ARC Centre of Excellence for Solar Energy Systems

Report for the year 2005

CEO348198

Australian National University

5th April 2006

Establishment and funding

The Centre was established late in 2003, and will operate until the end of 2007. Indicative funding from the ARC is $300,192 per year. Funding was first received from the ARC in November 2003. The Centre is located in the Department of Engineering within the College of Engineering and Computer Science at the Australian National University.

Personnel

Principal Researchers

Prof AW Blakers (RD)	Director
Dr VA Everett (CI)	Deputy Director
Dr KJ Weber (CI)	Principal Researcher
Dr P Deenapanray (CI)	Principal Researcher

Chief Operating Officer and Centre Manager

Mr Ray Prowse

PhD Candidates

Mr Evan Franklin

Mr Jin Hao

Ms Wendy Jellett

Other people working in areas relevant to the Centre of Excellence

Mr David Barton – PhD candidate. Working on the social issues of sustainable technologies

Mr Kidane Belay – Research Assistant. Cell fabrication

Mr Bruce Condon – Electrical Engineer

Mr James Cotsell – Research Associate. Concentrator receivers

Dr Joe Coventry – Research Associate. Silicon concentrator cell assemblies for dish concentrators

Ms Nina De Caritat – Research Assistant. Cell fabrication.

Mr Chris Holly – Laboratory Process Manager. Concentrator solar cells

Mr Neil Kaines – Laboratory Manager

Ms Josephine McKeon – Research Assistant. Cell fabrication.

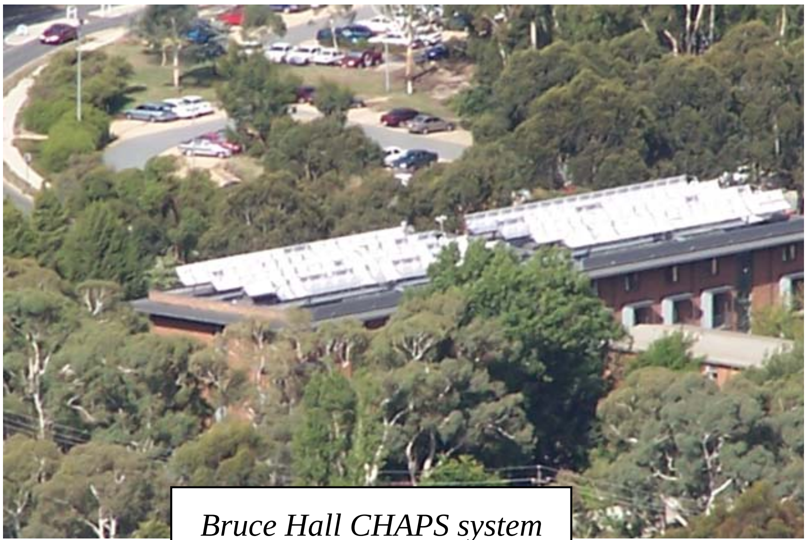
Mr Sam McKeon – Laboratory Assistant

Ms Sonita Singh – Research Assistant. Cell fabrication

Research Program

The focus for the *ARC Centre of Excellence for Solar Energy Systems* is the development of improved silicon concentrator solar cells for 10-50 sun linear concentrators. The development of integrated high-performance linear concentrating systems is underway with funding from a variety of sources.

Photovoltaic Trough Concentrating Systems



Bruce Hall CHAPS system

Linear solar concentration systems have the potential to provide more cost effective conversion of solar energy into a useful form of energy, such as electricity and hot water. In effect, glass mirrors, which cost much less than solar cells, replace most of the solar cells, allowing reduced energy conversion costs.

Trough concentrators typically produce a solar intensity at their focal line of 10-40 times normal solar intensity, or 10-40 "suns". This corresponds to about 1-4 W/cm^2.

Solar radiation produces both heat and electricity in a photovoltaic array. The heat and electricity must be removed from the solar cells in a way that keeps the operating temperature low and the parasitic resistance losses small. This requirement impacts upon the design of the solar cells.

Combining solar photovoltaic and thermal elements to form a hybrid system has the potential to further improve the cost effectiveness of solar energy conversion. Combined electrical and thermal efficiencies of up to 70% have been achieved in Combined Heat and Power Solar (CHAPS) systems designed and built at ANU.

