SUMMARY OF ACHIEVEMENTS
2010-2015

NCPRE

NATIONAL CENTRE FOR PHOTOVOLTAIC RESEARCH AND EDUCATION

Indian Institute of Technology Bombay

NATIONAL CENTRE FOR PHOTOVOLTAIC RESEARCH AND EDUCATION

Summary of Achievements 2010-2015

1. Introduction

The National Centre for Photovoltaic Research and Education (NCPRE) was established at the Indian Institute of Technology Bombay (IITB) in October 2010, with funding of Rs. 47.5 crore for 5 years from the Ministry of New and Renewable Energy (MNRE), Government of India. Coming as it did a few months after the formal launch of the Jawaharlal Nehru National Solar Mission (JNNSM) in January 2010, the mandate of NCPRE was to provide the research, education and training backdrop required for achieving the JNNSM targets.

Given the highly cross-disciplinary nature of photovoltaics (PV), it was felt that NCPRE should be a broad-based Centre, leveraging IITB's excellent track record of collaboration between Departments and goal-oriented group activity. A team of faculty members from several Departments got together, and, together with students, have been working on several major aspects of photovoltaics – solar cells, materials, power electronics, storage, deployment, module reliability, modelling and simulation. At present, **30 faculty members from 8 Departments participate in NCPRE, together with 120 post-graduate students and research assistants**, ably supported by several administrative and technical staff members.

NCPRE has progressed very well since its inception in 2010. This Summary provides an overview of the activities and achievements of NCPRE over the last 5 years.

2. Creation of Facilities

Through the funding received from MNRE, as well as inputs from IITB, several new laboratories and facilities specific to photovoltaics have been created. Equipment worth about Rs. 23 crore has been purchased, deployed and used (this includes 31 major equipments costing more than Rs. 10 lakhs each). **The facilities and laboratories have been widely used not only by NCPRE faculty and students, but also by other faculty and students from within and outside IIT (26 other institutions), as well as 14 PV industries.** Table 1 shows the laboratories newly set up by NCPRE, and the usage data. The funding from MNRE has thus created a major 'resource centre' in terms of facilities which are available for use by researchers from NCPRE as well as outside. Figure 1 (a) to (d) shows some of the labs created.

Table 1: Laboratories created by NCPRE

Name of the Lab	Area (sq ft)	Class	No. of lab users
NCPRE Fabrication Lab	1800	Clean Room	**53** (27 NCPRE and 26 Non-NCPRE)
NCPRE Characterization Lab	580	Semi clean	**103** (42 NCPRE and 61 Non-NCPRE)
NCPRE Devices and Interfaces Lab	830	Semi clean	**24** (4 NCPRE and 20 Non-NCPRE)
NCPRE Energy Storage Lab	325	General	**18** (4 NCPRE and 14 Non-NCPRE)
NCPRE Module Lab – I	1184	Semi clean	**28** (12 NCPRE and 16 Non-NCPRE)
NCPRE Module Lab – II	224	General	**10** (9 NCPRE and 1 Non-NCPRE)
NCPRE FESEM Lab	315	Semi clean	**167** (93 NCPRE and 74 Non-NCPRE)
NCPRE Students' Fab Lab	132	General	**8** (5 NCPRE and 3 Non-NCPRE)
Power Electronics Labs*	1000	General	**56** (34 NCPRE and 22 Non-NCPRE)

Fig. 1. (a) NCPRE Silicon Clean Room (b) Solar Cell Simulator in NCPRE Characterization Lab (c) ALD set-up in NCPRE Devices and Interfaces Lab (d) Module Simulator in NCPRE Module Lab - I

3. Education and Training

Education has been an important part of the activities of NCPRE, as the success of JNNSM would require trained manpower. NCPRE has contributed to education and training in a variety of ways: offering PV courses at IITB for UG and PG students; enhancing the number of M.Tech. and Ph.D. students in PV at IITB; running the **'Teach a 1000 Teachers' programme to train teachers from other colleges**; developing a **low cost PV lab kit and distributing 200 of them**; developing a low-cost students' solar cell fabrication laboratory; running many short-term courses for industry personnel, teachers as well as for master trainers for technicians. **A lab manual entitled 'Solar Photovoltaics: A Lab Training Manual'** and a technician training manual entitled **'Solar Photovoltaic Technology and Systems: A Manual for Technicians, Trainers and Engineers'** have also been published (the latter has been **translated into 4 languages** and are to be published). Some details are given in Table 2, and the low-cost lab kit is shown in Fig. 2.

