Global R&D in Solar PV

A Status Report prepared by

National Centre for Photovoltaic Research and Education (NCPRE)

Indian Institute of Technology Bombay

September 2020

Global R&D in Solar Photovoltaics

A Status Report prepared by
National Centre for Photovoltaic Research and Education (NCPRE), IIT Bombay

Introduction

Deployment of solar Photovoltaics (PV) has increased tremendously world-wide over the last two decades. This has been driven by reducing costs of solar PV energy, which has been a result of vastly increased shipments of solar modules, a wider manufacturing base and improvements in technology. There continues to be a great deal of R&D worldwide in PV technology, both for the mainstream silicon, as well as new materials which can provide higher efficiencies at lower cost. In addition, the rapid deployment of the solar PV has generated R&D programmes in several related fields, such as reliability, energy storage, grid connectivity, power electronics, weather forecasting for solar, and re-cycling. Government policy drives a lot of solar deployment, and research on policy is important to assess the relative effects of different government policy measures. All of these areas are being intensively researched globally – in academia, research labs and industry. This status report will present a bird's-eye view of this R&D. A Table at the end of the report presents the activities at some of the leading laboratories in the world in an easy-to-see format.

1. Silicon Technology

1.1 Silicon Wafers

Silicon has been the workhorse of solar cells since the earliest days. The silicon wafer used for making solar cells is traditionally produced by (1) making polysilicon from silane or trichlorosilane, (2) making ingots and (3) cutting the ingot into wafers. There continues to be a great deal of R&D in these areas. A relatively new (and energy-efficient) way to make polysilicon is the 'Fluidized Bed Reactor (FBR)' technology. The older Siemens technology, however, still dominates. The method of making ingots from the polysilicon can be different based on whether the final wafer required is mono or multi. Multi had dominated the technology till recently because of cost, but now mono is increasingly being used because of better performance. Even within mono, the newer method on which there continues to be R&D, is the 'Continuous Czochralski (CCz)' method which is more challenging but is energy-efficient and gives better quality wafers. The ingots are then sliced to get the wafers. Diamond Wafer Sawing (DWS) is the standard today, but new methods like Wire Electrical Discharge Machining (EDM) are being explored.

There is also R&D going on to go directly from gas to wafer, without the intervening steps. This R&D, if successful, holds promise for lower cost wafers (which today represents almost 50% of the cost of a silicon solar cell).

The R&D for polysilicon, ingots and wafers is being done today mainly in industry. MEMC in USA was the inventor of FBR and CCz. New developments are being tried by companies like GCL and LONGi, both Chinese companies. The direct gas-to-wafer processes are being explored by a couple of companies based in USA, one in Germany, and one in India. The German company Nexwafe is a spin-off from Fraunhofer ISE, a leading German research unit. IMEC in Belgium (an R&D unit) and State Key Laboratory of PV Science & Technology (SKL PVST) co-located at Trina in China, have also been working on this technology. In India, there is little activity of wafers, though SSN College of Engineering has been doing research on the growth of multi-crystalline silicon ingots, and NCPRE at IITB has been doing research on Wire EDM.

1.2 Silicon Solar Cells

For many years upto about 2010, the standard technology used to make silicon solar cells was the 'Aluminium Back Surface Field' technology. Advances in new silicon solar cell structures has resulted in the PERC (Passivated Emitter and Rear Cell) cell becoming the standard for manufacturing, and today about 70% of world-wide production is based on PERC, with mono-PERC dominating.

Besides PERC, there are several other important varieties of silicon solar cells. These include Heterojunction Technology (HJT or HIT) cell, the Interdigitated Back Contact (IBC) cell, and cells with carrier selective and tunnel oxide passivated contacts (TOPcon). Especially in the latter, there is considerable research going on world-wide.

