.

For perovskite solar cells, the research and development of which is recently progressing at a rapid pace, the aim is to achieve a system price of less than 100 JPY/W and a module efficiency of 20%.

	2020 (LCOE 14 JPY/kWh)		2030 (LCOE 7 JPY/kWh)	
	System price	Module efficiency	System price	Module efficiency
c-Si	200JPY/W	22%	100JPY/W	25%
III-V			125JPY/W	>30%
Perovskites			<100JPY/W*	20%

*module production cost : 15 JPY/W.

DEVELOPMENT OF INNOVATIVE SOLAR CELLS

The preceding section showed a roadmap aimed at 2020 and 2030. This section considers what kind of solar cells must be developed beyond that time frame, up to 2050.

The world's population is predicted to exceed 9 billion by 2050. There are still many places without electricity in Asia and Africa, and global demand for energy is expected to grow significantly as electrification in those regions progresses. It is entirely possible for this growth in demand to be supplied using renewable energies such as photovoltaics and wind power. As shown by the 2050 forecast in the ITRPV mentioned earlier, the growth in demand could be adequately met if photovoltaic systems on the scale of 5 TW–10 TW were introduced.

However, obtaining the land area required for installation is a challenge. Assuming an energy conversion efficiency of 20%, the area required to install a 10 TW photovoltaic system is 5×10^4 km². On a global scale, there is sufficient area for installation if one considers desert/arid regions, but substantial improvements in energy conversion efficiency to minimize the installation area are desired. If conversion efficiency was improved to 40%, the required installation area would be halved.

In light of this, various research and development is being carried out, aimed at greatly improving the energy conversion efficiency of solar cells.

The most reliable method is the use of multi-junctions. To date, conversion efficiencies exceeding 45% have been obtained using four-junction tandem solar cells, such as InGaP/GaAs/GaInAsP/GaInAs [1]. However, this type of solar cell is currently very expensive to manufacture, and so its system design makes use of low-cost concentrators with concentration ratios of 500–1000 times. At these high concentration ratios, concentrators can only use the direct component of sunlight, and are unable to concentrate the diffuse component. Therefore, in generating sufficient power, these systems are severely limited by sunlight conditions.

By 2050, it is possible that solar cells will have been developed based on a new principle that differs from the principle of photoelectric conversion on which they are currently based. Examples are intermediate-band solar cells and multi-exciton solar cells [7]. These solar cells have been proposed for a long time and R&D has been carried out, but their performance has not yet been demonstrated to surpass that of existing solar cells.

CLOSING

The cumulative installed capacity of solar cells, which was 234 GW in 2015, is predicted to reach 850 GW in 2024. Given this prediction, research and development of solar cells is expected to advance steadily. Si is currently dominant in terms of solar cell materials, and this situation is not expected to change greatly. In the future, the perovskite solar cell may emerge as a game-changing solar cell. Currently, perovskite solar cells are an active area of research and development, but there are many problems, including the fact that the absorber perovskite layer contains the toxic substance Pb and the fact that deterioration is found with long-term outdoor exposure. Solutions to these problems must be found as quickly as possible.

Meanwhile, energy management technologies will become increasingly important. The supply of power from photovoltaics is greatly influenced by weather conditions and varies dramatically with time. Energy management must be used so that this does not place a large burden on the grid.

Hereafter, it will be necessary to install storage equipment such as batteries in residential and other smallscale photovoltaic systems. This will allow excess electricity generated by the photovoltaic system that is not used by the household to be stored temporarily in the battery and can be used to supplement the power supply when the output from the photovoltaic system rapidly declines. Also, technologies for connecting with key energy sources currently in use (nuclear power generation, thermal power generation, hydroelectric power generation) must be developed. If the use of hybrid cars and electric cars increases in the future, it will also be necessary to connect to the batteries installed in these cars. It is expected that



Fig. 6: Three elemental technologies required for large-scale photovoltaics.

a time will come when the amount of electrical energy being used by each household is monitored and controlled using IT. This is referred to as the "smart grid."

Thus, with the large-scale introduction of photovoltaics, greater development of three elemental technologies all beginning with "S" will be required—solar cells, storage, and a smart grid as shown in Fig. 6.

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