Table 2: Highlights of Education Activities of NCPRE

PV Courses (UG + PG) at IITB	7 (2 have been converted to web-based video courses, 5 are under process)
M.Tech. projects at IITB	81 completed, about 50 in progress
Ph.D. students at IITB	21 completed, about 60 in progress
B.Tech. students who took courses in PV at IITB	159
'Teach a 1000 Teachers'	1 course in December 2011 – 946 participants from about 400 colleges
Short Term Courses conducted	32 Courses, Total number trained: 2776 (Industry: 721, Faculty: 1472, Students: 524, NGO Personnel: 59)
Courses for Master Trainers for Technicians	3 Courses, Total number trained: 121 (Industry: 43, ITI Faculty: 28, Other Faculty: 30, Students: 3, NGO Personnel: 17)
Low-Cost UG/PG Solar PV Lab Kits	Lab Kit cost is Rs. 50000; 200 kits distributed (165 through a separate grant from MNRE)
Books / Lab manuals	2 in English, and 1 each in Hindi, Marathi, Gujarati and Tamil
Low-Cost Students' Fab Lab	Consisting of 9 equipments like diffusion furnace, evaporator, lithography, etc. Total cost is approximately Rs. 22 lakhs

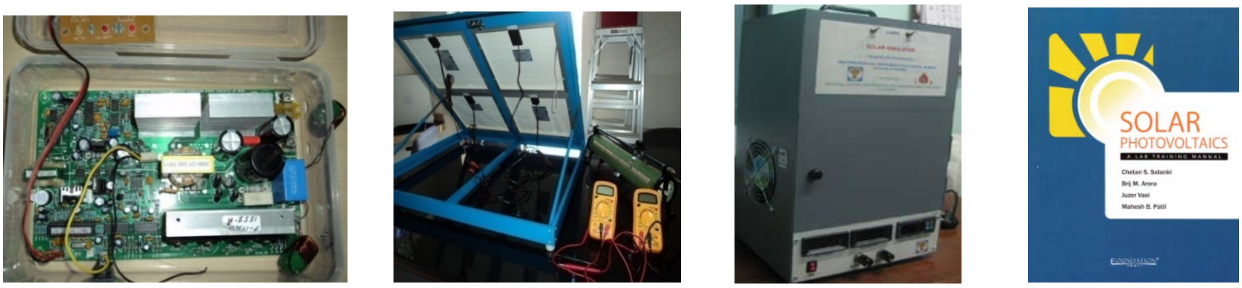

Fig. 2. (L to R) Components of the low-cost Lab Kit and accompanying Lab Manual

3. Silicon Solar Cells

The mainstream solar cell technology continues to be silicon, and therefore NCPRE's involvement in this area was deemed to be important, especially as it would allow interaction with industry in India. The target was to achieve **18% efficiency over a 100 cm^2 area**. Work on this at NCPRE started in August 2013 with the commissioning of the NCPRE Clean Room and installation of equipment. All unit processes were developed for **fabrication of solar cells on industry-size silicon wafers of size 5" X 5"** (Fig. 3(a)) and **6" X 6"**. The cell architecture developed is the screen-printed contact, aluminium back surface field structure, which is widely used by the industry. A stack of low temperature thermal oxide and PECVD SiNX:H is used for the front surface passivation. The best cell efficiency achieved so far is 17.84% on 155 cm^2 p-type mono-crystalline silicon wafers (Fig. 3(b)). The evolution of the cell efficiency is shown in Fig. 3 (c).