The R&D for silicon cells is being done in industry as well as academia. Many of the original advances, including the PERC concept, were made at University of New South Wales (UNSW) and the Australian Centre for Advanced Photovoltaics (ACAP) in Australia, and at Stanford University in USA. HJT (HIT) cells originated from Sanyo and Panasonic in Japan. Currently, much of the R&D on high-efficiency silicon cells is being done at Chinese companies like Trina and LONGi, since most of the manufacturing has moved there. In India, R&D on PERC is going on at IIT Bombay, IIEST Shibpur, and in companies like Adani Green Energy and Tata Power Solar. New concepts like carrier selective and TOPcon are being intensively researched at universities in USA (Georgia Tech), Germany (Freiburg), China (Kunming), Australia (UNSW and ANU) and India (IIT Bombay, IIEST Shibpur and NPL), as well at R&D Labs (ISFH in Germany, SKL PVST in China) and industry (Trina, LONGi).

1.3 Modules

The most important recent development in modules has been bifacial modules. There has been considerable research on these, including the use of backside glass and special application areas for bifacials (eg. agriphotovoltaics). The International Technology Roadmap for PV (ITRPV), issued annually, predicts that bifacials will go from 10% share today to 40% in 2030. Another important development has been the use of half-cells, going from 20% today to 60% in 2030. Various new cell interconnect strategies, eg. grid or mesh connects, are also being explored.

In the module, besides the cell, other important components are front glass, encapsulant and backsheet. All these are witnessing considerable R&D globally. Glass is becoming important because bifacials will need glass on both sides, and thinning the glass down to 2 mm or less is necessary. Flexible glass (eg. Willow®) will have niche applications. EVA has long been used as an encapsulant, but several new encapsulants, especially polyolefins, are being tested. Newer backsheets to replace the traditional Tedlar are also being explored.

Global R&D on bifacials and other module innovations are being led mainly by industry in China, Germany and USA. Waaree in India is exploring grid connects, and SunConnect has research on junction boxes. Glass research is being conducted mainly in industry, eg. Corning (USA), Borosil (India) and Saint Gobain (France). Encapsulant and backsheet research is being conducted in academia by polymer chemistry groups in USA, Spain, Austria, China and India, R&D labs (NREL, Fraunhofer, ISFH, SKL PVST) and industry (DuPont in USA, Renewsys in India, Borealis in Austria).

1.4 Characterization techniques

As silicon cells and modules have been deployed around the world, the need for adequate testing and new methods of characterization has become important. Some of these characterization techniques, which are seeing increased R&D, include electroluminescence (EL) and photoluminescence, quantum efficiency, lock-in thermography. EL has emerged as a very powerful technique for assessing initial quality of modules, as well as subsequent degradation in the field due to PID, cracks, disconnects, etc. Also, due to the large-scale deployment of PV in the field, R&D into new techniques for field assessment has become important. R&D in these areas can be seen at many places, including NREL and Fraunhofer, UNSW in Australia, and at NCPRE and NISE in India.

2. Thin Film Solar Cells and Tandems

Besides silicon, various thin film solar cells are also being deployed, though their share has fallen to 5% in 2020. However, R&D continues. One advantage of thin film cells is that they are potentially cheaper as they don't need the expensive silicon wafers. Also, if the active thin film is put on a flexible surface, we can have flexible solar cells.

2.1 CdTe Solar Cells

Cadmium Telluride (CdTe) technology has been around for many years, but continues to be in use today, mainly because of the success of a major USA-based company, First Solar. Recently, some Chineses companies (eg CNBM in Chegdu) have also started. This technology is proven, has high efficiency and relatively low cost.

R&D in CdTe is concentrated in First Solar (which continues to provide advanced products), and a number of universities in USA, eg Colorado State University and Toledo University.

