Funding Breakthrough Technology

Case summary : Photovoltaics

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This case summary is part of the 'Funding Breakthrough Technology' project. This project is in the commercialisation stream of activities of the EPSRC funded Cambridge Integrated Knowledge Centre (CIKC) in photonics and macro molecular material. Historical case studies of eight breakthrough technologies of the last 60 years are being investigated with the specific focus of how these technologies were supported and finance in their journey from the lab to market. The other case studies are Light emitting diodes (LEDs), Liquid Crystal Displays (LCD), Inkjet printing, Fibre optic communications, Giant Magnetoresistance (GMR) and Micro electronic mechanical systems (MEMS).

This case study was completed by Shu Sun as part of his fourth year Masters of Engineering (MET) long project under the supervision of Andy Cosh and Samantha Sharpe. All of the case study documents are works in progress. If you would like to comment on any of the case study summaries please contact Dr. Samantha Sharpe at the Centre for Business Research on email (s.sharpe@cbr.cam.ac.uk) or telephone (+44 (0) 1223 765 333. As these documents are works in progress we would request that the case studies not be cited without the author's permission.

Introduction

Photovoltaic technology is one of two main technologies used for harnessing solar energy, the other being solar thermal technology[1]. A photovoltaic cell is a device that converts sunlight directly into electricity by the photovoltaic effect, where photons in sunlight knock loose electrons and induce a current flow in the cell. Photovoltaic cells are generally classified into three generations, which indicate their approximate order of emergence.

The first generation of photovoltaic cells are single- and poly-crystalline, wafer-based silicon cells. These solar cells are large in size and manufactured from mainly very pure silicon in a fashion similar to electronic chips. Energy is extracted from photons through a single p-n junction. These cells have a theoretical maximum efficiency of 31%[2] and current cells are very close to this level. The manufacturing process is complex and energy intensive, thus expensive. The raw material cost, due to the demand for purity of the silicon, is also high. This leads to an overall expensive product and long pay back period. Its stability and efficiency, on the other hand, are its key advantages.

The second generation of photovoltaic cells attempt to address the problem of high material and production cost of the first generation. These cells are most commonly associated with thin film cells, designs that use minimal materials and cheap manufacturing processes. Instead of using a bulk material, these cells utilise a thin layer of material to absorb and convert sunlight into electricity. The associated manufacturing process, such as vapour deposition, is considerably cheaper as well. The most successful second generation materials have been cadmium telluride (CdTe), copper indium gallium selenide (CIGS), amorphous silicon (a-Si) and micromorphous silicon. The major drawback of these cells is their low efficiency (<10%).

[1] Solar thermal technology facilitates the transfer of heat from the sun to a liquid, usually water, via a heat exchanging device. This technology is primarily used to generate hot water for residential use.

[2] Shockley-Queisser limit

The third generation photovoltaic cells are largely under development at the moment, and they aim to maintain the low cost of second generation cells while improving on efficiency. These cells function very differently from their predecessors. First and second generation cells both rely on a p-n junction[3] to generate electrical current, while a defining characteristic of third generation cells is that they do not have p-n junctions. A whole range of new technologies, such as up-conversion[4] and tandem technology[5], are being developed to raise the theoretical conversion efficiency which governs first and second generation cells. Some emerging third generation cells utilising these technology are dye-sensitized cells, nanocrystal cells and organic cells.

Initial discovery and research

The photovoltaic effect was first discovered by Alexandre Becquerel in 1839. He was experimenting with electrolytic cells made up of two metal electrodes placed in a conductive solution. Becquerel found that when the cells were exposed to light electrical generation increased (DoE 2001).

This was followed by a series of accidental and deliberate attempts to build rudimentary solar cells, involving mainly selenium. In 1904, Einstein explained the theoretical basis of the photovoltaic effect, followed by experimental confirmation by Robert Millikan in 1916. Although selenium produced a photovoltaic effect, it had a very poor rate of transforming this effect into electricity. Therefore the next major breakthrough in the development of

[3] A p-n junction is formed when p-type (positively charged) material and n-type (negatively charged) material are placed in contact with each other. A p-n junction is formed by joining p-type and n-type semiconductors in close contact. At the junction the materials behave in a different was to either type of material individually. Specifically, current will flow readily in one direction (forward biased) but not in the other (reverse biased), this creates the basic diode. First and second generation solar cells are basically large p-n junctions.

[4] Up Conversion methods attempt to capture additional photons that are not captured with 1st and 2nd generation solar cells. Sunlight transmits across a broad wavelength range, but solar cells only receive photons through one band gap (energy range in a solid where no electron states exists) and only photons with enough energy to excite electrons over this band gap contribute to the energy current generated by the cell. Up conversion method attempt to also use less energetic photons to generate current by converting two or more low energy photons into one high energy photon which is then able to cross the band gap.

[5] Tandem or multi junction cells have two or more band gaps through which protons can pass and generate current. So as opposed to up conversion where the aim is to get more photons through the one band gap, tandem cells offer more than one band gap for excited photons to cross and generate current.

solar cells came with the movement from selenium to silicon. The Polish scientist Jan Czochralski was essential in this movement; he developed a method to grow single crystal silicon, or monocrystalline in 1918. This enabled the widespread production of single crystal silicon to be used in electronics. His method involved dipping a single rotating crystal silicon seed onto a rod into molten silicon. The result is a monocrystalline silicon ingot with practically no defects and good energy efficiency.

The movement to Silicon

The work of Bell Labs

The first silicon solar cell was created by accident in early 1940 by Russell Ohl, a researcher at Bell Labs. Ohl was investigating a piece of silicon (monocrystalline silicon produced using Czochralski's method), when he shone a flashlight onto the silicon and noticed that the voltmeter attached to the silicon registered an unexpectedly high reading (Green 2000). Further investigations by Ohl and his colleagues led to an understanding of the special properties of silicon particularly the p-n junction. This led to further work on semiconductors and the birth of the microelectronics industry.

Bell Labs was a hive of activity at this time, a highlight being the 1948 demonstration of the transistor which really set of the micro electronics revolution. Progress on the solar cell continued as well. Bell Labs, being the R&D arm of telecommunications giant AT&T, the monopoly telephone provider in the United States, was interested in the potential of solar cells for powering telecommunications systems, particularly creating an alternative to dry-cell batteries[6].

Daryl Chapin at Bell Labs was tasked with creating an alternative to dry-cell batteries. He had worked previously on other alternative sources of energy including wind and steam but was convinced that solar power offered the best prospects for the task. He started work in

[6] These batteries were used in remote communications. They operated well in mild and dry climates, but quickly degraded in hot or wet climates (Perlin 2004).

1952, initially using selenium but again encountered the problem of poor energy transfer well known with selenium.

Fellow colleagues at Bell Labs recommended that Chapin abandon selenium for silicon[7]. The chemist Calvin Fuller, would make a further contribution; attaching the metal electroplate proved difficult in the current semiconductor configuration. Fuller therefore suggested instead of doping the silicon with lithium, that phosphorous be used instead, this lead to a more efficient solar cells but didn't completely solve the problem of electrical contact points, or achieve the 6% efficiency (light to electricity conversion) rate that Chapin had set for the technology to be considered a real alternative to dry cell batteries. Further work by Fuller developed the solar cells further, using this time arsenic-doped silicon covered in a layer of boron (Perlin 2004). Lab tests on these cells achieved Chapin's 6% efficiency level. The solar modules were put into experimental use in 1955 in Georgia, but were removed in March 1956. In the field the batteries generated energy on a sunny day at about 2% efficiency. The density of the packaging the held the silicon cells was thought to be the cause of the poor efficiency.

National Fabricated Products licensed the technology from Bell Labs in 1955. They produced the first commercial silicon solar cell; the S-400. However National Fabricated Products were not able to engineer more efficient packaging, and so were not able to increase efficiency. The company was sold in 1956 to Hoffman Electronics[8] who also attempted to

[7] Chapin discussed the problem with his friend and colleague Gerald Pearson (who at the time was in the early stages of commercialising silicon solid state devices with another Bell Labs scientist, chemist Calvin Fuller). Fuller suggested silicon doped with gallium, in a hot lithium bath would produce an effective p-n junction to allow electrical generation. Pearson and Fuller performed some tests and showed that the materials could produce electricity from light. Further tests with Chapin showed that the prototype developed by Pearson and Fuller was the most efficient solar cell made to that point – it performed five times better than selenium (Perlin 2004).

[8] Hoffman Electronics was founded in 1941 and was initially a small radio manufacturer. They diversified into televisions, transistor radios, semiconductors and solar cells and solar power systems. They became a major player in silicon solar cells for the space market, dominating this market for much of the 1960s and 1970s. It was Hoffman solar cells that were used in the Vanguard I. In 1977 the main divisions of Hoffman Electronics were sold to Gould Electronics, with a small division focusing on audio visual displays remaining; Hoffman Video Systems is still operating today and is a major provider of corporate AV equipment in the USA.

commercialise the batteries for terrestrial use. Western Electric (Bell Labs parent[9]) and Hoffman Electronics both had products and catalogues available advertising photovoltaic modules, but it was soon apparent that there was no viable market for photovoltaics at the price it cost to make the silicon cells (McNelis 2001). Solar power technology would have to wait for the satellite and space age for its first major paying customers.

RCA and the Atomic Battery

At the same time as the solar cell development was taking place at Bell Labs, scientists at RCA (Radio Corporation of America) were also working on an alternative power source; the Atomic Battery. The battery's development coincided with the US 'Atoms for Peace' program (a campaign designed to rejuvenate the US' global reputation following the atomic bombs of Hiroshima and Nagasaki and show the positive side of research into nuclear energy[10]) announced by President Eisenhower in December 1953. RCA's Atomic battery was announced with a media presentation in 1954. In reality the battery, which was powered by radioactive waste strontium-90 was no where near as effective as the solar cells that Bell were developing. The work at RCA and their public announcement however did force Bell Labs to develop prototypes and public notices about their solar battery and its progress, which in turn led to the 1955 experimental trial (Green 2005).