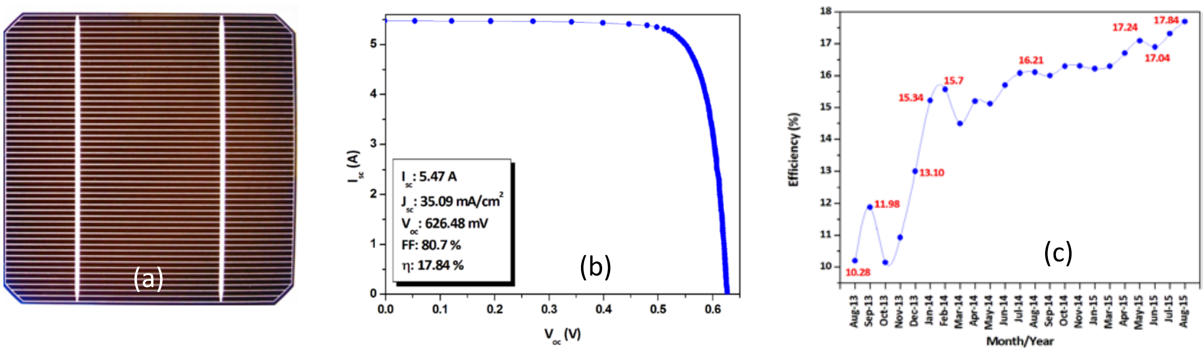

Fig. 3. (a) Photo of a 5" X 5" solar cell (b) I-V characteristics of a 17.84 % efficiency cell (c) The evolutionary path to the current 17.84 % efficiency.

During the two years of the development of the cell process, the silicon cell research team at NCPRE, which includes a large number of students, has gained significant expertise in various unit processes, process integration, characterization techniques and loss analysis methods. We have also developed wafer level characterization setups for electroluminescence (EL) and photoluminescence (PL). The cells fabricated at NCPRE have been extensively characterized using EL, PL, I-V, QE, spectrophotometry, contact resistance scan, lifetime, etc., and for developing models for 2D simulations. Using the cell baseline process as a platform, we are **currently engaged with several industries for: silver paste development; demonstration of double print contact process; and analysis and design of front contact grid**. The cells fabricated at NCPRE have been extensively characterized for developing models for 2D simulations.

Several novel processes are being developed by Ph. D. students working in the project. Examples include: Nickel/Copper front metallization has been done by electroless plating of Ni and electroplating of Cu (an active area cell efficiency of 18% has been demonstrated on 16 cm^2 area cells); a PERC cell process with SiN_X:H back-surface passivation, laser fired Al back contacts and Ni/Cu front contacts has been demonstrated with an efficiency of 15.5%; dielectric-metal-dielectric plasmonic structures have been developed for reducing front surface reflections (an improvement in J_{SC} of 1.2 mA/cm^2 is demonstrated);

a low temperature 350°C plasma oxidation process has been developed, and the layer integrated in our cell process and compared with thermal oxide; a spray coating process for Al_2O_3 is being developed and a surface recombination velocity of 28 cm/s demonstrated on p-type silicon surface.

Also as a part of the silicon solar cell activity, a Wire Electrical Discharge Machining (WEDM) technique was also developed for wafering of silicon. WEDM has shown the capability to reduce wafer kerf loss down to about 50 μm, and also to obtain thinner wafers of less than 150 μm. These wafers will now be used in our solar cell process to assess their suitability for cell fabrication.

4. New Materials and Devices

One of the major activities taken up at NCPRE under 'New Materials and Devices' was the development of > 5% semiconductor-sensitized solar cells, where the dye of a DSSC is replaced by a thin semiconductor layer, usually on a mesostructured scaffold. As a part of the NCPRE activity, we have developed and set up an atomic layer deposition (ALD) system (Fig. 1 (c)) for depositing various Extremely Thin Absorber (ETA) layers on a mesoporous layers. The system was successfully employed to deposit conformal thin films of various semiconducting absorber layers on porous oxide structures and blocking interfacial layer at TCO/porous-TiO_2 interface in ETA configuration. A detailed study on preventing the recombination losses by surface passivation using ultra-thin ALD grown metal oxides at the absorber/transporter interface has been performed. Amorphous Sb_2S_3 as an absorber material yielded a cell with an open circuit voltage of 380-400 mV and a short circuit current of approximately 1.5 mA/cm^2. Initial studies on annealed crystalline Sb_2S_3 based ETA cells have resulted in a V_{oc} of 500 mV and a J_{sc} of ~ 9.5mA/cm^2 with an overall efficiency of ~ 2%. Subsequently, in an effort to minimize the back recombination in the sensitized mesoporous structures, we also employed organic-inorganic lead halides (perovskites) as sensitizing material in the meso-structured scaffold based on titania. With optimization of the device structure, ~ 8.9% efficient devices were obtained, as shown in Fig. 4. The devices were fabricated in a complete solid state configuration with spiro-OMeTAD as hole transport layer.

