HISTORY OF SOLAR ENERGY RESEARCH IN BRAZIL

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ABSTRACT

Brazil has large, unelectrified, geographic regions with very high insolation throughout the year. Development of solar energy research in Brazil evolved through establishment of well-equipped laboratories, spread of post-graduate education and basic research during 1958-72, intense applied research on solar thermal viz. collectors, refrigeration, furnaces, cookers, driers, and distillation; and photovoltaics viz. c-Si solar cells, Cu_2S, CIGS, CdTe and a-Si:H thin-film solar cells and module manufacturing during 1973-83 and again after 1994 with higher emphasis on field-deployment of photovoltaic (PV) systems during the last few years. The boost provided by the recent expansion of research, development and industrialization and emphasis on universalization of energy through rural electrification point towards a bright future for solar energy research and applications in Brazil.

1. INTRODUCTION

Brazil, the largest country in Latin America, has an enormous land mass, a tropical climate, and is blessed with mineral and natural resources including fairly regular, very high insolation in most parts of the country. There are large unelectrified geographic regions with very high insolation throughout the year, some having amongst the highest levels in the world. Mean daily insolation in the north and northeast of Brazil ranges from a minimum of 184 W m^{-2} (Ze Doca, Maranhão) to a maximum of 260 W m^{-2} (Petrolina, Pernambuco). This fact, together with the typical low energy consumption of the local population makes solar the most appropriate choice of alternative energy. The emphasis on industrialization since World War II, and the growth in postgraduate education, research and development later have resulted in a strong and wide-spread industrial base, a large number of trained personnel, and fairly well equipped research and development institutions in Brazil. Solar energy research in Brazil dates back to the 1950s. The first period, from 1958 to 1972 was dedicated to fundamental studies. These studies promoted the basis for the following years, 1973-1983, that were characterized by technology development. The Brazilian Association of Solar Energy was created in 1978 with regional offices in various states; however the activities ceased after ten years. From 1986 to 1994, solar research activities were practically discontinued due to the lack of specific funding in this area. Fortunately, there has been substantial growth in the activities after 1994. Scientists from universities and utility companies met to establish plans and a program for renewable energy in Brazil. The *Declaration at Belo Horizonte* and *Permanent Forum of Renewable Energy* were formulated through these meetings in 1994 and 1996 respectively. In parallel, the electric utilities sector perceived the need for using new energy sources for meeting the goals of universalization of energy established by the Government. The overall outcome was the initiation of new financing programs that have led to the present phase of great advancement of technology.

2. EARLY RESEARCH

Solar energy research on flat plate solar collectors, selective surfaces, ammonia/water solar refrigeration, small solar furnaces and photovoltaic (PV) panels started around 1955 at the Instituto Nacional de Tecnologia (INT) in Rio de Janeiro state and the Centro Tecnológico de Aeronáutica (CTA) in São Paulo state in Brazil. In 1958, the Instituto Tecnológico de Aeronáutica (ITA) in CTA and INT organized the 1st Brazilian Solar Energy Symposium. In 1963, funding ceased due to the perception that solar devices would not compete with fossil fuels at prevailing price levels and most of the activities in the area, except in solar water heaters and driers were discontinued.

3. SOLAR THERMAL

In 1967, ITA built and tested small solar stills and solar cookers. In 1969, limited funds were received for the design of a small steam engine. In 1972, the postgraduate course in Thermal Sciences at ITA obtained financing to develop concentrating and flat plate collectors, solar stills, driers and engines for isolated regions of Brazil. ITA also advised Centro Estadual de Pesquisas de Cacau (CEPLAC), in Bahia state, on solar-assisted drying of cocoa beans. In 1972, ITA helped inaugurate the Solar Energy Laboratory (LES) at the Federal University of Paraíba (UFPB) to improve rural energy availability as a stimulus for social development in the arid Northeast. In 1973, LES received funding to set up the first Brazilian solar radiation measuring network covering the state of Paraíba.