In a CHAPS system, the solar cells are mounted on an extruded aluminium receiver "looking down" at the mirrors. About 20% of the radiation incident on the solar cells is converted into electricity, with the balance becoming heat. Water is circulated behind the solar cells in order to extract the heat.

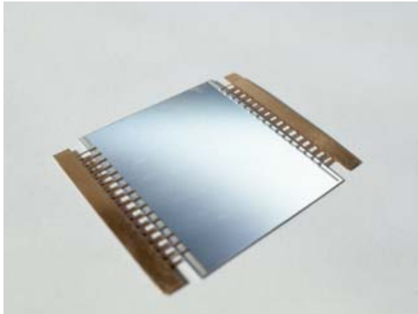
A variety of linear concentrators have been constructed by ANU (with separate funding from the ARC CoE) to act as test-beds for linear concentration technology and components. Receivers have been developed for the mounting of solar cells at the focal line of the linear concentrators. These receivers incorporate provision for thermal expansion mismatch, efficient extraction of heat and electricity, bypass diodes and long service life. Advanced glass-on-metal-laminate mirrors have been developed that offer high reflectivity, shape accuracy, simplicity and long field life. Mechanical support structures have been designed that combine rigidity and survivability with low cost. Sophisticated tracking and control software and hardware has been developed. A complete testbed is available for the linear concentrator solar cells being developed with funding from the ARC Centre of Excellence.

A 160m^2 air-cooled two-axis tracking system was constructed in Perth. Water-cooled single-axis tracking 30m^2 and 300m^2 demonstration CHAPS systems have been constructed at ANU on the roofs of the Fenner Building and Bruce Hall (a college of residence) respectively. A low-profile linear microconcentrator is under development for deployment on house roofs. This system is a scaled down version of the CHAPS system, and will take advantage of the unusual shape and characteristics of Sliver solar cells.

Experimental rooftop CHAPS system on Faculties Teaching Centre

Conventional concentrator solar cells

The fabrication of about 4000 monocrystalline concentrator cells (each with an area of 20cm^2) was completed, to populate the receivers in the Bruce Hall CHAPS system. The cells were specifically designed for the system. The design is a compromise between cost, performance and yield. Typical cell performance is around 20% at 25C and 30 suns illumination. This exercise yielded valuable information with respect to statistical analysis of performance and yield. It was found that both performance and yield increased as the design was bedded down.



High efficiency concentrator cell with tabbed bus bars

The cell metallisation technique was refined, and a patent application was lodged relating to the formation of metal contacts. These contacts are capable of being formed simply and reliably. They exhibit high adhesion, tolerance of temperatures up to 800 degrees C, low contact resistance required for concentrator applications and low surface recombination rates required for high conversion efficiency. These contacts are also being used extensively in the fabrication of Sliver cells both at ANU and Origin Energy.

Sliver concentrator solar cells

Andrew Blakers and Klaus Weber invented sliver solar cells in 2000. The technology is the subject of a $40-50 million commercialisation by Origin Energy. A factory has been built in Adelaide and first sales occurred in 2005. Large-scale sales are expected to commence in 2006. The Appendix to this report contains further information about Sliver solar cell technology. Three patent applications were filed in 2005 pertaining to ideas that have arisen under this program of work.

The Sliver cell fabrication process is described in the Appendix.

Sliver technology was originally conceived for non-concentrator applications. However, Sliver solar cells also perform well under 10-30 suns concentration, which is the range delivered by trough concentrators such as those developed at ANU and described above. The development of Sliver concentrator solar cells is a major focus of work in the Centre of Excellence. Substantial further progress was made in understanding the performance and limitations of Sliver concentrating solar cells.

Sliver cells were developed because they promised inherent advantages over conventional solar cells. The largest component of the cost of solar cells (~50%) is the expensive high-grade silicon wafers used in the construction of the cells. Sliver technology allows a 10-fold reduction in the amount of silicon used per megawatt of solar panel. Another large component (~25%) is the processing of the wafers to form solar cells. Sliver technology allows a 30-fold reduction in the number of wafers that need to be processed per megawatt of solar panel.