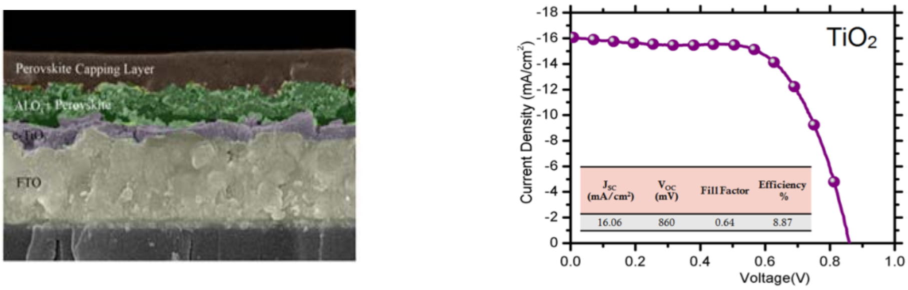

Fig. 4. Structure of a semiconductor (perovskite)-sensitized solar cell, and its I-V plot yielding η = 8.9%

As is now known, **the perovskite $MAPbI_{3-x}Cl_x$** (methyl ammonium lead iodide-chloride mixture) is ambipolar in nature with large diffusion lengths and a high absorption coefficient. This allows the removal of mesoporous scaffold layer, resulting in a simple planar bulk heterojunction device. Thermal co-evaporation or vapour-assisted vacuum deposition was employed by us to deposit the perovskite absorber layer, and **planar cells with efficiencies as high as 14%** have been obtained, as shown in Fig. 5.

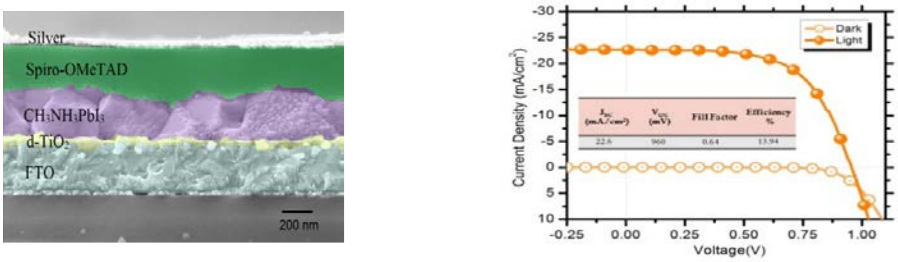

Fig. 5. Structure of a planar perovskite solar cell, and its I-V characteristic yielding η = ~ 14%

In addition to the work on SSSC and perovskites, NCPRE members have also worked on OPV, conventional DSSCs and QD based devices. In OPV devices, a comparative study was conducted of polymer solar cells (PSC) fabricated with defect-free poly (3-hexylthiophene) (DF-P3HT) and Region-Regular (RR) P3HT. A maximum efficiency of 3% and 4.1% were achieved for RR and DF P3HT devices respectively with a Fill factor of 68% in the DF-P3HT case, which is one of the highest reported values. Transient photocurrent and photovoltage measurements were done on these devices to estimate the decay time constant (τ), charge carrier density (n) and bimolecular recombination coefficient (k). In DSSCs, work on TiO_2 nanorod based devices has been carried out. Work has also been conducted on QD based wavelength shifting for PV devices, and QD-based all-Si tandem cells.

5. Power Electronics and PV Systems

Besides the work on solar cells (both silicon and other materials), NCPRE has a great deal of activity on power evacuation strategies through power electronics interfaces and PV microgrids, as well as on storage aspects related to PV systems.