2.2 CIGS Solar Sells

Solar cells made of Copper-Indium-Gallium-Sulphur (CIGS) constitute the second important thin film technology in the market. Solar Frontier in Japan is the leading manufacturer. CIGS is eminently suitable for flexible solar cells and Flisom in Europe focuses on this niche market. R&D in flexible CIGS solar cells is taking place at ETH and EMPA in Switzerland, Purdue University in USA, and Flisom in Switzerland. One aspect of flexible is the use of roll-to-roll manufacturing using flexible plastic or glass as the substrate, which can result in very high throughput and low cost. In India, ARCI, Hyderabad is active in CIGS and flexible substrates.

2.3 Organic Solar Cells

People have been trying organic photovoltaics (OPV) for several decades because of their ease of fabrication and low cost. However, efficiencies could not go above 12-13% until 2019 when they jumped to > 17%. This has generated a resurgence of R&D worldwide in OPV. Many universities in China, USA and India, as well as leading research labs like NREL, Fraunhofer and AIST (Japan) have re-initiated research in the area. In India, IISc, IITD, IACS, IITB (NCPRE), NPL and NCL are active.

2.4 Perovskite Solar Cells

Perovskites are hybrid organic-inorganic materials which have been known for over a century, but came into prominence for PV only a few years ago. Dramatic improvements have produced cells with efficiency > 24%. They are an active area of research in universities, research labs and industry worldwide. Leading university research teams are EPFL (Switzerland), UCLA and MIT (USA), Oxford (UK), Sungkyumkwan (S. Korea), Tokyo Inst of Technology (Japan), Nanyang Technological University (Singapore), UNSW (Australia) plus NREL and Fraunhofer. Several companies - Oxford PV (UK), Frontier Energy (Korea) and Hunt Perovskites (USA) - have been formed to commercialize this technology, and they are also aggressively pursuing R&D. In India, IISc, IITB, IITK, NCL and NPL, among many others are actively involved. It should be noted that the technology is still in development, with problems of attaining large size, long life, reliability, and need to replace lead, which need to be solved before actual deployment. These are all areas of intensive research.

2.5 Tandem Solar Cells

Tandem solar cells, which have two or more cells in series on the same substrate, have been around for many years, but so far were used for very complex and expensive ultra high-efficiency III-V cells (> 40%) for space applications. However, in recent years, tandems have become an intensive area of research for new types of terrestrial solar cells. The most common such tandem structure being explored is perovskite-on-silicon, but others like perovskite-on-CIGS and perovskite-on-perovskite are also being explored. Tandem research is being pursued at most universities listed above, plus Ohio State University, and also at places like Helmholtz-Zentrum (Germany) which holds the current record of 29%. In India, IITB (NCPRE) is the leading research entity.

3. PV Reliability and Energy Yield

Rapid and widespread deployment of PV which needs to last in the field for 25 plus years has focused attention on reliability and durability of modules, as well as soiling, both of which affect the energy yield of the solar plant. There are several important aspects of this work.

3.1 Field Assessment of PV Installations

Performing actual measurements on real-life installations in the field is the best way to ascertain the performance and health of PV systems. This has been undertaken in many countries world-wide, and the data have been analysed. NREL has played a major role in compiling data not only from USA but other countries as well. They noted that historically, the average degradation rate (loss of power) is approximately 0.8%/year. Field measurements and analysis have yielded many interesting R&D problems. These include potential-induced degradation (PID), hot climate effects, new measurement techniques suitable for field, and search for better encapsulants. World-wide, this research is led by research laboratories (NREL, FSEC, ISFH in Germany, INES in France, AIST in Japan), academic institutions (University of Central Florida, Arizona State University, Polytechnic University of Madrid, Leibniz University, Huazhong University) and industry (DuPont, Corning, IBC Solar, LONGi Solar). In India, NISE has had a long history of studying field reliability, and during the last 7 years NCPRE has played a major role, together with NISE, through the 'All-India Surveys of PV Module Reliability' which were conducted in 2013, 2014, 2016 and 2018. These surveys revealed very interesting actionable results.