Responding to the 1973 oil crisis, the Brazilian government substantially increased funding of solar energy research all over the country, especially to the institutions that already had expertise in this research area. A redefinition of priorities in 1973 led CTA to wind up and transfer its solar activities. A 1.5kWe solar furnace at the Materials Research Laboratory was transferred to LES. LES began to develop solar stills, driers, absorption, refrigeration and natural cooling with guidance from ITA, University of California, Berkley and foreign experts from France, India and Canada. In 1975, ITA´s Solar Engine project (and its financing) was transferred to LES. The design used R-11 as the working fluid with a hot temperature of 80^oC. The main research area in the postgraduate course in Thermal Engineering inaugurated in 1975 was Solar Energy. In 1978, a 1kW Solar Engine prototype was completed but operated unsatisfactorily because of feed pump leakage due to low liquid R-11 viscosity. In 1977, LES also tested a 1 kW commercial solar water pumping unit manufactured by Sofretes (France)for two years, prior to installation in a village in the semi-arid region of Ceará state. In 1976, LES started research on desiccant solar air conditioning for humid climates. Laboratory results at LES were satisfactory. A small prototype was constructed in Mato Grosso state (1) but the large quantities of airborne dust and soil rapidly clogged the system in that location. In order to facilitate dust removal and provide accumulation for desiccant solar air conditioning systems, a small (cross-sectional area 1 m^2 and depth 40 cm) circular calcium chloride salt gradient solar pond was constructed and tested in 1982. Maximum temperatures of 87ºC (ambient air 25.4ºC) and minimum temperatures of 68.5ºC, (ambient air 23.8ºC) were attained. Higher temperatures could have been achieved in a deeper pond with reduced wall shading.

After the reduction in oil prices drastically reduced solar thermal funding in 1980, experimental research in the mechanical engineering postgraduate program of UFPB concentrated on radiometry and flat plate and cylindrical parabolic collectors, though theoretical investigations continued in all areas. An electrically compensated pyranometer project was started at UFPB in 1980, to develop a cheap instrument for national networks (2). The research continued through 2002 with the cooperation of the electrical engineering department. The results were satisfactory but the number of imported pyranometers already installed in measuring stations deterred production. In 1982, a prototype small liquid piston water pump was built and tested. In spite of the low maximum thermal efficiency of under 0.3%, the system could be attractive where waste heat is available due to low cost and simpler construction and maintenance.

4. SOLAR PHOTOVOLTAIC

Development of crystalline silicon (c-Si) cells was carried out at the Microelectronics Laboratory (LME) of São Paulo University (USP). It resulted in successful single-crystal silicon ingot growth by Czochralski method, texturing, deposition of transparent, conducting and anti-reflection coatings of SnO_2, simultaneous deposition and diffusion of phosphorus to obtain p-n junction formation using a conventional liquid source and a conventional diffusion furnace, selective electroless Ni deposition, Sn-Pb solder dip, etc. 12.5% c-Si solar cells were prepared. The research and development activities in microelectronics served as a basis for this development.

During the ‘70s, research and development of first generation thin-film solar cells of Cu_2S/CdS was carried out at the Instituto Militar de Engenharia (IME) in collaboration with the Institut fur Physikalische Elektronik (IPE) at Stuttgart University. It was realized that countries such as Brazil and India with a high level of insolation would be ideal places for harnessing solar energy. There existed certain idealism that these countries did not need to resort to the use of nuclear energy for satisfying their energy needs and therefore, research groups in the developed world should encourage and support groups in the developing countries to realize this goal. Thus IPE provided guidance and know-how for the installation of a complete line at IME for the fabrication of 5 cm x 5 cm Cu_2S/CdS thin-film solar cells. The research culminated in the development and fabrication of a 5% efficient 30 cm x 30 cm, fully encapsulated CdS/Cu_2S mini-module (3). After successful testing, it was deployed on the roof of the IME building and tested periodically. Because of the problem of its rapid degradation, the research was reoriented to copper-indium selenide solar cells in collaboration with the National Renewable Energy Laboratory (NREL), formerly known as the Solar Energy Research Institute. Stoichiometric $CuInSe_2$ thin films with chalcopyrite structure were prepared by three-source elemental co-evaporation (4). The solar cell development work at IME counted on the foundation of research on preparation and characterization of CdTe, CdSe, CdS, InP and SnO_2 thin films, highly pure Al thin films, single and multilayer coatings of contact materials, resistive films and photolithography. In 1997, IME initiated a project on research and development of CdS/CdTe thin-film solar cells in cooperation with NREL. The emphasis was on the study of the microstructure and physical properties of the layers in the cell (5). Specific funds from the Centro de Pesquisas e Desenvolvimento da PETROBRAS (Brazilian Oil Company) and from the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), a government funding agency have provided conditions for obtaining the first CdS/CdTe solar cells in Brazil by the end of 2004. The efficiency confirmed at NREL is 4.4%, a low value compared to the world-wide record of 16.4%, but it can be increased after improving the processing stages.