The motivating theme of the power electronics activity has been to devise strategies and circuits which are robust, reliable and efficient, and therefore which can be deployed in the rural sector of India. Accordingly, the following systems have been developed. (1) Development of a **reliable and efficient stand-alone 500 VA solar PV systems for rural house hold applications** (Fig. 6 (a)). While developing these schemes the main consideration was to reduce the number of intermediate power conversion stages, which led to the increase in efficiency and also the reliability of the system due to the reduction in component count. Four different topologies have been developed. Operating full load efficiencies of the topologies are ~ 90%. (2) **Development of solar PV pumping systems**. In the agricultural sector, induction motor driven irrigation pumps are the main work horse, so a power electronics interface along with a PV module to feed the already deployed induction motors would optimize resources. A drive has been developed wherein the front-end converter is an interleaved dc to dc converter to reduce the size of the magnetic elements. It is known, however, that Brushless DC (BLDC) motor based pumps would be more efficient than conventional induction motors. Hence for new installations, a low-cost tubular BLDC motor (using ferrite magnets instead of rare earth magnets), shown in Fig. 6 (b), has been designed and fabricated having an estimated efficiency of ~ 90%. (3) A **reliable 5 kVA transformer-less roof top grid connected system** has been developed (Fig. 6 (c)), using a multilevel inverter topology so that the size of the magnetic filtering devices is reduced considerably. The switching devices of the converters are SiC devices and the part load efficiency of the overall system is found to be 94%.

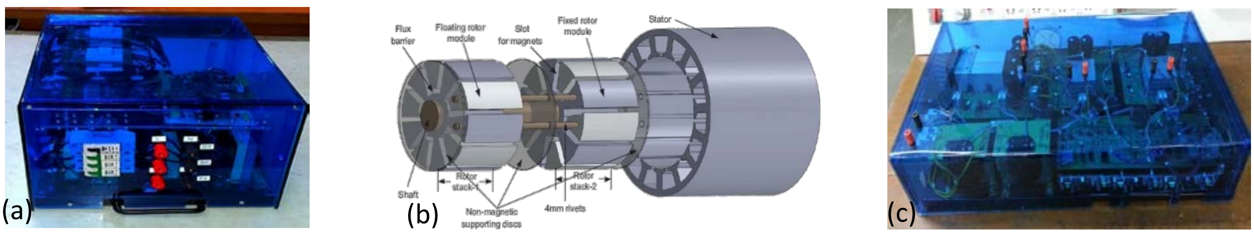

Fig. 6. (a) 500 VA stand-alone inverter (b) BLDC motor (c) Grid-connected 5 KVA system for rooftop

In addition to work on power electronics, NCPRE has also worked on solar PV microgrids in the following areas: novel techniques for analysis of sources in microgrids; novel inertia design methods for islanded ac microgrids with static and rotating energy sources; new strategies for energy management in microgrids; and new techniques for transient response improvement in microgrids during islanding.

In the area of storage, NCPRE has concentrated on the **development of Li ion battery storage suitable for PV applications.** The activities include: development of low-cost ($LiMn_2O_4$) and high energy density ($LiMn_{1.5}Ni_{0.5}O_4$) cathode systems for Li-ion batteries; development of high-performance and high tap density $LiFePO_4$ cathode; novel anode systems for Li-ion and Na-ion battery systems. This work has resulted in several patents, and we now have the technology to make industry grade Lithium-ion battery with 0.75 Ah pouch cell. We have started making such battery cells and have been testing them in solar lantern applications.

6. Characterization, Modelling and Module Reliability

Characterization plays an important part in PV, from the characterization of new materials to cells to modules. NCPRE has set up excellent characterization facilities for all these measurements, which are widely used as shown in Table 1. In addition, techniques like electroluminescence (EL) and photoluminescence (PL) have been developed in-house, and new variants developed. The in-house PL system is shown in Fig. 7 (a). **A new portable EL image processing system and technique** (Fig. 7 (b)) has been developed which allows module images to be taken in the field in daylight conditions (normally modules would have to be taken to a dark room lab). EL images taken in a dark room and in the field in daylight are shown in Figs. 7 (c) and (d), indicating excellent match.

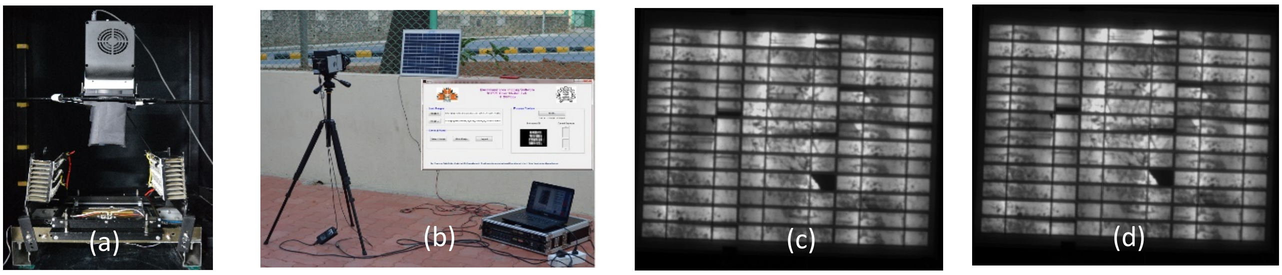

Fig. 7. (a) In-house PL system (b) Portable Daylight PL system (c) Module EL image taken in dark by conventional EL technique and (d) Module EL image taken in field by daylight EL technique