3.2 Novel Instrumentation for Field Testing

Emphasis on field measurements has created a special need for test and measurement equipment suitable for deploying in the field. This includes measuring I-V curves of individual modules, daylight electroluminescence (EL), aerial infrared (IR) and EL mapping. Some of this work is more development (rather than research) oriented, and has often been led by industry, especially start-ups. Examples include Stratasense (USA), DaySy, PV Diagnostics (India), AirProbe (India), and SolarMarq (India), and background research from Case Western Reserve University, Sandia Labs (USA), AIST (Japan), TUV Rheinland (Germany) and NCPRE (India).

3.3 Physics of PV Reliability and Accelerated Testing

To ensure long-term reliability and durability of PV deployed at TW scale in diverse global regions, the underlying physics of degradation needs to be understood well. This has generated research world-wide, with emphasis on two aspects – how to increase the life from 25 to 35 (or more) years, and how to ensure durability in harsh environments. The former aspect has been spearheaded by research laboratories and academic institutions in advanced-solar countries (NREL and Sandia in USA, Fraunhofer and ISFH in Germany, AIST in Japan, SERIS in Singapore), and the latter in countries having harsh climates (USA, India, Middle East). Much fundamental understanding has been emerging. It is expected that this understanding will also help in creating better protocols for accelerated testing, which in turn informs standards and certification. In India, the major institute working on physics of reliability is NCPRE, which has developed significant new understanding in the areas of encapsulant browning and microcrack development (both of which are problems widely seen in the field in India).

3.4 Standards and Certification

Related to accelerated testing of PV modules is the development of standards and protocols for certification. The global certification standards are set by IEC, and in India, BIS closely follows these. Certification has become very important as the present tests can only detect manufacturing defects or infant mortality issues. The aim is to be able to predict the life of PV modules, and extend the life to 35-50 years. Further, the PV community now realises that deployment in diverse regions may require different tests (hot climates versus snow loading, for example). This requires a tight coupling between physics, accelerated testing and certification. Several national laboratories (NREL, Sandia, AIST, Fraunhofer) and certification laboratories (UL, TUV Rheinland) world-wide have been involved in this and the IEC and IEA coordinate research across the globe. NCPRE has been closely connected with these groups, as well as with BIS in India (having membership of IEC TC82/WG2, BIS ETD28, and IEA PVPS Task Group 13). An international Workshop at NCPRE in 2015 on "PV Module Reliability in Hot Climates" has sparked global activity to come up with specific standards for such regions, with obvious relevance to India.

3.5 Soiling and Cleaning

This is an area of great concern in India and other dust-prone regions. There is a fundamental component of the research in terms of developing hydrophilic or hydrophobic anti-soiling coatings, and an engineering component relating to automated (robotic) cleaning of PV modules. Research in these areas is being conducted by industry, national labs and academia. Examples include NREL (USA), AIST (Japan), Fraunhofer (Germany), DEWA (Dubai), Arizona State University and Boston University (USA), University of Santiago (Chile), King Abdullah University (Saudi Arabia), UPM (Malaysia), Beni Suef University (Egypt). Several companies are developing robotic cleaning apparatus, such as Eccopia (Israel). In India, NCPRE and IIEST Shibpur are working on anti-soiling coatings, and several new Indian companies like Skilancer, Indisolar, Nocca Robotics and Ganges Internationale have developed robotic cleaning solutions. IIT Gandhinagar, together with UL India, is working on several aspects of soiling and cleaning.

4. Storage and Grid Connectivity

Since PV is an intermittent source of energy, it is desirable to have storage connected to the PV generator. For stand-alone (off-grid) systems, this is obviously necessary if one wants power at night. Even for grid-connected PV systems, this becomes important as global deployment of solar PV approaches 1 TW, and the aim is to have solar energy accounting for increasing fractions of many countries' electricity needs. Such grid-interactive storage would allow continued operation during parts of the evening and night, and also can be used for maintaining steady outputs over shorter times (milliseconds to minutes) which ensures that grid stability is not compromised. Of course, storage by electrochemical means (batteries or supercapacitors) is being intensively researched due to applications in several other fields (electronics, EVs), but the type of batteries most suitable for PV, and their charging/discharging capabilities has opened up as an important area of research. Besides, non-battery storage like pumped hydro and chemical (eg, hydrogen) are also being explored.