The space age

The work on photovoltaics at Bell Labs fortuitously came just prior to the space age. The first satellite was launched in the US in 1957, beginning the space age in earnest and providing a ready market for power sources with a high specific power capability (power to mass ratio) and longevity (Hardingham 2001). The US military (through the US Signal Corps) began funding research and development into photovoltaic module power sources for

[9] Western Electric was the manufacturing arm of AT&T, as a wholly owned subsidiary of AT&T it was incorporated in 1915. After AT&T divesture in 1984, AT&T Technologies took on the corporate character of Western Electric, which in turn was separate into several divisions.

[10] The success of this program to capture government and corporate attention in the later years of the 1950s is given a reason for the takeover of the nuclear power industry as opposed to the solar power industry in the later decades of the 20th century. Both technologies were at the same stage of development, it could even be said solar was slightly ahead, with Bells solar cell more able to generate more power than RCA's Atomic battery (Perlin 2000).

satellites[11]. This triggered a period of intense research and development, mainly concentrated on increasing efficiency and robustness, as the photovoltaic modules needed to be able to withstand space radiation. The previous main drawback, cost, was no longer an issue in space use since it contributed a minute fraction to the mission cost.

Vanguard I, launched in March 1958 was the first satellite to use a photovoltaic power source. The satellite launched with two separate transmitters, one battery operated and the other powered by solar cells fabricated by Hoffman Electronics for the US Army Signals Research and Development Laboratory. The battery operated transmitter lasted twenty days. The solar cell powered transmitter lasted until 1964, when it is believed that the transmitter's circuitry failed rather than the solar cell (Bailey, Raffaelle et al. 2002). The first commercial satellite using photovoltaics, the Telstar, was launched in 1962. Photovoltaics' proven reliability and longevity meant from this point onwards they became the default power source for space use, and ever since almost all communication and military satellites have been solar powered (Bailey, Raffaelle et al. 2002).

For space applications photovoltaics made sense because of their light weight and reliability and although the costs were acceptable within a satellite mission budget, the same applications were not suitable for terrestrial markets (Bailey, Raffaelle et al. 2002). This together with the specific performance and radiation hardening features of space photovoltaic applications saw the solar cell market diverged into two streams from this point forward. The terrestrial market focused on reducing manufacturing costs and increasing the rates of production, and whilst space applications benefited from these advances to a limited extent in the forthcoming decade, space photovoltaic R&D was focused on pushing the bar in terms of cell efficiency, no matter the cost (Bailey, Raffaelle et al. 2002). The relationship between the two streams of photovoltaic development was described as 'synergy and diversity' (Bailey, Raffaelle et al. 2002).

[11] In fact the US military already had solar cell research programs underway – the first thin-film solar cells were being developed at the US Air Force Laboratory in Dayton Ohio on 1955 (Perlin, 2000).

First wave of terrestrial photovoltaics commercialisation

From the 1970s attention on the terrestrial applications of photovoltaic cells re-emerged. This emergence was the result of a number of factors, notably the oil embargo of 1973 but also a repositioning of PV firms currently servicing space requirements looking towards the terrestrial market. Cost was the major issue to be addressed for a viable terrestrial market, and engineering and manufacturing techniques needed to be developed to bring these production costs down.

The first company established to specifically manufacture terrestrial PV cells was Solar Power Corporation[12] in 1972 by Elliot Berman (Perlin 2002). The corporation was funded by Exxon, and it grew out of initiative to develop low cost PV cells using organic materials. The initial target market was for remote power supply (telecommunications, coast guard etc) but eventually the ambition was to develop product that would compete with conventional power sources (McNelis 2001). The Corporation's first product was a low cost, simple and by space standards, crude PV module. The module was marketed as an 'interim product' as the manufacturing experience gained for the corporation was seen to be as important as the product. In 1973 Solar Power Corporation also set up Solar Power Ltd in the UK for its international marketing. Then, in turn, Solar Power Ltd initiated a co-operation agreement with Lucas Industries, with Lucas Industries distributing Solar Power's product[13].

Government policy encouraging photovoltaics

The oil embargo in 1973 triggered a period of intense growth of photovoltaics. In 1970 US domestic production of oil peaked and in 1974 the US received their first 'oil shock' from the oil embargo (Hart 1983). The Government realised the importance of energy security and implemented policies, such as public procurement and tax credits, to encourage the

[12] Solar Power Corporation was formed in the same year as Solar Technology International (another major terrestrial PV firm) in 1975 as part of a strategy by the Exxon group to maintain control over the energy market. The corporation was sold to Solarex in 1984.

[13] This co-operation agreement would be formalised in the creation of a new firm, Lucas Solar. In 1982 Lucas Solar merged in a joint venture with BP, to form BP Solar. When Amoco and BP merged in 1999, each of their solar power subsidiaries (Solarex in Amoco's case and BP Solar in BP's case) also merged; the current subsidiary is called BP Solar (McNelis 2001).

adoption of renewable energy. In 1973 the US Solar Energy Research Institute[14] at Golden Colorado was established and in 1974 the Solar Energy Research, Development and Demonstration Act was passed through Congress.

This provided $75m (US) of funding for appraising the potential of a number of alternative energy sources including photovoltaics. This was followed by the 1976 Energy Conservation and Production Act, which set up a stream of funding for a commercialisation plan for photovoltaics. In addition to this commercialisation plan, two years later in 1978 the Federal Photovoltaics Utilization Program (FPUP) was also established. FPUP's aim was to encourage photovoltaics commercialisation by providing an initial market through government procurement, on which it was hoped a private uptake of PV cells would follow (Hart 1983). The FPUP made available varying amounts of funding for government departments to use in the purchase of PV equipment for federal facilities. The first program, made available $12m, the second $98m over three years (1979-1981), and the third $1.5billion over ten years[15]. This third program provided funding to various 'block purchases' aimed at creating different markets; blocks one and two were aimed at purchasing PV devices suited to small and remote applications; blocks three and four for intermediate remote applications; and block five was aimed at residential applications (Hart 1983).

The US government was clearly the most active in encouraging the development of the PV market in the 1970s and early 1980s. Programs investigating the use of photovoltaics for energy supplies were investigated in Japan, Australia, Germany and the UK, but appear to be small scale, attracting neither the amount of funding or the 'whole of government' approach that the US programs had. Opinions on the success of the US programs in accelerating the commercialisation of PV applications are mixed (Hart 1983; Sklar 1990). On one hand sales of PV equipment increased dramatic in the years of the programs'

[14] The US Solar Energy Research Institute was the designated national laboratory of the U.S. Department of Energy (DOE). It changed its name in 1991 to the National Renewal Energy Laboratory.

[15] Despite the provision of $98m in the second program only $25m was actually expended. The third program ($1.5billion over ten years) also suffered from budget cuts after the 1981 change of administration (from President Carter to President Reagan).

operations (Sklar, 1990), but the lack of connections between individual procurement purchases and energy cost reduction advantages and overall market penetration meant that the US did not see lasting industry-stimulating benefits of the government procurement programs (Hart 1983).

Main commercial players 1970s onwards

Oil companies, rich and weary of the risks in their oil business, saw photovoltaic companies as good investment targets to use the excess money they had and lower their business risk. Worldwide production of photovoltaic cells increased from almost zero to 10MW in 1982, primarily as a result of the US government procurement programs (Petrova-Koch 2009). The high level of investment also meant more R&D funding for photovoltaic companies and several key second generation technologies appeared, e.g. amorphous silicon.

The acceleration of interest in terrestrial applications during this time is shown in the changing composition of research papers delivered at the PV international conference. At the 1974 International Conference on PV Power Generation in Hamburg, Germany there were seven sessions. One of the seven was devoted to terrestrial applications, the rest focused on space. There were 46 papers and 165 participants. Twenty four years layer at the 1998 Second World PV Solar Energy Conference in Vienna there were nine sessions, eight dedicated to terrestrial applications of PV technology and one to space applications. There were 905 papers and 1890 participants (McNelis 2001). The overall increase in activity is also evident in the number of patents granted by the US PTO in technology class 136 (Thermoelectric and Photoelectric batteries) as shown in Figure 1.

Other firms involved in terrestrial PV development at this time included Sharp in Japan,[16] Philips, through their French subsidiary RTC[17] and two other US based firms, ARCO Solar and Solarex. Case summaries of these latter two firms are presented next.

[16] Sharp started investigating photovoltaics in 1959 and had established a small production plant by 1964. Their first product was a 225w module for solar powering the lighthouse on Ogami Island in 1966. Up until 1972, Sharp solarised 256 lighthouses along the Japanese coast (Green 2005).

[17] RTC installed solar powered electrolysis and air navigation beacons in Chile from 1961 to 1972 (Green 2005).