Sliver cells have several features that make them well-suited to concentrator applications. These include:

- They are long (10-100mm), narrow (0.7-1mm) and thin (50 μm). This unusual shape allows their use in both conventional and unconventional receivers, including the narrow receivers required for microconcentrators.
- The cells are flexible, which allows them to be wrapped around curved receivers.
- The cells are bifacial which allows light to be absorbed equally well into either surface, allowing a wider range of possible concentrator designs.
- The cells are shadow tolerant because they have a small reverse breakdown voltage due to the presence of adjacent regions of heavy doping. This means that shadows cast

by structural elements of the concentrator system moving across a series-connected cell string do not result in large losses in electrical output. Bypass diodes are therefore not required.

- Series connection of Sliver cells can build a high voltage (hundreds of volts at a rate of about 10 volts per linear cm) in a small area, resulting in a correspondingly small current. This results in reduced resistive losses in connectors.
- Slivers from Origin Energy's commercial one-sun production line (expected to be available from late 2006) are likely to be suitable for application at 10-20 suns. These cells will be far below the cost per cm^2 of cells from a dedicated concentrator manufacturer, were one to set up in business.

Work undertaken in connection with Sliver cells during 2005 included the following:

Evaluation of the doping uniformity of the sidewalls

It is quite difficult to achieve uniform doping of phosphorus into the deep and narrow grooves between adjacent Sliver cells. If the doping is light in the centre of the grooves then excessive emitter series resistance will ensue. Methods were devised to profile the sheet resistance of the sidewall diffusions. This allowed optimisation of the temperature, time and gas flows of the sidewall diffusion to achieve relatively uniform doping. This was an important development in respect of concentrator Sliver cells, and allowed the fabrication of cells with high Fill Factors in the range 10-30 suns.

Optimisation of adjacent diffusions

Large reductions can be achieved in Sliver cell process complexity at the cost of reduced opportunity to independently control the surface concentrations and profiles of the boron and phosphorus diffusions. We have found a process window that avoids unwanted shunts and surface recombination while still allowing simple processing and low reverse breakdown voltage.

RIE

Work was undertaken on the influence of reactive ion etching on the minority carrier lifetime in p-type Si. RIE is a directional etching process that we use to selectively remove dielectric layers from the surface of wafers during processing. If RIE could be continued into the silicon then simplification of Sliver processing would be possible.

Unfortunately, it was found that if the RIE was not terminated before all of the oxide was removed, so that some silicon etching occurred, then damage to the minority carrier lifetime in the wafer resulted. It was found that reducing the power of the etching when close to the surface could ameliorate this damage.

Other aspects of RIE etching, including directionality, were investigated.

Streamlined Sliver solar cell processing

Substantial advances were made in streamlining the Sliver fabrication process, using techniques described above together with other developments. Compared with the Sliver fabrication process of late 2003, about 40% of the process steps have been removed. No new capital equipment is required to achieve this result, and indeed several major capital items are eliminated. This has important benefits for factory cost, cell manufacturing cost and yield.

Luminescent concentrator systems

Initial work was conducted on incorporating Sliver cells into luminescent solar concentrators. Luminescent solar concentrators are thin sheets of plastic (1-2mm thick with an area of ~$1000cm^2$) impregnated with dyes that absorb sunlight and re-emit in narrow wavelength bands. Total internal reflection conducts the emitted light to the edges of the plastic sheets.

Sliver cells are ideal for the conversion of this light to electricity because they have high quantum efficiency at these wavelengths, they are long and thin and they are bifacial. They can be attached to the edges of the plastic sheets with relative ease.

Modified one-sun solar cells for concentrator applications

Initial work was conducted into modifying commercial solar cells designed for operation under one-sun illumination intensity so that they can operate under 10-30 suns. The main issue to be considered is the large increase in series resistance losses that result, which causes a reduction in fill factor. On the other hand, ideality factor falls to unity, shunt losses vanish and the open circuit voltage increases by about 100mV at 30 suns. We found a way to modify some types of solar cells so that efficiencies above 17% could be obtained in the concentration range 10-30 suns. This is high enough to be very interesting commercially. The main advantage of modifying one sun cells is that they come from very large production runs, and are therefore much cheaper per cm^2 than cells from dedicated concentrator solar cell manufacturers. In point of fact, no manufacturer is producing concentrator cells designed for use in the range 10-50 suns.