4.1 Storage for PV

Early PV systems, which were mostly stand-alone (or off-grid) needed some form of storage Lead-acid batteries were the commonest form of storage. In recent years, however, as storage is being introduced even for grid-connected PV systems, the dynamics of storage has shifted. The type and sizing of batteries for PV depends on the end use, and research into various strategies for optimum cost or optimum stability is ongoing. (Research into the actual chemistry of various batteries, is of course important, but will not be described here.) Battery types include all variants of lithium ion batteries (LIB), flow batteries, sodium batteries, as well as supercapacitors, each having their advantages and disadvantages. R&D into these areas is being conducted at NREL, Fraunhofer, and AIST. In India, there is work on this at CECRI, IISc, NCPRE, IIT Delhi, TERI and NCL. Pumped hydro research is at IIT Roorkee and Australian National University, which has found over 500,000 sites globally which can be used for pumped hydro.

4.2 Grid Connectivity

Much of the future deployment of solar PV will be grid-connected, and one of the earliest questions has been whether the grid can tolerate large amounts of this intermittent and infirm source. Much progress has been made in this regard, and research continues. Use of batteries (BESS – Battery Energy Storage Systems) has been made possible, even at large scales, due to dropping costs and reduced LCOS (levelized cost of storage). Not only does storage make solar energy less infirm, but can also provide various benefits like frequency regulation, demand response, etc. In India, IITD, IISc and NCPRE have R&D programmes in this area, and companies like NTPC are also working on various aspects. Of course, combining solar with storage and controlling the grid-connected system appropriately requires research in power electronics, which is described next.

5. Power Electronics for PV

Power electronics found an important application in early solar PV, since the DC power needs to be inverted to connect to the grid, and to power up AC appliances in stand-alone off-grid installations. More recently, with the integration with storage and wind, and the need to improve the efficiency, power electronics has come to play an even more important role. Several aspects of power electronics are being researched, and these include: new inverter topologies, low-cost but robust inverters for rural applications, power electronics for solar-powered water pumps, micro- and mini-grids, panel-based microinverters, silicon carbide (SiC) and gallium nitride (GaN) based power electronics, power electronics for solar-based EV charging, real-time power flow control, and smart controllers for PV/storage. India is fortunate because it has traditionally been strong in power electronics. As more solar power is injected into the grid, it will increasingly depend on power electronics to ensure the grid remains stable. New approaches will be needed to improve the reliability and resiliency of the nation's electric grid by improving the interface point between solar and the grid. Such new, cost-effective power electronics designs will make solar energy dispatchable even with high penetration levels of solar. Two of the most important areas being researched are new topologies and use of Wide Band Gap (WBG) power devices like SiC and GaN.

Since the voltage of PV array varies over a wide range with changing atmospheric conditions, the conversion efficiency of the inverter is expected to be high over a wide range of PV voltages. Also, to achieve an efficient and compact design, the use of newer transformerless circuit topologies is preferred. The application of multilevel inverter circuits, which are known to reduce the voltage stress and the size of passive elements, are also being researched. In addition to efficiency and power density, the reliability of solar inverters is of prime importance to reduce the LCOE. Research is underway on active power decoupling circuits to extend the lifetime of capacitors. In these solar inverters, it is desirable to integrate energy storage systems, and this has spurred research on new circuit topologies.