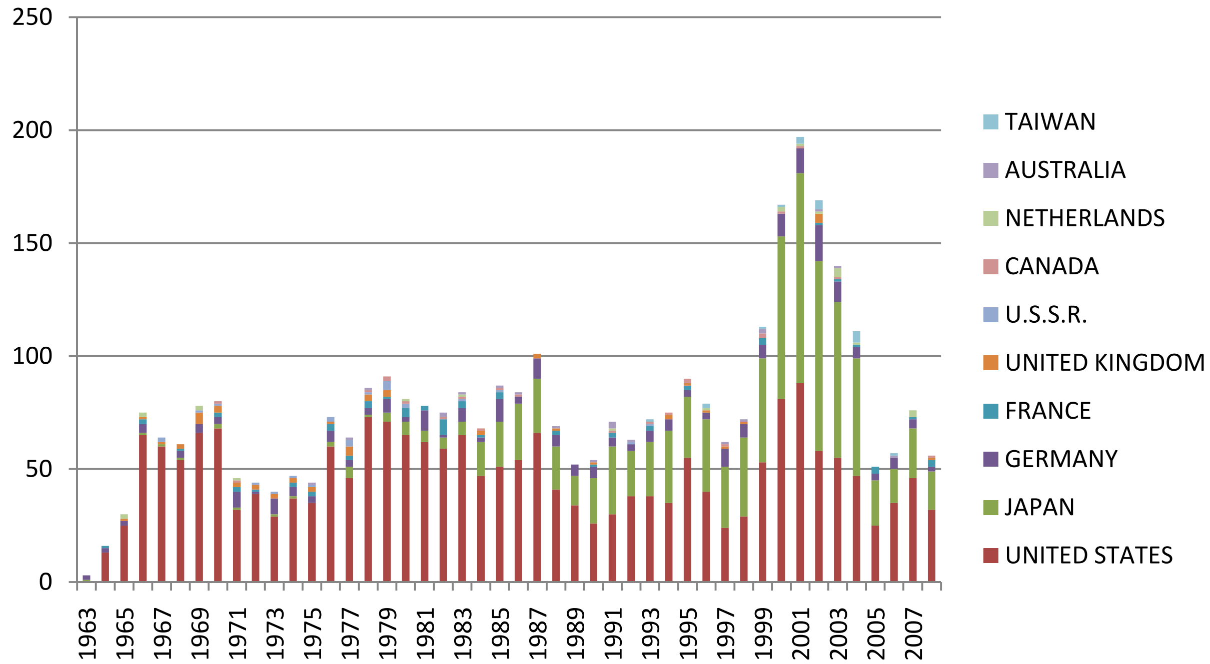


Figure 1: Granted patents in US PTO Technology class 136 Batteries: Thermoelectric and Photoelectric

Case 1 - ARCO Solar[18]

The origin of ARCO Solar traces back to Solar Technology International (STI). Bill Yerkes, the founder of STI, was working as the President of Spectrolab in the 1970s. Spectrolab, a subsidiary of Textron Corporation, produced mainly space solar cells and was starting to investigate terrestrial solar cells.

In 1975, Textron sold Spectrolab to Hughes Corporation, which subsequently decided to abandon the terrestrial photovoltaics of Spectrolab all together. Yerkes was then replaced by Hughes' own management team and made redundant. Within three days, Yerkes decided

[18]A significant amount of collected materials about this case comes from Perlin, J. (2002). From space to earth: the story of solar electricity. Cambridge MA, Harvard University Press. and Berger, J. (1998). Charging ahead: the business of renewable energy and what it means for America. California, California University Press. To avoid interruption of flow by reference numbers, any references to these two sources, apart from interviews, are not shown specifically in the case, while the use of other sources are cited as before.

to set up his own company, STI. Initial funding came from himself and family and friends: $10,000 each from his mother, two aunts and a friend, and $100,000 from himself. A production facility was quickly set up in late summer and Yerkes concentrated efforts on improving the production process of making crystalline silicon modules.

In 1976, STI got its first significant order from a motor home company when Yerkes convinced it to install small panels on its motor homes to keep batteries charged during storage. The Jet Propulsion Laboratory (JPL[19]) placed another important order under a Department of Energy (DOE) block purchase program[20]. STI's panels passed JPL's rigorous testing program, this approval of quality helped STI to gain the trust of customers and sales picked up subsequently. Yerkes then brought in more investors to obtain capital for more advanced manufacturing equipment.

STI's progress was still hampered by a lack of capital. Major investors remained wary about risking money on a small firm that was competing with firms like Exxon's Solar Power Corporation. In mid-1977, a consultant for ARCO (Atlantic Richfield Oil Company), a large US oil company, appraised Yerkes' operation and recommended ARCO to buy it. ARCO, further persuaded by Yerkes' expansion plan, bought STI and Yerkes made a 500% return on his original investment. ARCO immediately poured money into the newly formed ARCO Solar to set up a research lab of 100 people and a new 10,000 square feet production facility. Yerkes remained in the new entity as vice president of engineering and technology.

In the next ten years, ARCO invested over $200m in ARCO Solar. Initially, the company enjoyed much success, with Yerkes leading the operation of a new plant and dramatically simplifying the production process. Within just two and half years of acquisition, ARCO

[19] The Jet Propulsion Laboratory (JPL), an organisation under NASA, played two major roles during the first phase of terrestrial photovoltaics development in the 1970s and 1980s. Firstly, its solar simulator allowed photovoltaic companies to measure the exact power of their cells and the build quality for free. This meant start-up firms could actively participate in the technology's development without having to purchase the testing equipment, and secondly the certification by JPL gave customers significant amount of confidence in the products.

[20] This refers to the third government program, the Federal Photovoltaics Utilization Programme in the US.

Solar's revenue rose to over $17m and it became world's largest photovoltaics company. However, the company's fortune took a nosedive afterwards due to a series of questionable decisions on both R&D and capacity building which are discussed below.

ARCO Solar R&D

Part of Yerkes' reasons for selling STI to ARCO was the potential for a significant R&D program. And indeed, after the acquisition, ARCO Solar implemented a large research team and a research program on three different types of second generation photovoltaics: amorphous silicon (a-Si), copper indium diselenide (CIS) and cadmium telluride (CdTe). In the early to mid 1980s, 50 of ARCO Solar's 100 researchers worked on a-Si, 45 on CIS, and 5 on CdTe.

In 1983, in order to cut costs, the management team decided to reduce R&D effort to two technologies. According to interviews conducted by John Berger with Yerkes (Berger 1998), instead of a thorough technical and business evaluation, the decision was made through a poll of the 100 researchers. Researchers naturally voted for the technology they were working on and a-Si and CIS were selected and CdTe abandoned. This was despite technological insight suggesting that CdTe was the more viable alternative. Performance by the small CdTe team in the previous year had progressed efficiency by as much as the two other larger teams had achieved in the past five years. A further mistake was made when a-Si panels were introduced to the market despite concerns over degradation. The panels had to be withdrawn and the company's reputation of quality was damaged.

Capacity Building

In 1982, ARCO Solar built a 1MW solar power plant for Southern California Edison (SCE). The plant cost nearly $18 per watt and made very expensive electricity at >$1/kWhr while SCE only paid an average of ~4 cents/kWhr. Despite such heavy gross loss, ARCO Solar was able to make a 13% return on this capital intensive investment when the plant closed in 1992 due to the federal and state tax credits and grants it received[21].

The initial success of this plant emboldened ARCO to start a 6.5MW solar plant, which would have been the world's largest photovoltaic power plant and would sell its power to Pacific Gas and Electric Company (PG&E). This plant was originally designed to use directional mirrors to track the sun, thus allowing more power to be generated. In order to capture state and federal tax credits before policy changed, ARCO Solar started construction quickly and never properly tested the new design. The plant was completed in 1985 at a cost of $65m. A critical fault with the new design was then found and the plant was never used.

This series of questionable decisions meant that despite ARCO's $200m investment in ARCO Solar since its acquisition, the company never showed a profit. With the added cost of a lost litigation case against Solarex (see the Solarex case following). ARCO sold ARCO Solar to Siemens in 1990 for an estimated price of $30 - $50 million in a stock transaction (Wald, 1989 #110). The sale excluded the 1MW and 6.5MW plants described above, which were sold to a separate consortium for ~$2m. With the purchase of ARCO Solar, Siemens became a major player in the PV manufacturing business, the renamed firm, Siemens Solar, is still one of the global top ten PV firms (McNelis 2001).

Case 2 - Solarex[22]

Solarex was an American photovoltaics company. It was founded by Dr Joseph Lindmeyer and Dr Peter Varadi. Both were working on space solar cells in the early 1970s for a satellite company called the Communications Satellite Corporation (COMSAT). While at COMSAT,

[21] Tax credits in 1970s and early 1980s - After the Oil Embargo in 1973, US energy tax policy underwent significant change. In 1978, the Energy Tax Act was passed by the Congress Lazzari, S. (2006). Enegy Tax Policy. C. R. Service, Washington DC.. This Act implemented a series of tax credits schemes targeted at both residents and businesses and a windfall tax targeted at energy companies. The most important policy for photovoltaic companies was the 15% investment tax credit – meaning businesses would be able to claim back 15% of its capital expenditure. Similar schemes were also implemented at the state level to different extents.

[22] A significant amount of collected materials about this case come from Berger (1998). To avoid interruption of flow by reference numbers, any references to this source, apart from interviews, are not shown specifically in the case, while the use of other sources are cited as before.

Lindmeyer developed a photovoltaic cell that was 50% more efficient than any other at the time. COMSAT patented and used this technology on all of its space satellites. Based on an interview conducted by John Berger with Lindmeyer (Berger 1998), Lindmeyer did not benefit financially from his invention as he was a salaried employee, and as a consequence, resolved that 'if he ever made a major technical breakthrough again, he would do so in a company of his own...to reap the financial rewards'. He then designed a new production process that would cut down the cost of producing photovoltaic cells dramatically, thus making them possible for terrestrial use, but COMSAT was not interested and wanted to focus on its satellite business.

At a New Year's party in 1973, Lindmeyer teamed up with Varadi and decided to quit COMSAT to set up their own company to develop terrestrial cells. In February, Solarex was founded. Varadi took on the task of raising finance. Attempts to obtain funding from venture capitalists were not successful, as VCs were weary of photovoltaics and did not trust two scientists to manage a business. But the pair was then able to raise $250,000 from friends and acquaintances. Things moved quickly and manufacturing began in August. Within eight months, Solarex became profitable.

Solarex's fast growth was in jeopardy when COMSAT sued it for patent infringement in 1974. According to Lindmeyer in the interview with Berger (1998), an engineer at Solarex, who used to work at COMSAT, told his old friends at COMSAT that Solarex had stolen its technology. The case turned out to be a misunderstanding by the engineer who subsequently retracted his allegations. Even though the case no longer stood up, getting it dismissed legally could still have tremendous financial impact on this start-up firm. Lindmeyer resolved this issue by getting personal help from the Senator of Alaska, who was an active supporter of renewable energy and had close relationships with COMSAT's top management. The case was promptly dropped and Solarex went back to its normal business with minimal impact.