Activity plan for the next twelve months

Activities planned for 2006 include the following:

- Further characterisation of Sliver solar cells, particularly for concentration where series rather than shunt resistance is the main parasitic loss.
- Incorporation of several new ideas for streamlining cell fabrication.
- Further investigation of RIE etch-damage
- Increased public awareness of the Centre of Excellence for Solar Energy Systems through a strategic publicity and communication campaign.

Commercial and contractual constraints in respect of Sliver solar cells

It appears that the commercial value of Sliver solar cell IP is enormous – in the range hundreds to thousands of millions of dollars. Legal/commercial constraints will continue to heavily restrict publications in this area, with the exception of patents. ANU has an extensive Sliver patent portfolio.

Advisory Board

An Advisory Board has been established and met on Friday 15th April 2005. The Advisory Board meets meet once per year. The next meeting will be in April 2006. Brief Biographies of members of the Board are attached.

The role of the Advisory Board is to provide strategic advice on the research focus of the Centre, to provide an independent perspective on Centre structure and operating principles, to provide advice on intellectual property and commercialisation management and to assist with external contacts, linkages and relationships as the opportunity arises.

Substantial interactions between Centre researchers and most members of the Advisory Board continued throughout 2005.

Education and training

Researchers associated with the Centre delivered lectures and tutorials in undergraduate courses ENGN 2224, ENGN 4519, ENGN 6519, ENGN 3213 and Phys 3053. Several final year Engineering students undertook Projects during 2005.

Three PhD students, Mr Evan Franklin, Mr Jin Hao and Ms Wendy Jellett, are associated with the Centre.

Industrial interactions

Centre activities have links with three commercial projects underway at ANU:

- The commercialisation of Sliver solar cell technology, which was invented by Blakers and Weber at ANU. Origin Energy is investing $40 million in a factory in Adelaide for the production of non-concentrator Sliver solar modules. First commercial sales occurred in 2005, and mass sales will commence in 2006. Sliver solar cells as concentrator solar cells are an important focus for the Centre of Excellence. An ARC Linkage grant (LP0347095) between ANU and Origin focuses on micromachining techniques for the formation of Sliver solar cells.
- Success in the development of high-performance concentrator solar cells will assist the commercialisation of tracking parabolic trough solar concentrator systems developed at ANU. A $300m^2$ demonstration system has been constructed on the roof of Bruce Hall College of Residence at ANU in conjunction with Rheem/Solahart.
- ANU and ActewAGL are developing a microconcentrator system that will supply electricity and hot water to domestic dwellings. This system will take advantage of solar cell technology developed in the Centre. The work is supported by an ARC Linkage grant (LP0454195).

Awards and prizes

The following honours were accorded to researchers in the Centre:

- Klaus Weber, Andrew Blakers and Vernie Everett, in conjunction with Origin Energy: Winner, Banksia Award 2005, Environmental Leadership in Infrastructure & Services, "SLIVER Cells - a Breakthrough in Solar Technology"
- Andrew Blakers, Klaus Weber and Vernie Everett, in conjunction with Origin Energy: Winner, Aichi World Expo Global Eco-Tech 100 Award for SLIVER solar cell technology, 2005
- Klaus Weber, Vernie Everett and Andrew Blakers, in conjunction with Origin Energy: Winner, Australian Institute of Energy Innovation in Energy Science & Engineering Award "Sliver cells – A breakthrough in solar technology", 2005
- Vernie Everett, Andrew Blakers and Klaus Weber in conjunction with Origin Energy: Finalist, Sherman Eureka Prize for Environmental Research, 2005
- Andrew Blakers: Election to Fellowship of the Australian Academy of Technological Sciences and Engineering
- Andrew Blakers: Election to Fellowship of the Australian Institute of Energy

Publications

<u>Book Chapters</u>

1. A. Blakers, "Energy for Today", invited chapter in "Sustainability for the ACT", Sustainable Experts Reference Group, ACT Government, ISBN 0 642 60374 X, 2005
2. A. Blakers, "Solar Energy in the Built Environment", invited chapter in "Making Canberra Sustainable", Ed. Bryan Furnass, Sebastian Clark and Penny Ramsay, ISBN 1 74027 340 0, 2005