Characterization of module reliability and degradation in India has been taken up in a major way by NCPRE (together with NISE). We conducted two **'All-India PV Module Surveys' in 2013 and 2014**, where modules at various sites covering all climatic zones and different technologies were taken up as shown in Table 3 and Fig. 8 (a) and (b). The 2013 as well as 2014 data have generated many interesting results. One of the concerns arising from this field data is the higher than expected degradation rate (% reduction in P_{max} per year) in the hot climates of India, as seen in Fig. 8 (c). This will be discussed in detail at the international workshop being co-organized by NCPRE at IITB in October 2015, entitled **'PV Module Reliability in Hot Climates'**. Fig. 8 (d) shows the 2013 survey report, which has attracted much attention. In addition to the All-India surveys, continuous monitoring of PV modules of different technologies has been going on for the last 3 years on the NCPRE rooftop to assess relative performance and degradation.

Table 3: All-India Surveys of PV Modules, 2013 and 2014

Year	No. of Sites	No. of Modules	Types of Technologies	Measurements Performed
2013	26	63	Mono c-Si, Multi c-Si, a-Si, CIGS	Visual Inspection; Illuminated *I-V* characterization; IR imaging at some sites; Socio-economic Survey
2014	45	1080	Mono c-Si, Multi c-Si, a-Si, CIGS, CdTe	Visual Inspection; Illuminated *I-V* characterization; Dark *I-V* characterization; IR imaging under illumination; IR imaging in dark; EL Imaging; Interconnect Failure Test; Dry insulation resistance measurement; Wet insulation resistance measurement; Performance Test of Off-grid Inverters; Socio-economic Survey

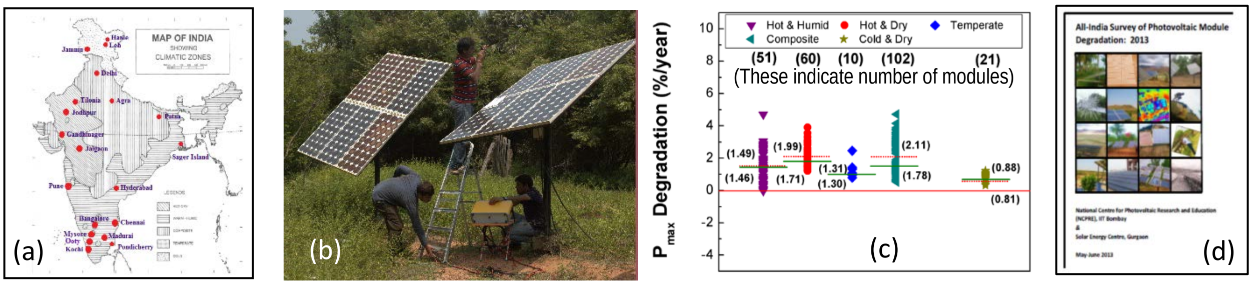

Fig. 8. (a) Sites for the 2014 All-India Survey (b) Taking data in the field (c) Power degradation (%/year) for different climatic zones for > 5 year old c-Si modules (d) 2013 Survey Report.

Activities in the modelling and simulation areas, which assist the other research activities of NCPRE, include: SEQUEL-based simulation of power electronics circuits; modelling/simulation of shading effects; simulation of plasmonic effects, modelling of the WEDM technique, and process simulation of silicon solar cell fabrication.