During Solarex's early years, it relied on niche markets[23] for sales. It made solar watches, was the first to collaborate with Japanese companies to make solar calculators and produced remote-area power supplies for radio repeaters. Orders from these small markets were erratic and management of the business was very difficult.

Solarex's big break came in 1979 when it obtained equity funding from four companies (see Figure 2 for details). Holec and Leroy Somer invested to obtain Solarex's expertise and license in manufacturing photovoltaic cells in order for them to exploit the European markets. The most significant investment for Solarex was the $7m investment from Amoco. Amoco's investment is representative of the interest of oil companies in photovoltaics at the time[24].

Holec (Dutch electrical equipment manufacturer)	$860k for ~5%
Leroy Somer (French electrical manufacturer)	$860k for ~5%
ENI (Italian oil company)	N/A
Amoco (US oil company)	~$7m for 20%

Figure 2: Equity investment in Solarex. Source: NYT (1980) (DoE 2001).

With a powerful backer and a booming photovoltaics market due to supportive government policies (e.g. tax credits and bulk purchase program), Solarex underwent a period of significant expansion. Using Amoco's investment, Solarex spent $7m on a new 'breeder' plant where the plant was powered by photovoltaics to produce photovoltaics. Amoco also showed its support by installing Solarex photovoltaic panels on one of its service stations in Chicago, where it was headquartered.

[23] The markets Solarex relied on during its early years are called 'niche' here for two reasons: firstly, these early markets represent applications of this technology in very specific uses, e.g. power for watches or power for calculators, whereas a mass market would represent the use of photovoltaics as a general power source for a much wider range of things. Secondly, these markets tend to be relatively small in comparison to the overall energy market. Using solar calculators as an example: Casio, by far the dominant market leader, sold a total of 1 billon calculators from 1957 – 2006; given the low power consumption of calculators, the total value of photovoltaics used for calculators in those 50 years is unlikely to have exceeded $1bn significantly.

[24] The Oil Embargo had two direct effects on oil companies in America. Firstly, they profited substantially from the high oil price. Secondly, it made them re-evaluate the risk of their oil business. The combination of these two factors prompted several oil companies to make significant investment in photovoltaic firms. The four most prominent investments were (Perlin 2002): Exxon in Solar Power, Mobil in Tyco Labs, ARCO in Solar Technologies International, Amoco in Solarex.

To keep up with the rising demand, Lindmeyer and Varadi were looking for economic supplies of silicon and decided to build a plant in Martinsburg using a new quartz refining technology. Accounts about this decision and the ensuing process differ dramatically, based interviews conducted by Berger with a number of people involved at the time (Berger 1998).

Peter Varadi claimed that after the 'large facility was set up, it turned out not to be needed' as the market was never big enough to justify it. Solarex physicist Wohlgemuth said the new quartz technology was based on the result of a 'single experiment that was later seen to be flawed and unrepeatable'. Lindmeyer, on the other hand, insisted that a series of experiments were conducted and the results were promising. The Martinsburg cost Solarex $15m. Lindmeyer did secure in 1980 a $9m DOE contract to develop the refining process further, which would have offset a portion of this big loss. But the contract was terminated after only a year when the Reagan administration reduced DOE's budget significantly[25].

The combination of a declining oil price and the withdrawal of government support caused the solar market to sour. In 1983, Maryland Bank, with which Solarex had a $7m debt, demanded full repayment within 3 months triggered by a reporting mistake by the Solarex CFO. Due to a souring market and the loss on the Martinsburg facility, Solarex could not repay the money or re-finance. Efforts to find a new backer such as GE were also fruitless. Amoco eventually took over Solarex.

In the interview with Berger (1998), Lindmeyer claimed that Amoco schemed to acquire Solarex at a cheap price. Maryland Bank was willing to lend such a significant amount to Solarex because Amoco was an investor. According to him, Amoco declared to Maryland Bank that it had lost interest, prompting Maryland to demand repayment. Furthermore, he said that Amoco and Solarex had an agreement that if Amoco's share in Solarex ever reaches 40%, it would buy out all the shareholders at the highest historic price, and just

[25] Following Reagan's election, the previous tax policies were repealed and the Department of Energy funding for photovoltaic development was cut down by 50%, from $150m to $75m. This free market approach has a detrimental effect on many small solar companies at the time, between 1984 and 1986, 127 solar companies went bankrupt Surek, T. (2009). Progress in US Photovoltaics: looking back 30 years and looking ahead 20. Colarado, NREL..

before the full acquisition, Amoco's share was 39%. Wohlgemuth, on the other hand, offered a different perspective: 'everything that got shipped out the door at the time cost more to make than they got back from it…Solarex got into financial difficulty. Either the company was going to go bankrupt…or Amoco was going to buy and continue to fund it.'
The magnitude of Solarex's downfall is enormous. Just three years earlier, an article in the New York Times (Parisi 1980), on the subject of innovation in America, singled out three companies as exemplars of innovation, Solarex was one of them alongside Apple and Genentech.

Despite all its troubles during that period, Solarex still had the motivation and ambition to innovate. Just before the acquisition by Amoco, Varadi helped Solarex to first acquire Solar Power, the Exxon solar subsidiary, and more importantly, to acquire RCA's amorphous silicon capability, including all patents, key employees and machinery. Amorphous silicon technology was at the time one of the first thin film solar cell technologies and was regarded as the future of photovoltaics. In 1984, Solarex, using the acquired technology, started producing a-Si cells for consumer applications. However, in the next decade or so, the development and exploitation of this technology at Solarex became static. Instead, the Amoco-controlled Solarex used its a-Si patents in a chain of patent lawsuits against other companies commercialising this technology. This series of litigation may have contributed to the slow progress in what was a very promising technology. Despite its activity in protecting its IP, Amoco/Solarex's contribution to the progress in a-Si technology was almost non-existent during this period. Instead, it was United Solar, a small start-up that improved the efficiency of a-Si year-on-year (Surek, 2009). Some have indeed questioned the case here of technology suppression[26].

[26] Technology suppression involves the non-use and non-diffusion of a technology by those who control it. It is an incredibly difficult case to present legally since the ownership of a patent gives the right to the owner to do what he/she wishes to do with it. The Amoco/Solarex case of suppressing a-Si technology, even if proved true, would be entirely legal. However, such cases have gained the attention of policy makers and indeed, the Amoco/Solarex case was brought to the attention of the California Energy Commission by Eileen Smith Saunders, K. M. and L. Levine (2004). "Better, faster, cheaper - later: what happens when technologies are suppressed." Michigan Telecommunication Technology Law Review **23**., an advocate for solar development, in a Congressional Hearing in 1998. Other cases of illegal suppression, however, do exist. The most notorious example is the antitrust case in 1960s brought against the Detroit Four (GM, Ford, Chrysler and AMC) for a communicated effort in acquiring and delaying the introduction of air pollution control equipment (Saunders and Levine 2004). The case ended in settlement of an unknown figure and was clear evidence of the use of corporate power to suppress technologies of conflicting interest.

Movement of the solar market

In the 1980s the initiative in photovoltaic development moved from the US to other countries (as evidenced by individual countries share of patents in Figure 3). 1981 saw the election of the Reagan administration and this was followed by a reorientation of federal government programs and funding, which in this case saw funding and emphasis shift away from alternative energy sources including photovoltaics. This period of time also saw the easing of the oil crisis which had encouraged the investment by oil companies. Generally, the returned security of oil sources led to a downturn in market interest in terrestrial PV.

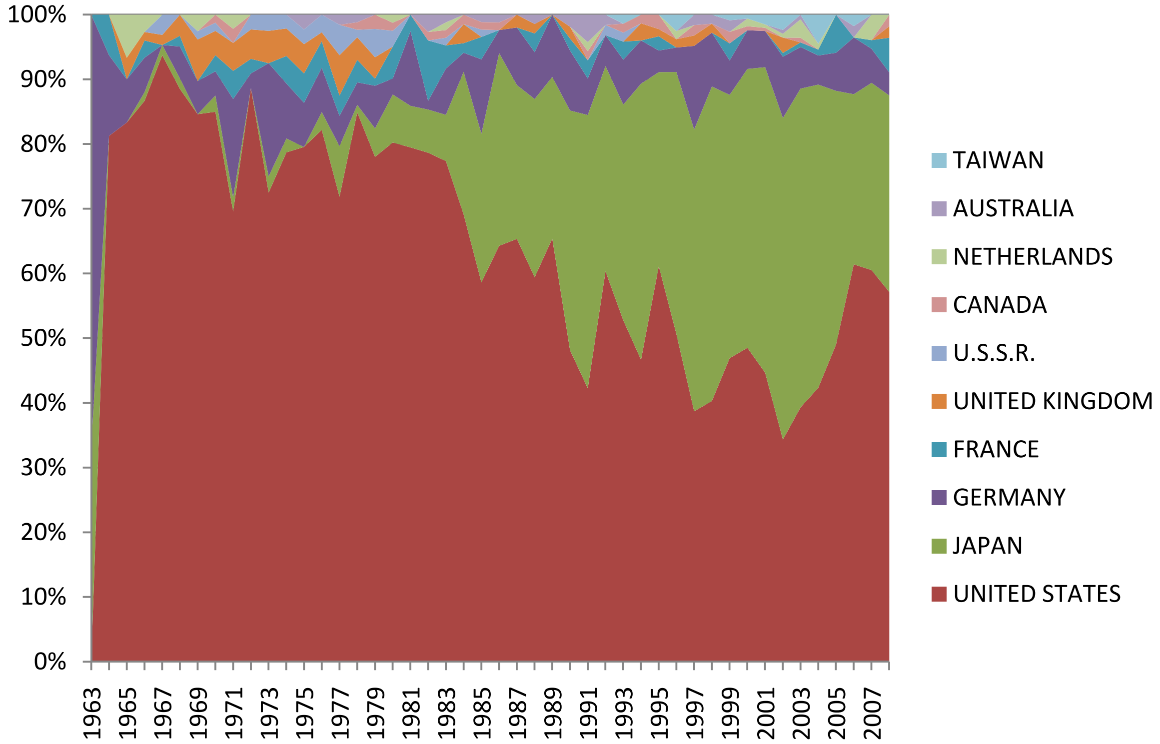


Figure 3: Country share of granted patents in US PTO Technology class 136 Batteries: Thermoelectric and Photoelectric

Research on solar cells for space, however continued unabated. The largest collection of space solar cell arrays was constructed during the 1980s for what was to become the

International Space Station in 1988. During this time satellites had also grown in size and power consumption, this meant research was further focused on increasing efficiencies in light-power transformation but also starting to look towards lighter, more efficient (weight/ output ratios) in the form of thin-film systems (Bailey, Raffaelle et al. 2002).