Journal papers

1. Michelle McCann, Klaus Weber and Andrew Blakers, Surface Passivation by Re-Hydrogenation of Silicon Nitride Coated Silicon Wafers, Progress in Photovoltaics, Volume 13, pp 195-200 (2005)
2. K.J. Weber and A.W. Blakers A novel silicon texturisation method based on etching through a silicon nitride mask, Progress in PV, Vol 13 pp 691-695, 2005

Accepted Journal papers

1. J. Coventry and A.W. Blakers, Understanding the causes of non-uniform radiation flux on a linear PV concentrator, submitted to 'Progress in Photovoltaics', accepted July 2005
2. K. J. Weber, V. Everett, P.N.K. Deenapanray, E. Franklin and A.W. Blakers, Modeling of static concentrator modules incorporating Lambertian or V-groove rear reflectors, accepted September 2005
3. Reactive Ion Etching of Dielectrics and Silicon for Photovoltaic Applications, Prakash N. K. Deenapanray, C. S. Athukorala, Daniel Macdonald, W. E. Jellett, E. Franklin, V.E. Everett, K. J. Weber and A. W. Blakers, accepted to Progress in PV October 2005

Patents

1. Vernie Everett and Andrew Blakers, “Elongates”, PCT filed 9th August 2005
2. A.W. Blakers, S. Deenapanray and V. Everett, “A Method for localised processes” (provisional filed June 2005)
3. Andrew Blakers, Klaus Weber, Vernie Everett, Sanju Deenapanray and Evan Franklin, “A Structure and a Method I”, (provisional filed July 2005)
4. Andrew Blakers and Klaus Weber, “A Semiconductor Processing Method”, Complete patent filed 15th October 2005

Conference papers

1. Klaus Weber, Andrew Blakers, Vernie Everett, Sanju Deenapanray and Evan Franklin, Sliver solar cells, 31st IEEE PVSC, Florida 2005
2. Andrew Blakers, Klaus Weber, Vernie Everett, Sanju Deenapanray and Evan Franklin, Sliver solar cells, Australian Institute of Physics Congress, Canberra, January 2005
3. A.W. Blakers, V. Everett. P.N.K Deenapanray, E. Franklin and K.J. Weber, Recent developments in Sliver solar cell technology, 20th EC Photovoltaic Solar Energy Conference, Barcelona, June 2005
4. H. Jin, K.J. Weber and A.W. Blakers, Silicon/Silicon Oxide/LPCVD silicon nitride stacks: the effect of oxide thickness on bulk damage and surface passivation, 20th EC Photovoltaic Solar Energy Conference, Barcelona, June 2005
5. P.N.K. Deenapanray, C.S. Athukorala, D. Macdonald, V.E. Everett, K.J. Weber and A.W. Blakers, Influence of reactive ion etching on the minority carrier lifetime in p-type Si, 20th EC Photovoltaic Solar Energy Conference, Barcelona, June 2005
6. A.W. Blakers, “Solar energy in Australia”, International Conference on Alternative Energy, Hong Kong, June 2005 (invited)
7. A.W. Blakers and J. Smeltink, “CHAPS Systems”, Concentrator Industry Forum, Brisbane October 2005
8. A.W. Blakers, K.J. Weber, P.N.K. Deenapanray, V. Everett, E. Franklin and W. Jellett, “Sliver solar cells”, PVSEC 15, Shanghai, October 2005
9. A.W. Blakers, “Solar Energy Solutions”, Greenhouse 2005, Melbourne November 2005

Visitors and outreach

Activities over the period January 2005 to date are listed below. There has been a rapid increase in interest in the solar energy activities at ANU as concern over the consequences of climate change increase. There is growing recognition of the great significance of Sliver solar cell technology for the photovoltaic industry and for climate change policy.