During the early ‘70s, the Fundação Centro Tecnológico de Minas Gerais (CETEC) organized a robust research program on solar energy. During the ‘80s the first planar solar collector in the country and lab-scale process of shape memory TiN alloys for use in solar engines were developed. A proprietary study of the feasibility of implanting a plant for the production of polycrystalline electronic grade (EG) Si was also concluded. Based on this and a few other studies CETEC, Universidade Estadual de Campinas (UNICAMP) and Centrais Elétricas Brasileiras (ELETROBRAS) started working to implement variants of the Siemens process for the production of EG-Si (6). CETEC’s research resulted in a $SiCl_4$ lab and pilot plant from metallurgical grade (MG)-Si. UNICAMP’s research got further and resulted in patents to deposit polycrystalline EG-Si. In the mid-‘90s, UNICAMP refined MG-Si by e-beam to 99.990% Si. More recently, CETEC resumed its work on the Siemens process, aiming at EG-Si in the long run and a solar grade (SG)-Si pilot plant before the year 2009. It is worth mentioning that the State of Minas is currently responsible for 24% of all the worldwide production of MG-Si. The State Utility Company - CEMIG is responsible for the supply of electrical energy for this purpose. Laboratory scale processing of silanes has been improved and intensified to provide statistically relevant information. The chemical vapour deposition (CVD) of poly-Si will be initiated in June 2005. Preparation and characterization of lab-scale device quality RF CVD a-Si:H has been investigated extensively. CETEC has been processing $Si_{1-x}C_x$-based thin films with plasma-assisted e-beam reactive evaporation and has obtained encouraging results. The next phase of the project will develop sputtering and plasma-enhanced chemical vapour deposition (PECVD). The latter is supposed to use monosilane, also a CETEC product. It is expected that these efforts will result in sustainable Pilot Plant Processing of low cost a-Si:H/c-Si solar cells. The durability of these cells will be evaluated in co-operation with Pontifícia Universidade Católica do Rio Grande do SUL (PUC-RS) in a new 40 kW solar simulator laboratory. In December 2003, CETEC and CEMIG established the Nuclei for Excellence on Solar Materials Engineering. The initial total area of the centre is 1000 m^2 for thin-film processing, refining solidification of Si as well as device performance measurement.

Other activities in this period deserve to be mentioned. For example, the development of amorphous hydrogenated silicon (a-Si:H) thin-film solar cells was carried out at UNICAMP. A-Si:H, a-SiN:H, a-SiC:H and a-GeSn:H thin films were prepared by plasma-assisted deposition. Testing of space-worthy solar cells was also initiated at Instituto de Pesquisas Espaciais (INPE). A series of solar cells workshops was organized in conjunction with the Brazilian Vacuum Congress. A new company - Heliodinâmica - was established at São Paulo for fabrication of c-Si photovoltaic modules.

1986-1994 was a period marked by precipitous reduction of funding in this area. This scenario led to the extinction of several solar energy groups that were forced to reorient their area of research. However, the period after 1994 is marked by significantly larger expansion of research development

Fig. 1: 2 kWp a-Si:H grid-connected BIPV installation in Florianopolis, SC, Brazil

and deployment activities. The substantial new funding from the Federal and State Governmental programs for alternative energy led to creation of new research groups. Three groups have reported the efficiency of their crystalline silicon solar cells: 11% at USP in cooperation with INPE. These cells were used in the first Brazilian complete space mission satellite, launched on February 9, 1993 (7); UNICAMP reported a c-Si solar cell with 16% efficiency by combining inexpensive surface texturization, standard doping, back-surface field (BSF) and a chemically sprayed TCO (8). More recently, a 17% efficient bifacial solar cell was developed through Brazil-Spain cooperation (9).