Thin-film photovoltaics, or the second generation, became the focus of R&D programs worldwide. The aim was to reduce production costs to make the technology more competitive as an alternative power source. Thin film photovoltaics cells are made by depositing thin layers of photovoltaic material onto a substrate. The traditional method for creating these cells was to use a screen printing type method. Kyocera in Japan developed a plasma nitride screen printing method in 1985 which went on to become a mainstream commercial production option and allowed Kyocera to offer a 10-year warranty on their PV cells; the longest warranty on the market at this point in time.

Another advance was to emerge from the University of NSW[27] in the form of the 'buried contact' approach, which in turn was effectively commercialised in 1992 by BP Solar as the 'Saturn Cell' (Watt 2003). Instead of using the common screen printing technique the 'buried contact' approach used a laser to form grooves in the PV cell surface so that the cell's electrical contacts could be partially buried. This reduced the part of the cell surface which was covered by the grid contacts and hence not available for sunlight, thereby increasing the individual cell's efficiency (Watt 2003). Efficiency levels were 18% compared to the best performing of the screen printing method, of 14% (Watt 2003).

BP Solar licensed the technology from the University of NSW on a 20-year limited exclusivity licence in 1985 (Watt 2003). It commenced production of the Saturn Cell in Australia and then Spain in 1992 (Green 2005). Other solar cell companies also licensed the University of

[27] Photovoltaic research started at the University of NSW in 1981 as the Microelectronics Special Research Centre, later evolving into Photovoltaics Special Research Centre and currently the Special Research Centre for Third Generation Photovoltaics. In total the various research centres have received $24m in core funding plus external grants. From 1985-1995 the Australian Federal government provided $25m in PV related funding (to both universities and industry) in the form of tax concessions, R&D credits and grants (Watt 2003).

NSW ‘buried contact’ technology, but due to intense merger and acquisition activity in the industry over this period (and as evidenced by the case studies) no other companies got much further than R&D programs. The University of NSW also sought to commercialise their research through the creation of a spin-out firm, Pacific Solar, as detailed next.

Case 3 - Pacific Solar

Pacific Solar traces its origin back to University of New South Wales (UNSW) in Sydney, Australia. Dr Martin Green, a researcher at UNSW, became interested in photovoltaics when Telecom Australia began equipping its microwave repeaters in remote areas with photovoltaic cells as power source[28]. In the 1980s, Green led a team in UNSW focusing on improving the efficiency of crystalline silicon cells (Perlin 2002). The fundamental research was funded by the Australian Research Council (ARC) and further development by National Energy Research, Development & Demonstration Council (NERDDC) and New South Wales State Energy R&D Fund (NSW SERDF). In 1985, using ‘buried contact’ technology, Green’s group produced the world’s most efficient photovoltaic cell at 20%. UNSW immediately considered commercialising this technology and was in licensing negotiation with Tideland Energy, a pioneering Australian photovoltaic company founded by Stuart Wenham and Bruce Godfrey, both having studied under Green (Watt 2003). In the same year, BP bought Tideland Energy to establish BP Solar Australia and acquired a 20-year exclusive right to the Buried Contact technology (Green 2007).

The acquisition caught the attention of the Australian government. In 1989, it funded the Centre for Photovoltaic Devices and Systems at UNSW (Perlin 2002). With the expansion in funding from the government and revenues from the BP licensing arrangement, Green began research into thin film technology. Two important people also joined Green at this

[28] In the 1970s, the Australian government generously funded Telecom Australia, a quasi-public agency, to try to provide every citizen, no matter how remotely situated, with telephone and television service comparable to that enjoyed in the larger population centres. Due to the size of the country and the sparseness of the population, a real problem was reliable power supply. Photovoltaic panels had significant advantages over other power sources in terms of maintenance, reliability and longevity. This led to significant deployment of photovoltaic panels by Telecom Australia, and essentially started the photovoltaic industry in Australia (Perlin 2002).

time: Stuart Wenham of Tideland Energy went back to work with Green, and Zhengong Shi from China began his PhD under Green (Pacific Solar 1997).

From 1989 to 1995, Green's group researched and invented Crystalline Silicon on Glass (CSG) technology. And in 1995, Green and Wenham approached Pacific Power, a utility company in Sydney, in an attempt to gain investment for commercialisation. Pacific Power was very interested and wanted full exclusivity. Ultimately, Pacific Solar was set up. Pacific Power invested $50m for 70% equity, Unisearch Limited, UNSW's commercial arm, took 30% share and all patents were transferred to Pacific Solar (1998). Green became the Research Director, Wenham and Shi his deputies, and David Hogg, who was working for Unisearch, became the Managing Director. Paul Basore, who was leading photovoltaic research at the Sandia National Laboratories in US, was attracted by this utility-led company and joined as a deputy research director as well (Perlin 2002).

From 1995 to 2000, Pacific Solar focused most of its efforts in a 5-year development program to bring the CSG technology to a manufacturing- and market-ready state. In 1996, it also began to pursue a more near-term opportunity by obtaining funding of $5.9m over a period of three years from R&D Syndicate (a consortium consists of industry players and government agencies) to develop an inverter, which is a device linking photovoltaic modules to electricity grid and promised to ease the installation process of photovoltaic systems for households (Pacific Solar 1999, 2000, 2001, 2002)

Over the next few years, Pacific Solar made steady advance in its CSG technology and integrated its inverter into an easy-mount rooftop photovoltaic system called Plug&Power. In 2000, it began selling the Plug&Power system incorporating its own inverter and mounting structure and outsourced photovoltaic modules. Its research in CSG technology, however, was still ongoing and in its annual report in 2000, it expected to have CSG cells in mass production by 2004 (Pacific Solar 2000).

To facilitate a move from a research oriented organisation to one focused on commercial operations, Pacific Solar actively promoted its Plug&Power system. In 2000, to increase sales and obtain extra funding, it teamed up with Eurosolare, the solar subsidiary of Italian oil company ENI, which became Pacific Solar's distributor for Plug&Power in Europe and invested in Pacific Solar for 25.6% equity. Pacific Solar also obtained a $500,000 grant from the federal government under the Renewable Energy Commercialisation Program (RECP) to further develop the Plug&Power system (Pacific Solar 2001). In the following year, one of Pacific Solar's key technology directors, Dr Shi, left the company to start his own photovoltaics company, Suntech Power, in China (see Box 1).

Sales in Plug&Power system grew quickly, achieving annual revenue of $1m in 2002. Pacific Power also won $1m in grants under RECP to take its CSG technology into a manufacturing-ready state during the following year (Pacific Power 2008).

In late 2002, Pacific Solar's major investor and source of funding, Pacific Power, became an entity wholly owned by the NSW state government[29]. In December, NSW government pledged a further $6.5m for Pacific Solar to take CSG forward (ABC 2004). However, in early 2003, 'unexpected changes to government funding support programs' caused Pacific Solar to abandon its CSG ambition (Fyfe 2003). Details on which funding changed could not be found. But it is most probable that the $6.5m pledge in the previous year was scrapped as the Howard's government moved from funding renewable energy to investment in clean coal technology in 2003 and the NSW state policy changed with the federal policy.

[29] http://web.archive.org.web/20030413132015/pacificsolar.com.au/html/MediaReleases.html

BOX 1

Suntech Power

In Sep 2001, following a visit to Wuxi, China and persuaded by the support of the local government, Zhengrong Shi left Pacific Solar to set up Suntech Power in the industrial park in Wuxi, an investment grade city 70 miles west of Shanghai. Shi invested $400,000 of his money for 25% equity, while a consortium of six local state enterprises including the investment arm of the Wuxi government contributed $6m for 75% equity. The Wuxi government also helped Suntech to secure a $5m research grant from the Chinese government (Powell 2009).

Suntech moved fast. After merely a year, a 10MW crystalline silicon solar cell production line was in operation. Due to the local low cost of labour, Suntech became profitable very quickly in 2003. In December 2003, another 15MW line came in operation. Such fast expansion led to a clash between Shi and the government-appointed chairman over how to use the resources for expansion. Through his own personal skills, Shi managed to persuade other board members to ease the chairman out. But from this event, he realised that 'having a controlling a position in the company is critical' (Renewable Energy World 2005). Thus in 2005, using investment funds from a Goldman Sachs-led consortium, Shi bought out all state-sponsored shareholders for $80m, through a series of bridge loans and manoeuvres. The consortium ended up with 53% equity, while Shi retained the rest (Powell).

Later in 2005, Suntech made its IPO on NYSE, generating $455m for 18.2% of the company, valuing it at $2.5bn and making Shi the richest person in China (Crunchgear 2009). From that point onwards, Suntech went from strength to strength and became the third largest photovoltaic manufacturer in the world in 2008. During the current recession, Suntech has suffered somewhat, laying off 10% of its workforce late 2008. It is, however, recovering well and performing better than its competitors. During the 1st quarter of 2009, it became the first photovoltaic company to reach a total production capacity of 1GW and is anticipating a more buoyant market driven by China and US in the coming year as these two countries adopt more encouraging solar policies (UNSW 2007).