7. Deployment and Policy

NCPRE has been involved in several deployment-related activities and surveys. At the request of KSEB, the NCPRE team undertook a survey of rooftop **PV potential in semi-rural Chendamangalam panchayat in Kerala,** performing an exhaustive survey of all buildings and electricity usage patterns in the panchayat, covering 6500 structures including residences, shops, institutions, and public buildings (Fig. 9 (a)). The survey found that there is a **potential of 11 MW of rooftop PV which can supply annually about 12 million units of electricity as against the panchayat's requirement of 6.8 million units**. A unique study in Thiruvananthapuram to utilize rooftop PV for shifting the peak load was carried out by NCPRE, and launched by **KSEB as the 'SunShift' programme**. NCPRE also helped design the hardware system for this programme. **A survey of rooftop potential in Mumbai city has been undertaken**, by evolving a comprehensive methodology which combines GIS based imaging, together with some site visits to calibrate the GIS data (Fig. 9 (b)), and estimation of shadowing effects from nearby structures (Fig. 9(c)). This work was done by NCPRE jointly with Centre for Urban Science and Engineering (C-USE, IITB), Bridge to India (BTI), Observer Research Foundation (ORF) and IEEE Bombay Section, and has yielded **a preliminary rooftop PV potential of about 1.5 GW for Mumbai**. The methodology developed is being extensively documented so that it can be applied to other urban areas as well.

Fig. 9. (a) Exhaustive survey in Chendamangalam (b) GIS + Site Visit Methodology used in Mumbai BMC wards (c) Estimating shadow-free rooftop area in a building.

NCPRE has also been involved in several policy-related activities, discussions and workshops. NCPRE and its faculty members participated intensively in the **"Technology Foresight Study for Solar PV" commissioned by TIFAC, and held 2 related workshops at IITB**. NCPRE also organized workshops on **"Make in India for a Solar India"** and "Future Directions for PV Research in India". NCPRE, together with Prayas and BTI, worked on the technical and policy aspects of connecting distributed rooftop to the grid, resulting in a joint report entitled, **"Grid Integration of Distributed Solar Photovoltaics in India"**.

8. Papers, Patents and Reports

The research work done in NCPRE by faculty and students has resulted in a number of papers, presentations at conferences, patents and reports. These are given in Table 4. In addition, 19 Quarterly Progress Reports have been sent regularly to MNRE documenting the progress made every quarter.

Table 4: Research Output

Journal Papers	Conference Presentations	Reports	Patents
126	218	6	13

9. Industry Affiliate Programme and Outreach

At the initiation of NCPRE, it was decided that in order for its work to be relevant to the solar PV industry in India, it should engage strongly with industry. Accordingly, an **'Industry Affiliate Programme' was launched in 2011, which currently has 18 industry / NGO members**.

In order to ensure good outreach and dissemination of information, NCPRE launched its website www.ncpre.iitb.ac.in in 2011. NCPRE has also participated in exhibitions including Intersolar India (5 times) and Solarcon (2 times), where its booths have attracted a lot of attention.

10. NCPRE as a PV Resource Centre

Through the work carried out during the last 5 years in various aspects of photovoltaics, **NCPRE has emerged as a major 'PV Resource Centre' for India**. NCPRE has a critical mass of faculty, students, and research staff, coming from different backgrounds. The critical mass and diversity of expertise together ensure that any problem in PV can be adequately addressed.

Arising out of the establishment of NCPRE, the PV group at IIT Bombay has got engaged in a number of other PV-related activities in India and internationally. These include: a major involvement in the **Solar Energy Research Institute for India and the US (SERIIUS)**; the launching of the SOUL programme for a unique methodology for the distribution of 1 million solar lamps for school children; and the launch of a start-up company in IITB's technology incubator.

11. Future Plans

The 5-year funding period for NCPRE came to an end in October 2015. The Ministry of New and Renewable Energy has approved Phase II of NCPRE, with the intention that the facilities, expertise, manpower and resources created should continue to be available and utilized. Phase-II will focus on the following areas: High-efficiency silicon solar cells with efficiency >22%; Perovskite single-junction and tandem-junction solar cells with high stability; Development of indigenous Li-ion battery pack and charger; Commercialization of power electronics systems developed during Phase-I; Grid stability issues for distributed rooftop solar PV; Reliability and durability of PV modules in Indian climates, and development of accelerated test protocols; Performance assessment of PV plants. Besides these R&D areas, the complementary focus on education would also continue, with a new thrust on entrepreneur training.

In conclusion, NCPRE has made excellent progress since it was established in 2010. **NCPRE has emerged as a major centre for PV education and research in India, and one of the leading centres in the world.**