Power semiconductor devices using Wide Band Gap (WBG) materials, such as GaN and SiC have superior electrical and thermal characteristics as compared to Si-based devices. This enables the design and development of high efficiency and high-power density converters. While GaN-based devices ares suitable for low and medium power application, SiC-based devices are suitable for the medium and high-power application. In solar applications, it is expected that the high efficiency of GaN-based inverter will yield a lower LCOE. SiC-based devices have high voltage ratings, enabling the design and development of high-efficiency and high-power density grid-connected transformerless solar inverter. Both GaN and SiC devices are revolutionising power electronics, and leading to new types of circuits for solar applications.

Research in power electronics for PV is being conducted at all levels – academia, research labs and industry. Some examples globally are Georgia Tech (USA), North Carolina State University (USA), NREL and Oak Ridge National Laboratory (USA), AIST (Japan), and companies like SMA, General Electric, Siemens, Hitachi, Tesla, Yaskawa. In India, the following academic institutions are very active: IISc, IIT Delhi, IIT Bombay, IIT Kharagpur, and companies like Tata Power Solar and Tata SED have R&D programmes in WBG. TERI has worked on aspects of microgrids.

6. Solar Resource Forecasting

Prediction of solar energy generation in advance has become important as PV plus battery systems are connected to the grid. Accurate forecasts improve reliability, and also reduce costs by allowing efficient solar energy trading and avoidance of penalty for incorrect forecasts. For this the solar resource forecast is important not only for the week and day ahead, but even for the next 10-30 minutes. This has led to a lot of research and the evolution of new methods (including total-sky imaging) plus numerical and statistical forecasting. Work on this is actively being pursued globally in R&D Labs (NREL, Fraunhofer), Universities (State University of New York, Uppsala University) as well as companies (Clean Energy Research, Avenston, Reuniwatt). In India, NIWE and GIZ-India (a collaboration with Germany) are the leading actors in this area, which needs to be much strengthened.

7. Novel Deployments of Solar PV

Most deployments of solar PV are either on ground in large utility-scale solar parks or on rooftops. However, many new areas are emerging, and these have been the subject of a great deal of R&D. Some of these are: *floating solar*, which has many advantages but also several challenges; *agriphotovoltaics*, which seeks to combine land usage for farming and energy generation; *hybrid solar-wind* energy farms to reduce the infirmity of each; *building-integrated PB (BIPV)* which is seeing a resurgence due to new types of PV; *solar-powered desalination* and refrigeration; *PV in mobility* which includes PV powering of buses, trains and auto-rickshaws, etc. All these areas provide exciting opportunities for R&D in India and globally.

8. Solar Re-cycling and End-of-Life Solutions

Is there life after death? As we look forward to 1 TW of deployment of solar within a couple of years, it should be remembered that 99.9% of those panels would still be within their 25 year lifespan. It is estimated that in 2030 there will be 8 million tons of PV waste (200,000 tons in India), and by 2050 60 million tons. It is important to start research today on recycling and end-of-life issues, and conduct informed life-cycle assessment (LCA) studies. As of today, recovery of materials from disused panels is not economical either in terms of cost or energy. Even extraction of precious materials like silver is not economical. New recycling strategies, or even use of less efficient (and more expensive) panels which are amenable to better re-cycling may be required. Several national laboratories (NREL, Fraunhofer, AIST) have research programs in LCA of solar panels; and universities like UNSW, Tokyo University and several universities in EU (which has the strictest standards) have research programmes. Some solar companies have also been involved (First Solar, Sanyo). In India, TERI and CMET Hyderabad have programmes on re-cycling.