While Suntech's first generation photovoltaic cells are selling through the roof, Shi also ensured the building of a technology edge by keeping a close working relationship with his former employer UNSW. In 2005, Suntech appointed Stuart Wenham, former Technology Director at Pacific Solar and current Director of Centre of Excellence for Advanced Silicon Photovoltaics and Photonics at UNSW, as its CTO. Furthermore, it has sponsored numerous research programs in UNSW and regularly sends its own engineers to work in UNSW (Suntech Power 2009).

In June 2004, a team of former employees from Pacific Solar set up a new company called CSG Solar in Saxony-Anhalt, Germany[30] (see Box 2 for the movement of people). With financial backing from Q-Cells, REC and IBG, a state-backed venture capital for development in Saxony-Anhalt, CSG Solar purchased all the physical assets and worldwide rights relating to CSG technology. CSG Solar raised a further €24m from the three existing investors alongside Apax Partners and Good Energies Inc. With such high levels of funding, development moved quickly and CSG Solar began mass production in 2006.

Meanwhile, two key people, Green and Wenham, have taken director-level positions at UNSW and companies stemming from Pacific Solar (CSG Solar for Green, and Suntech for Wenham). This has fostered a close collaborative relationship between the companies and the research centre at UNSW. CSG Solar is currently working with UNSW to advance CSG technology and Suntech has funded numerous research positions and programs at UNSW.

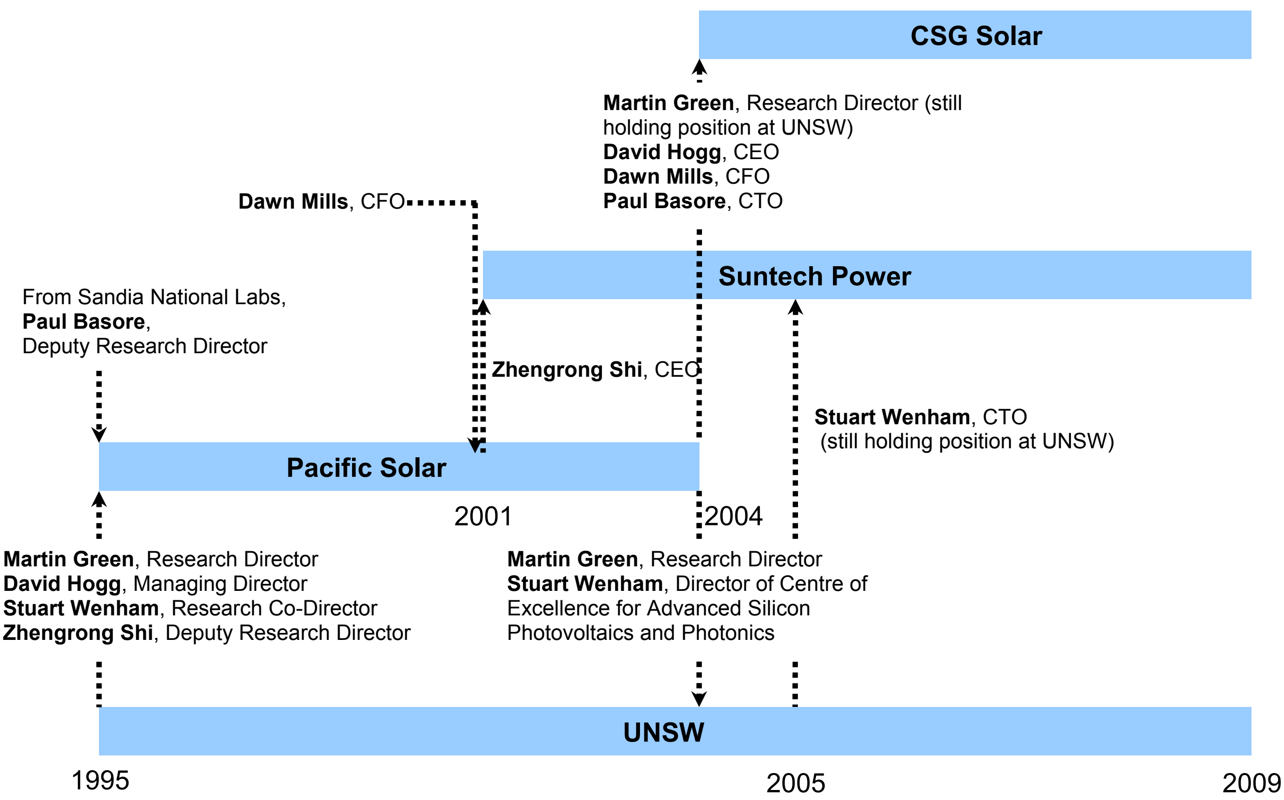
Later commercialisation

Driven by the support of the local government in Germany and funding from private investors in Europe, commercialisation of CSG technology continued as former employees set up another company in Germany. With more funding specifically for making production work, the new entity has successfully moved beyond the commercialisation phase and is moving into early growth.

[30] Saxony-Anhalt, a federal state located in the east of Germany, is widely cited as the Solar Valley. It has the highest density of PV supply chain worldwide and accounts for half of all solar cells produced in Germany in 2008. Many solar companies, including CSG Solar, have been attracted to locate in Saxony-Anhalt by a number of factors:

1. Saxony-Anhalt gives generous investment incentives to cover up to 50% of capital expenditure;
2. The state investment corporation, IBG, actively provides equity funding;
3. Due to the close proximity of equipment suppliers, manufacturing setup and project realisation is faster;
4. The state has several research institutions, e.g. the Fraunhofer Centre for Silicon Photovoltaic. This facilitates R&D cooperation. It is unknown whether CSG Solar has been or is cooperating with the Fraunhofer Centre. However, the Fraunhofer Centre is actively engaged in the CSG technology research and has been the main source of efficiency verification for CSG Solar Welles, E. O. (1998). Going for broke. Inc..

BOX 2



Note: Positions next to personnel names represent positions taken up at the organisation he/she was moving to.

The Photovoltaics Market Since 2000

A combination of economic (high energy price), environmental (global warming) and political / legislative (e.g. Kyoto and EU emissions trading scheme) drivers have led to a rapid increase in global investment in clean energy (Figure 4), and photovoltaics have been a recipient of significant proportion of it, resulting in fast expansion of the global photovoltaics market (Figure 5).

Within the photovoltaics market, companies compete mainly on two competitive criteria: conversion efficiency and dollar/watt ($/W). Currently, first generation cells dominate the market due to its high efficiency, stability and reliability, accounting for 90% of total production in 2007. Second generation cells, although still a very small proportion of the market, are growing fast, and achieving 126% growth in 2007. Despite its lower efficiency compared to the first generation, second generation cells are able to achieve a very competitive $/W due to its lower material and production costs. While some second generation firms have undergone successful commercialization, e.g. First Solar, the second largest PV producer in the world in 2008, is currently selling its modules to be used in utility-scale solar power plants and on residential roofs , third generation PV cell is still at development stage, mainly within university laboratories or R&D focused start-ups.

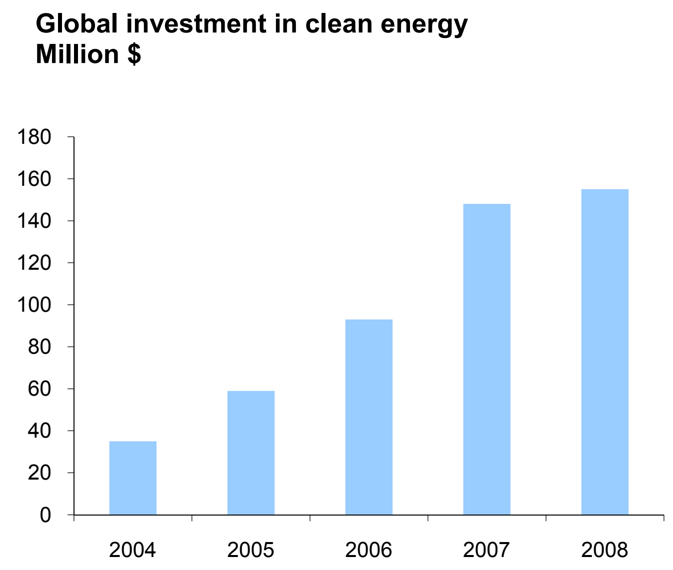


Figure 4: Global investment in clean energy 2004 – 2008. Source: New Energy Finance (2009).

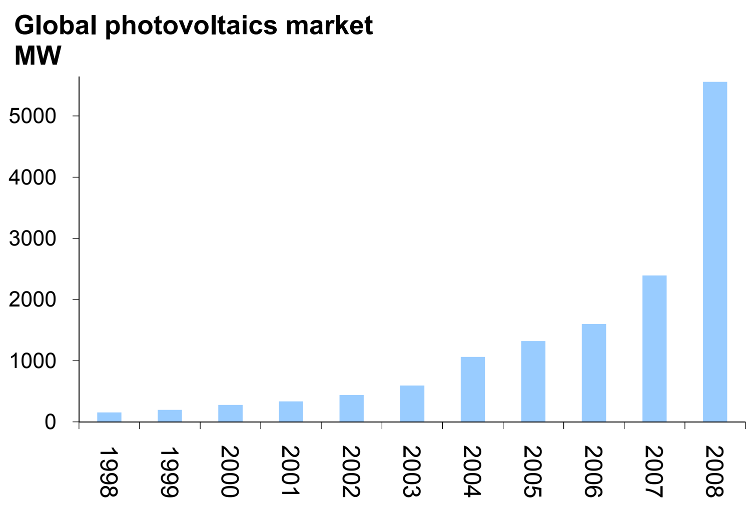


Figure 5: Global photovoltaics market 1998 – 2008. Source: Surek (2009)

Case 4 - First Solar[31]

First Solar is currently a company focusing on CdTe cells and has become the second largest photovoltaic company in the world in terms of MW produced in 2008. Its origin traces back to Glasstech Solar, founded by Harold McMaster in 1984. McMaster was an expert in glass and amassed a fortune by selling his previous company, Permaglass, to Guardian Industries, which created the third largest glass company in the world. With his immense reputation, McMaster was able to gain funding from 57 local investors from his home town Toledo, Ohio. However, within the next five years, he spent $12m of investors' money on combining his glass production expertise and a-Si technology to little effect.