LABSOLAR, the solar energy research laboratory at Federal University of Santa Catarina (UFSC) began solar thermal and radiometry research in 1989 and photovoltaics in 1997. In 1997, the first grid-connected, building-integrated, thin-film PV system in Brazil was installed at LABSOLAR, on the main campus at UFSC (10). It consists of a 2kWp thin-film amorphous silicon (a-Si:H) array. The PV array uses unframed modules designed for building-integrated PV (BIPV) applications. Fig. 1 shows the BIPV system. The main objectives of the project are twofold: (i) demonstration and dissemination of the concept of PV in buildings in Brazil; and (ii) a long-term experiment on the seasonal effect affecting the performance of a-Si:H thin-film solar cells. In 1999, LABSOLAR worked on a 4.7 kWp stand-alone project for a hybrid PV-Diesel system for deployment on 150,000 m^2 Ratones Island, close to Florianopolis. The PV system was added to an existing Diesel generator set and the 28.8 kWh (@48V) battery bank that provides 2 days of storage. In 2001, LABSOLAR installed the first hybrid Diesel/PV system without storage in the Amazon. This 20.4 kWp PV installation was added to an existing Diesel mini-grid to demonstrate the economic and technical potential of medium to large systems without battery banks for the supply to villages in the Brazilian Amazon region, where hundreds of mini-grids fed by Diesel thermal units exist. Fig. 2 shows the PV system installed in the Amazon. In 2001, LABSOLAR, together with NREL and the Arizona State University (ASU), designed a 4-year experiment to assess the performance of a-Si:H devices operating in different climatic conditions. Three identical sets of commercially available a-Si:H PV modules from five different manufacturers were simultaneously deployed outdoors at three sites with distinct climates (Site A - NREL: Golden, Colorado-USA, climate: dry continental, with cold winters and warm summers, Site B – ASU PV Testing Laboratory: Mesa, Arizona-USA, climate: dry desert, with cool winters and hot summers and Site C - LABSOLAR: Florianopolis-Brazil, climate: humid, coastal, with warm winters and hot summers) in a round-robin exposure experiment. In collaboration with private companies and utilities, LABSOLAR has also been carrying out research and demonstration projects. One such partner is PETROBRAS. LABSOLAR is in the process of installing the largest grid-connected PV system in Brazil, a 44.4 kWp system using six thin-film PV module types from different manufacturers, and two petrol stations with 10 kWp of BIPV modules each in collaboration with PETROBRAS. With the state utility CELESC, and with the neighboring state utility CEMIG, LABSOLAR also has co-operation agreements that encompass education and training on PV, as well as scientific and demonstration projects. The Brazilian Center for Development of Solar PV Energy (CB-Solar) was created in 2004 at the PUC-RS with support from the Ministry of Science and Technology (MCT), State Government of Rio Grande do Sul, municipality of Porto Alegre and the state electric utility. CB-Solar is the most modern and well-equipped photovoltaic research centre in Latin America having a total area of 700 m^2 with 190 m^2 of clean room (10,000, ISO7), divided in seven laboratories (Fig. 3). The solar cell laboratory is the largest among

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Fig. 2: Hybrid Diesel/PV installation in the Amazon, with a fully monitored, north-facing 20kWp PV system at latitude tilt (10^o), and Diesel thermal plant in the background.

Fig. 3: Clean room facilities (190 m², 10.000 class, ISO 7) designed to produce silicon solar cells and PV modules.

them. It has rooms for diffusion furnaces, chemical processing, photolithography, thin-film deposition, encapsulation, etc. There are other laboratories for characterization, indoor measurements, outdoor measurements, simulation and certification of PV modules. The activities of CB-Solar consist of the development of new and more efficient structures for PV energy conversion, analysis of technologies for economic fabrication of solar cells and PV modules, study and establishment of new PV systems and training of necessary manpower. The clean room was designed to produce single-crystal and multicrystalline Si cells and modules with different metallization techniques and various methods for diffusion of impurities using conventional and rapid thermal furnaces. Modules can be tested following IEC standards and monitored under outdoor conditions and integrated in PV systems. As a part of its activities, CB Solar initiated a project on research and development of a production line of low-cost crystalline silicon PV modules using labor-intensive technologies.

The most recent and important Brazilian event on solar energy, the 1st National Symposium on Solar Photovoltaic Energy was held at PUC-RS in July 2004. 135 participants from Universities, Research Centres, state electric utilities, CNPq, FINEP, Ministry of Mining and Energy (MME) and MCT identified the various Brazilian entities in the area of solar PV energy and assessed their potential. Technological aspects such as production of SG silicon by alternative routes, thin-film solar cells, low-cost silicon solar cell processing and rural electrification were discussed. The survey of the PV activities of various groups showed the existence of ongoing collaborative research among institutions and also stimulated new collaboration programs.

There were new advances in the area of solarimetry. These resulted in significant developments such as the publication of two atlases viz. Atlas of Solarimetry in Brazil (in Portuguese) published in 1997 by the group of alternative energy sources at UFPb, and Atlas of Solar Irradiation in Brazil (in Portuguese) published by LABSOLAR and INPE. Various other projects are being implanted in this area. Several of these have been funded by the Centro de Referência para Energia Solar e Eólica Sérgio de Salvo Brito (CRESESB) with headquarters at Centro de Pesquisas de Energia Elétrica – (CEPEL) belonging to ELETROBRAS and attached to MME. CRESESB has provided strong support for disseminating the knowledge of renewable energy sources and training of personnel. Another important milestone was the creation in 1994 of the Brazilian branch of the International Solar Energy Society.