Visitors

- 27/2/06: Visit by Dr Hermann Scheer, Member of the German Parliament, President of the European Association for Renewable Energy and General Chairman of the World RE Council
- 1/3/06: Visit by Senator Lyn Allison, Democrats Energy & Climate Change spokesperson
- 3/3/06: Visit by Senator Bob Brown, Senator Christine Milne and Dr Deb Foskey MLA of the Greens
- 7/3/06: Visit by the Governor General, Major General Jeffery
- 17/3/06: Visit by Mr Anthony Albanese MP, ALP Environment spokesperson
- 30/3/06 Visit by Mr Kim Beazley MP, Opposition Leader and Mr Anthony Albanese ALP Environment spokesperson
- 31/3/06: Visit by Senator Christine Milne of the Greens
- 3/4/06: Visit by Dr Steve Morton, Group Executive, Sustainable Energy and Environment Group, CSIRO
- 5/4/06: Visit by Lt. Col. Jack Galbraith and Capt. Adam Rankin of the ADF

Articles and seminars

- 14/2/05: Full-page interview in the Canberra Times with Roslyn Beeby
- June 2005: various mentions of the winning of a Banksia Award by ANU and Origin Energy for Sliver cells.
- 17/10/05: 800 word article in the Canberra Times by Roslyn Beeby on Solarisation
- 18/10/05: 600 word article in the Canberra Times by Scott Hannaford on sustainability
- 18/10/05: Radio 2CC interview, 7min, solar energy
- 9/2/06: 800 word article on energy conservation and Sliver technology in the Canberra Times
- 23/2/06: Sliver solar cells, seminar delivered to ABARE
- 8/3/06: 400 word article + picture on ANU solar technology in the Canberra Times on the Governor General’s visit.
- 10/3/06: Sliver solar cells, ANU Colloquium
- 13/3/06: Solar Energy Solutions, delivered to the National Council of Women (ACT)
- 13/3/06: “Moments in the sun”, 600 word article in ANU’s “On Campus” monthly newsletter

Expenditure for the year

An annual certified statement is attached incorporating details of expenditure for the year covered by the Centre's report and preceding years as well as estimates of future expenditure.

APPENDIX

SLIVER SOLAR CELL TECHNOLOGY

Overview

Sliver solar cell technology was invented at the Australian National University in 2000 and developed with financial support from Origin Energy. The technology has startling potential for rapid and dramatic reductions in the costs of solar energy conversion, by up to three quarters. It is a fundamental technical breakthrough with profound implications for the PV industry and energy and climate change policy worldwide.

ANU continues research into Sliver technology. Origin Energy is commercialising Sliver technology at their new factory in Adelaide - first sales occurred in 2005 and mass sales are expected late this year (http://sliver.com.au).

This paper describes the exciting prospects for Sliver solar cell technology.

Solar energy

There are five available energy sources: solar energy in its various forms, fossil energy, nuclear energy, geothermal energy and tidal energy. Of these five, only solar energy can provide very large-scale energy in a long-term sustainable and environmentally acceptable manner. The other four energy sources can supplement solar energy to increase the diversity, and hence the stability and security of energy supply.

Fossil fuel reserves are finite, and these valuable resources will be depleted by large-scale burning. The escalating consumption of fossil fuels produces large quantities of greenhouse gases, causes local and regional pollution, and requires large-scale mining. In addition, the highly non-uniform distribution of fossil fuels gives rise to international tensions. Nuclear energy has problems of waste disposal and devastating accidents, and is inextricably linked to nuclear weapons proliferation and the risk of terrorist strikes. While geothermal and tidal energy can make a useful contribution, they both have limited geographical availability.

Solar energy includes both direct radiation where energy is harnessed directly from sunlight, and indirect forms of energy such as biomass, wind, hydro, ocean thermal, ocean currents and wave energy caused by the effects of the Sun on Earth. Most of these energy forms will be part of the energy resources mix when solar energy becomes the dominant traded-energy form. Some solar energy technologies are more advanced than others, and the eventual solar energy mix will vary from region to region. The key to successful mass-utilisation of solar energy is diversity.

Photovoltaics, solar thermal energy, which is also referred to as solar heat energy, and wind energy are the only solar energy technologies in sight that can provide very large quantities of sustainable energy with sufficiently high efficiency (more than 20%) to limit land requirements. These conversion technologies have small environmental impacts and insignificant military applications. In some countries biomass may also make a substantial contribution to energy supply, despite low solar-to-electricity conversion efficiency of around 0.2% in total.