In 1990, he reorganised the company as Solar Cells Inc (SCI) and decided to switch focus to another relatively unknown technology, CdTe. Despite his previous difficulty with a-Si and his offer to pay back any of his investors; McMaster still managed to raise another $15m, including $2m from himself. An interesting insight into McMaster's motivation for being so persistent in making his photovoltaic company work was given by Bob Nicholson, a mechanical engineer at SCI – 'Time was running out on Harold [McMaster]. You go down in history if you're the guy who made solar energy affordable, not if you're the inventor of the curved windshield [referring to McMaster's expertise in glass production]" (Solar 2000).

SCI subsequently engaged in a pure development program. McMaster's vision for the firm was a similar one he achieved in his previous glass business: highly automated deposition process churning out large amount of photovoltaic cells continuously. In 1993, a prototype production machine went online, capable of 20kW production. Several key employees suggested generating small sales from this pilot production base and gradually ramping up volume. McMaster, however, remained focused on going from nothing to production for mass market and wanted to delay production for sales until a 100MW line, equivalent to all of the worldwide photovoltaics production at the time, could be built. Such a vision meant

[31] A significant amount of collected materials about this case come from Edward Welles' 1998 article in Inc (Solar 2000). To avoid interruption of flow by reference numbers, any references to this source, apart from interviews, are not shown specifically in the case, while the use of other sources are cited as before.

that SCI burnt through cash very quickly without any returns for investors for 6 years. Such a state in any other company would have led to investors exerting pressure for sales. SCI's investors, on the other hand, were members of McMaster's local community and trusted him greatly. SCI was also able to obtain $5.8m in government grants for R&D up to 1996.

In 1996 SCI ran out of cash. McMaster issued more stock, which he bought himself and boosted his stake from 22% to 67%. The National Renewable Energy Laboratory also committed to providing the firm with $1m grant. With continued commitment from McMaster to research and perfect the technology and manufacturing process, SCI's technology became the talk of the industry. However, by 1998, it still had not made one sale and the company's future was becoming a concern. Several companies became interested in partnering with SCI, including Shell, Enron and AFG, a Japanese glass manufacturer. But all of these talks broke down. Eventually, it was left with one option: entering into a JV with Detroit Edison, a utility firm, where all of the technology developed by SCI would be transferred into the JV and each partner would own 50%. Such a move would mean a drastic culture change for SCI, from being in charge of its destiny to one heavily influenced by the demands of a powerful utility firm. This deal eventually did not go through; details over which party opted out were not known.

In 1999, the company's fortune turned. John Walton, through the investment arm of the Walton family, True North Partners, bought a 50% stake in SCI for $45m and renamed the company First Solar (Marketwatch 2000). From 1999 to 2006, True North Partners invested ~$250m in First Solar to perfect its production process and gradually raised its stake to 82% (First Solar 2003).

During the same time, Germany's feed-in tariff[32] (see Box 10) created a bigger photovoltaics market. First Solar would capture this opportunity and began shipping in significant

[32] Feed-in tariff is an incentive structure set by government legislation, where the national or regional utilities are obliged to buy the electricity generated by renewable sources at above-market prices. Germany's feed-in tariff was introduced in 1991, but only became significantly influential when it was modified in 2000 under the Renewable Energy Sources Act where the feed-in tariff was raised above the retail electricity prices and guaranteed for up to 20 years. The feed-in tariff for photovoltaics is particular substantial, being the highest of all renewable sources and almost 10 times higher than the

numbers in 2003, achieving revenue of $3m (First Solar 2004). From 2003 to 2006, revenue would at least triple each year (First Solar 2004, 2005, 2006), with Germany being the primary source of revenue[33]. Such rapid growth raised tremendous investor interest in the company, and in its IPO in 2006, First Solar raised $400m. In the follow-on offering next year, it raised a further $618m at five times the price (First Solar 2008). Since then, First Solar has not looked back: it has become world's second largest photovoltaics manufacturer in 2008 and reached a market capitalisation of $15bn (03/06/09).

Third generation EPFL and Dye-Sensitized Solar Cells

Dye-Sensitized solar cell (DSC) is a third generation solar cell. Based on photochemistry rather than solid state semiconductor physics, DSC mimics photosynthesis to generate electricity. This type of cell is made of very low cost organic material and can be manufactured using automated and fast techniques such as printing. In addition, it can also be engineered into transparent or flexible sheets and could generate electricity under very low light conditions, thus rendering it particularly useful for certain applications, such as in-door power and building façade.

The DSC cell concept was invented by Michael Gratzel at Ecole Polytechnique Federale de Lausanne (EPFL) in 1991 and a patent was granted to Gratzel and EPFL for the DSC concept. Commercialisation was not undertaken until 1994, when the Australian government through its Energy Research and Development Corporation (ERDC) formed a consortium to bring DSC technology to Australia and became the first license holder (Fyfe 2003). The consortium was led by Sustainable Technologies Australia (STA)[34], and included five research

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market price of electricity. Such a strong incentive brought an unprecedented expansion of the German market, where the capacity of photovoltaics installed increased by 40 times, from 62MW in 2000 to 2405MW in 2006, making it the largest market for photovoltaics. For many leading photovoltaics firms, the German market has been the primary source of revenue in the past nine years, although Spain has become more important since the introduction of feed-in tariffs there in 2007.

[33] Germany accounted for 95% of First Solar's revenue in 2004, 99.5% in 2005, 95% in 2006, 90% in 2007 and 74% in 2008 Frondel, M., N. Ritter, et al. (2008). "Germany's solar cell promotion: dark clouds on the horizon." Energy Policy **36**: 4198-4204.

[34] STA was established in 1985 as Silicon Technologies Australia. It listed on the ASX in 1994 and became Sustainable Technologies Australia.

organisations[35]. The research organisations were responsible for the further R&D of DSC, while STA was responsible for commercial development (Bossert, Tool et al. 2000). EPFL subsequently granted license to another seven organisations[36] (STA 1998).

From 1994 to 1998, the first phase of R&D was completed by the STA-led consortium, costing approximately $6m (STA 2001). Meanwhile in 1994, Leclanche, a Swiss battery manufacturer, set up a daughter company called Greatcell Solar to exploit DSC technology for indoor battery charging. In 1998, STA started working with Greatcell towards a JV project, with STA having gained support of the local government of Canton de Vaud for substantial tax relief. The talk broke down in 1999 over excess equity demand by Greatcell (STA 2001).

In 2000, through a management buy-out led by Deputy Chairman Gavin Tulloch and Managing Director Sylvia Tulloch, STA became a private company owned by the Tulloch Management Group and changed name to Sustainable Technologies International (STI) (STA 2004). In 2001, STI established the world's first DSC production line. STI further secured its collaborative relationship with EPFL by appointing Graetzel as the Chairman of its Technology Advisory Board.

In 2003, the Tulloch Management Group bought a controlling share in Greatcell with the intention to leverage Greatcell's small manufacturing base in Switzerland and STI's know-how to ramp up production (Dyesol 2005). This raised the interest of several European investors. However none of those interests would materialise. In 2004, Tullock Management decided to change strategy and set up another company in Australia called Dyesol. Instead of trying to take DSC from labs to mass production, the vision for Dyesol was to act as a supplier of technology, manufacturing system and materials, and to deliver an early harvest of financial returns without the need for a large investment in manufacturing facility, in

[35] Monash University, Australian Nuclear Science and Technology Organisation, University of Technology Sydney, Queensland University of Technology and Australian National University.

[36] INAP, Leclanche, Solaronix, Swatch, Toyota, Solterra, Glas Trosch

another words, a semi-consulting company. The Tulloch Management Group was able to raise funding for Dyesol from angel investors and float Dyesol in the following year to raise a total of $30m. Dyesol subsequently acquired STI.

Since then, considerable licensing and collaborative activity has gone on in the DSC market. Konarka, a leader in organic solar cells, acquired the organic cells research group of Siemens in 2004 and subsequently licensed all of its DSC technology to G24i, a UK based company (Dyesol 2008). Dyesol, meanwhile, has sold its technology and expertise to help several companies setting up manufacturing operation, including G24i and Solar Technologies of Greece, and is under contract to develop the DSC technology specifically for use in the battle field by the Australian Defence.

ANALYSIS OF CASE STUDIES

All the different cases followed different development paths. However, a number of common themes which affects commercialisation paths exist. Some of these themes exist within each specific development stage, while others are influential throughout the entire development process. These themes have been grouped into 5 categories: the first three represents company's activities and mostly contain themes unique to a particular development stage, while the last two represents environmental factors and contain themes that tend to be influential throughout the entire development process.

Commercial activities

Niche applications of breakthrough technologies are particularly important during commercialisation phase. As seen in the cases of ARCO Solar, Solarex and indeed other first generation solar cell firms, niche markets such as solar calculators and watches acted as a proving platform to improve and perfect the production process and a spring board to launch the product into mass markets. Some of these markets were created by companies themselves, such as solar calculator and watches, while others were created indirectly by government legislations or policies, e.g. safety regulation on railways and telecoms expansion. Such a theme is also appearing in some of the third generation photovoltaics, as seen in DSC, where they are being firstly exploited in niche markets, e.g. in battlefields and in Toyota's cars.

Operational activities

For breakthrough technologies with no existing markets, testing and approval by a well known authoritative organisation could give products the quality stamp it needs to access a wider customer base. This was particularly evident in the first wave of photovoltaic companies including the case of ARCO Solar, and the role of JPL as a testing and quality authority was regarded as one of the most important roles the government played.