9. Policy

Enabling government policy was responsible for some of the earliest large-scale deployment of PV in Germany, Spain and other countries of the EU. For India, too, the JNNSM provided a visionary policy for deploying solar. Even though costs have come down, and one might have thought that market forces would dominate, policy continues to play an important role. Many smaller 'solar-emerging' countries require firm and consistent policy to attract investment for solar, and even in market-dominated places like USA, government policy plays a role. Policy affects various aspects of solar deployment such as bidding processes, setting of caps and floors of bids, feed-in tariffs, rooftop policies for reverse/gross metering, grid access and wheeling charges, land acquisition, financing incentives, creation of solar hubs, choice of technology, encouragement of hybrid+storage, etc. Even for manufacturing, government policy is important to decide safeguard and customs duty for import, incentives for manufacturing, public sector manufacturing, etc. Research on the outcome of various policy measures is very important to determine how policy shaped deployment and manufacturing, which will therefore provide a basis to predict the effect of proposed policies. Such research (which is often country-specific) has been done at the leading national laboratories (NREL, Fraunhofer ISE, AIST), by government ministries (MNRE, DOE in USA, MITI in Japan), and also by universities and research organizations – in India CSTEP, TERI, Bridge to India, and Prayas are good examples.

Global R&D at a Glance

The Table on the following page gives an overview of activities of various important national-level laboratories across the world. Of course, there are many other laboratories doing excellent work in specific areas of solar PV, but these are not included here. It is interesting to note that many of the laboratories shown are located at or have a very close tie-up with a university, which allows them to leverage the wide range of expertise available at the university. In China, interestingly, the State Key Laboratory (SKL) is co-located at Trina Solar.

Name of Research Laboratory	National Renewable Energy Laboratory **(NREL)**	Fraunhofer Institute for Solar Energy Systems **(Fraunhofer ISE)**	Institute for Solar Energy Research Hamelin **(ISFH)**	National Solar Energy Institute **(INES)**	National Inst. of Advanced Industrial Science and Technology **(AIST)**	Solar Energy Research Institute of Singapore **(SERIS)**	Australian Centre for Advanced Photo-voltaics **(ACAP)**	State Key Laboratory of PV Science and Technology **(SKL PVST)**	National Centre for PV Research and Education **(NCPRE)**
Location	Golden, CO **USA**	Freiburg **Germany**	Hamelin **Germany**	Le Bourget-du-Lac **France**	Fukushima **Japan**	**Singapore**	Sydney **Australia**	Changzhou **China**	Mumbai **India**
Located at / with	–	Albert Ludwig University of Freiburg	Leipzig University	CEA, University of Savoie	–	National University of Singapore	University of New South Wales	Trina Solar	IIT Bombay
Annual Budget (USD)	USD 490 M	USD 112 M	USD 14 M			USD 20 M	USD 12 M		USD 2 M
Activities									
1. Silicon Technology									
Silicon Wafers			✓		✓			✓	
Silicon Solar Cells		✓	✓	✓	✓	✓	✓	✓	✓
Modules		✓	✓	✓	✓	✓	✓	✓	✓
Characterization Techniques	✓	✓	✓	✓		✓	✓	✓	✓
2. Thin Films and Tandems									
CdTe Solar Cells									
CIGS Solar Cells	✓			✓	✓				
Organic Solar Cells	✓	✓	✓		✓	✓	✓		
Perovskite Solar Cells	✓	✓	✓	✓	✓	✓	✓		✓
Tandem Solar Cells	✓	✓				✓	✓	✓	✓
3. PV Reliability									
Field Assessment of PV	✓	✓			✓				✓
Novel Instrumentation for Field									✓
Physics of PV Reliability	✓	✓	✓	✓	✓	✓		✓	✓
Standards and Certification	✓	✓	✓	✓	✓				✓
Soiling and Cleaning		✓							✓
4. Storage and Grid Connectivity									
Storage for PV	✓	✓	✓	✓	✓	✓	✓		✓
Grid Connectivity	✓	✓		✓		✓			✓
5. Power Electronics for PV		✓				✓			✓
6. Solar Resource Forecasting	✓	✓		✓	✓				
7. Novel Deployments of PV	✓	✓		✓	✓	✓			✓
8. Solar Re-cycling	✓	✓	✓	✓	✓	✓	✓	✓	
9. Policy	✓	✓		✓	✓	✓	✓		