From the market side, the lack of minimum modern comfort in the countryside has led public authorities to search for alternatives and consequently increase the value of photovoltaic electricity generation. It did not come as a surprise that the current Brazilian administration set the goal of 'Universalization of Energy' i.e. providing access to electric power for 100% of Brazilians by 2015. The solar energy market has grown considerably in the last 10 years because of the Federal and State Governmental programs. Soon after the Environment Conference, Rio-92, the Brazilian state governments and the U.S. Department of Energy (DOE) reached an agreement to establish a project for the utilization of PV and wind systems in rural areas of Brazil. CEPEL, NREL and the participating utilities signed agreements. CEPEL managed the overall project and was responsible for providing technical support to the utilities and monitoring their performance. The state utilities executed the project and were responsible for installation and maintenance of the systems in their states. NREL procured the basic components which were donated to CEPEL and transferred to the utilities. Approximately 180 kWp of PV modules and 40 kW of wind turbines were installed. Almost 1200 systems were deployed. The project worked satisfactorily until the moment that utilities were re-organized and prepared for privatization. Then the reduction in personnel and changes in priorities led to an extinction of the projects and loss of previously trained personnel.

The Program for Energy Development of States and Municipalities (PRODEEM), established in 1994 is managed by MME. It has supplied electric power to rural communities located in remote regions, where the energy consumption is low. PRODEEM may be considered one of the largest PV based rural electrification programs in the developing countries (11). CEPEL is responsible for providing technical guidelines, including equipment specification, project evaluation, training of personnel and installation of PV systems, together with the local entities. Another ELETROBRAS project, *Ribeirinha*, is dedicated to the population that is located in the neighbourhood of the rivers in the state of Amazon. Another more recent and extensive MME Program is the "*Luz para Todos (Light for All)*". It is executed by the state utilities together with the state governments and has the objective to supply electric power to approximately 12 million people by 2008. In its first stage, it is expected to include 1.4 million families – 90% of them living in rural areas –by 2006. However, the high cost of transmission/distribution lines may become an impediment for the utilities reaching this goal. In this context, PV solar energy may represent a viable alternative mainly because Brazil presently can count on a large cadre of qualified, trained personnel. Two large utility companies have already decided to implement PV solar in places where this alternative choice is technically and economically feasible. Table 1 shows the distribution of systems and electric power of the PV modules that were installed during the various stages of PRODEEM. PRODEEM is mainly based on PV systems and since May 1996 CEPEL and MME have already carried out six International Biddings for acquisition of the necessary equipment, (CEPEL, 1996a; CEPEL, 1996b; MME/CEPEL, 1997; MME/CEPEL, 1998; MME/CEPEL, 1999 and MME/CEPEL, 2001) known as Phase I, II, III, IV and V, respectively, and a special phase named Pump (11). The amount of PV power already involved in the six phases of PRODEEM by the end of 2001 is ~5.2 MWp with over 8,700 PV systems. The installed systems are scattered throughout all the 26 Brazilian Federal States, with higher concentration in the Northeast and North regions of the country. After 2002, due to the problems faced in the sustenance of PRODEEM, MME decided to promote a huge re-organization in this Program, with the aim of reviving all the systems that were installed until the end of 2006, then transferring the operation and maintenance tasks to the utility companies all over the country as well as incorporating them in the Program *Luz para Todos*.

The discontinuity in funding took its toll forcing researchers to redirect research areas with the notable exceptions of IME which continued activities in the same areas because of the strong base and critical mass; and LME, USP which transferred solar cell production know-how to INPE.

TABLE 1: PV SYSTEMS AND POWER INSTALLED DURING THE DIFFERENT STAGES OF PRODEEM

Phase	PV electric energy systems		PV water pumping systems		PV public lighting systems	
	Qty	*kWp*	Qty	*kWp*	Qty	*kWp*
I	190	*87*	54	*78*	137	*7.5*
II	387	*200*	179	*211*	242	*17*
III	677	*419*	176	*135*	x	*x*
Pump	X	*x*	800	*235*	x	*x*
IV	1,660	*972*	1,240	*696*	x	*x*
V	3000	*2,172*	x	*x*	x	*x*
Total	5,914	*3,850*	2,449	*1,355*	379	*24.5*

Qty: number of PV systems, kWp: PV power

5. CONCLUSIONS

Considerable progress was made in the fields of solar thermal and photovoltaic energy in Brazil during 1973-83. This was followed by a relatively subdued progress. Large projects of research, development and rural electrification that have been launched since 1992 and especially during the last few years are bringing the potential of solar energy within the grasp of the huge underprivileged masses in Brazil. These facts combined with a rich body of basic and applied knowledge and several strong projects aiming at pilot production of SG silicon and solar cells, show that Brazil has a sunny future for the full use of the potential of solar energy.

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