The transition from an R&D focused organisation to one focused on manufacturing and commercial activities is one of the most difficult and important operational activities companies need to go through. Apart from the importance of sufficient funding, decisions over how much capacity to add and which technology to use are equally important. It is vital that these decisions are not hastened by the desire to exploit short term policy benefits as seen in ARCO Solar's hastened decision to exploit tax credits, but are made after thorough evaluation.

Funding

The time required to take a technology from the laboratory to market can be long and successful commercialisation requires sustained level of funding. First Solar was fortunate to have a patient and trusting group of angel investors to take it from conception through commercialisation to growth, whereas Pacific Solar lost its funding and had to restart in a different country.

Funding for initial mass production is particularly difficult as a one-off massive amount of investment is required, which represents high risk for private investors and maybe beyond the capacity of government funds. This is particularly evident in the case of First Solar, which needed $100m to move into mass production. In the first wave of photovoltaic commercialisation, this high level of investment was provided by the cash-rich oil companies. Funding difficulties at this stage could have devastating effect on the company and render previous investment worthless.

Policy environment

The external policy environment was shown to have a substantial impact on the behaviour of the photovoltaic market. Public procurement and tax credits created the first major solar market in the US after the oil embargo, now German and Spanish policies are creating another surge.

Policy instability was a key factor contributing to the difficulties a number of studied companies encountered, e.g. Solarex with the termination of DOE purchase contract and Pacific Solar with the scrapping of further funds from the state. This could be a major issue to the current photovoltaic market when photovoltaics policies in Germany and Spain change.

Certain policies were also creating the wrong incentives. As demonstrated by ARCO Solar, US tax credits in the 1970s encouraged companies to make capital intensive projects that were uneconomical. Current German feed-in tariff is improving in this respect by implementing a gradual fade out of the tariff, thus encouraging improvement in efficiency.

Another emerging theme is the role of local state government in attracting and supporting commercialisation activities. In the case of Suntech Power and CSG Solar, their location was heavily influenced by the support from the local governments of Wuxi and Saxony-Anhalt. This calls into question the effectiveness of central government policy against regional policy and should be researched further.

Industry environment

The energy industry is a major industry with powerful players. The dynamics between different players can shape the development of technologies. Energy companies, e.g. utilities, and oil majors, can be a major source of funding as demonstrated during the early years of Solarex and ARCO Solar; they could also be a major source of distraction and possible suppression, evident in the treatment of a-Si technology by Amoco/Solarex.

Furthermore, the tendency of photovoltaic companies to protect technology or to share and collaborate can have a major impact. In the Amoco/Solarex case, the desire to protect its technology and possibly to suppress it disrupted the development of a promising technology. A more open collaborative environment, on the other hand, might foster development and commercialisation as seen in the case of the EPFL approach to commercialising its DSC technology.

Movement of people in and out of organisations represents a major source of new company formation as seen in the case of UNSW and Pacific Solar. The maintenance of relationships between these interconnected organisations could foster collaboration and provide sources of funding for research organisation and sources of knowledge for companies.

CONCLUSIONS

Detailed research into a number of key companies in the historic development of photovoltaic technology has yielded several emerging themes. Such themes have been used to form a set of recommendations for key actors to facilitate future commercialisation. The two main actors are entrepreneurs / researchers and the government, while energy companies could potentially be an influencing force as well.

Entrepreneurs / Researchers

- Actively look for niche application for proving of product and process;
- Make capital expenditure decisions based on thorough technical and business evaluation, not just the short term policy incentives;
- Identify conflicting interest between key stakeholders, particularly large investors, and look to resolve these potentially damaging conflicts;
- Recognise the significance of the impact of government policy on global photovoltaic market and take the risk of policy changes into account during business planning.

Government

- Creation of institutions for the testing and approval of breakthrough technologies;
- Seeking the creation of competitive niche markets for breakthrough technologies through legislation;
- Provide a policy framework with incentives that encourage competition, improvement and further innovation;
- Provide a stable policy framework;
- Recognise the long time-frame for some technologies in going from laboratory to market and look to provide a sustained level of funding over this time-frame;
- Recognise the criticality of the transition from R&D focus to manufacturing focus for companies and assist in providing sufficient funding for this transition to avoid commercialisation being cut off just before production;
- Foster an open and collaborative relationship between research institutions and industry and encourage the movement of people to assist transfer of knowledge;
- Look into the tradeoffs between a centralised and regional approach to technology support policies.

Energy companies

Energy companies can play a major role in the development of the photovoltaics industry. For the benefit of the photovoltaics markets, when energy companies do invest in photovoltaics companies, treatment of these companies as units independent from their conventional energy business units could prevent potential conflicts of interest and foster a more stable environment for photovoltaics companies to grow. Investment flow should be based on a long term view rather than short term fluctuations in energy prices, thus preventing photovoltaic companies suffering from unstable waves of investment.

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Leading firms for PV Patents 1970-2009 (Patent Class 136, Batteries: Thermoelectric and Photoelectric)

	Top 20 Patent Holders 1970s	**Top 20 Patent Holders 1980s**	**Top 20 Patent Holders 1990s**	**Top 20 Patent Holders 2000s**	**Top 20 Total Patent Holders**
1	UNITED STATES OF AMERICA, NASA	ATLANTIC RICHFIELD COMPANY	CANON KABUSHIKI KAISHA	CANON KABUSHIKI KAISHA	CANON KABUSHIKI KAISHA
2	RCA CORPORATION	ENERGY CONVERSION DEVICES, INC.	SANYO ELECTRIC CO., LTD.	SHARP CORPORATION	SANYO ELECTRIC CO., LTD.
3	UNITED STATES OF AMERICA, DEPARTMENT OF ENERGY	EXXON RESEARCH + ENGINEERING CO.	MITSUBISHI DENKI KABUSHIKI KAISHA	KANEKA CORPORATION	SHARP CORPORATION
4	SIEMENS AKTIENGESELLSCHAFT	SANYO ELECTRIC CO., LTD.	UNITED SOLAR SYSTEMS CORPORATION	SANYO ELECTRIC CO., LTD.	UNITED STATES OF AMERICA, DEPARTMENT OF ENERGY
5	WESTINGHOUSE ELECTRIC CORP.	RCA CORPORATION	UNITED STATES OF AMERICA, DEPARTMENT OF ENERGY	BOEING COMPANY	UNITED STATES OF AMERICA, NASA
6	COMMUNICATIONS SATELLITE CORPORATION	UNITED STATES OF AMERICA, DEPARTMENT OF ENERGY	SEMICONDUCTOR ENERGY LABORATORY CO., LTD.	JX CRYSTALS, INC.	BOEING COMPANY
7	ATLANTIC RICHFIELD COMPANY	UNIVERSITY OF DELAWARE	BOEING COMPANY	MATSUSHITA ELECTRIC INDUSTRIAL CO., LTD.	RCA CORPORATION
8	ROBERTSHAW CONTROLS COMPANY	CHEVRON RESEARCH & TECHNOLOGY CO.	FUJI ELECTRIC CO., LTD.	MIDWEST RESEARCH INSTITUTE	MITSUBISHI DENKI KABUSHIKI KAISHA
9	LEEDS + NORTHRUP COMPANY	SEMICONDUCTOR ENERGY LABORATORY CO., LTD.	SHARP CORPORATION	GENERAL ELECTRIC COMPANY	ATLANTIC RICHFIELD COMPANY
10	NUCLEAR BATTERY CORPORATION	BOEING COMPANY	JX CRYSTALS, INC.	KONARKA TECHNOLOGIES, INC.	SEMICONDUCTOR ENERGY LABORATORY CO., LTD.
11	GENERAL ELECTRIC COMPANY	SIEMENS AKTIENGESELLSCHAFT	SOLAREX CORPORATION	NEOKISMET, L.L.C.	SIEMENS AKTIENGESELLSCHAFT
12	HUGHES AIRCRAFT COMPANY	UNITED STATES OF AMERICA, NASA	MIDWEST RESEARCH INSTITUTE	MITSUBISHI DENKI KABUSHIKI KAISHA	GENERAL ELECTRIC COMPANY
13	TRW INC.	SOLAREX CORPORATION	UNITED STATES OF AMERICA, NASA	UNITED STATES OF AMERICA, DEPARTMENT OF ENERGY	ENERGY CONVERSION DEVICES, INC.
14	LICENTIA PATENT-VERWALTUNGS-GMBH	STANDARD OIL COMPANY	MATSUSHITA ELECTRIC INDUSTRIAL CO., LTD.	CITIZEN WATCH CO., LTD.	MATSUSHITA ELECTRIC INDUSTRIAL CO., LTD.
15	3M COMPANY	GENERAL ELECTRIC COMPANY	PHOTON ENERGY, INC.	IBM CORPORATION	SOLAREX CORPORATION
16	ROCKWELL INTERNATIONAL CORPORATION	MASSACHUSETTS INSTITUTE OF TECHNOLOGY	SIEMENS AKTIENGESELLSCHAFT	EMCORE CORPORATION	KANEKA CORPORATION
17	TELEDYNE INDUSTRIES, INC.	KANEGAFUCHI CHEMICAL INDUSTRY CO., LTD.	UNITED STATES OF AMERICA, ARMY	CALIFORNIA INSTITUTE OF TECHNOLOGY	MASSACHUSETTS INSTITUTE OF TECHNOLOGY
18	SOLAREX CORPORATION	OWENS-ILLINOIS INC.	MOBIL SOLAR ENERGY CORPORATION	MASSACHUSETTS INSTITUTE OF TECHNOLOGY	JX CRYSTALS, INC.
19	UNITED STATES OF AMERICA, ARMY	HUGHES AIRCRAFT COMPANY	KANEGAFUCHI CHEMICAL INDUSTRY CO., LTD.	POWERLIGHT CORPORATION	EXXON RESEARCH + ENGINEERING CO.
20	GENERAL MOTORS CORPORATION	UNITED STATES OF AMERICA, AIR FORCE	NGK INSULATORS LTD.	SUNPOWER CORPORATION	UNITED SOLAR SYSTEMS CORPORATION