Photovoltaics (PV) is the science of converting sunlight directly into electricity via solar cells without the use of mechanical conversion or any moving parts. PV has found widespread use in niche markets such as consumer electronics, remote area power supplies and satellites. As costs decline, large numbers of photovoltaic systems are being installed on house roofs in cities in Europe and Japan. The cost of photovoltaic systems is not a strong function of scale, which means that photovoltaic systems are often the most economical energy source for small applications. Presently, over 90% of the world photovoltaic market is serviced by crystalline silicon solar cells. This strong market dominance is likely to continue for many years.

Most solar thermal electricity technologies use mirrors to concentrate sunlight onto a receiver. The resulting heat is ultimately used to generate steam, which passes through a turbine to generate electricity. Solar concentrator methods are equally applicable to concentrating photovoltaic systems. The usual ways of concentrating sunlight are point focus concentrators, in the case of dishes; line focus concentrators in the case of troughs; and central receivers in the case of heliostats and power towers.

Solar thermal electricity is not yet a commercial proposition. The reason for this is that, unlike photovoltaics, there are strong economies of scale. This means that small systems that might be suitable for an individual household are far too expensive. This lack of a niche market, in contrast to photovoltaics, will inhibit the development of solar thermal electricity in the short to medium term. In the longer term, solar thermal electricity will compete with photovoltaics, because the efficiency of specialist solar cells designed to operate at solar intensities above 500 times normal intensity, or “500 suns”, is similar to the efficiency of turbines. Solar thermal systems can be used to drive chemical reactions. This constitutes a form of chemical energy storage that can be recovered at will.

Wind energy is now a mainstream energy technology and is the cheapest of the new renewable energy technologies. However, constraints on resource availability will limit the contribution of wind energy to about 20% of worldwide electricity supply.

In most cases, storage of solar electricity is not a serious issue until the proportion of wind and solar in the mix rises above about 10%. This is not likely within 20 years, with some notable exceptions. This lead time will give adequate time to develop solutions. Some options for ensuring continuity of supply include diversity of technology, diversity of geographical location, energy conservation, load shifting from night to day, strong long-distance electrical interconnection, judicious use of natural gas, bio-fuels and coal to meet peak loads, sophisticated wind and solar prediction on every time scale from seconds to months, pumped hydro, compressed air, thermochemical energy storage and advanced batteries.

Photovoltaic energy conversion

Solar cells are made on wafers of pure, crystalline silicon typically 15 cm in diameter and 0.3 mm thick. In conventional solar modules, about 40 solar cells are connected together and packaged behind glass to form a solar power module with an area of about 0.5 m^2. PV modules are highly reliable, with modern modules carrying a 25-year guarantee. PV systems comprise PV modules, support structures, electrical interconnection, and inverters that convert DC electricity to AC electricity.

PV systems have traditionally found widespread use in niche markets such as remote area power supplies. Now, as costs come down, millions of PV systems have been installed in cities around the world. Apart from producing clean electricity, PV systems have many other attractive attributes such as distributed generation and peak load levelling capabilities.

Low cost PV electricity can readily provide much of the world’s electricity in a carbon-constrained world. It will not be surprising to those in the photovoltaics industry if half of the world’s electricity comes from photovoltaics by 2050. The other half could come from wind energy, solar thermal electricity, waves, biomass and other sources. This goal will be achieved assuming that world electricity consumption triples in line with population growth and rising living standards and that annual average growth rates in the PV industry over the past 15 years (23% per year) continue to prevail.

About 0.2% of the world's land surface would be required, which is approximately equal to the area presently covered by the built environment. The steady-state sales of the PV industry (for replacement of worn-out systems) would be A$0.5-1 trillion per year, which is about the same size as the electronics industry and current global defence spending.

An important interim milestone for the photovoltaic industry is to reach energy costs below peak daytime retail costs. When this occurs explosive growth in sales is likely, since building owners around the world will benefit financially from installation of their own photovoltaic system. On current trends, this is likely to happen around 2015.

A world electricity supply based on photovoltaics would be truly sustainable in the very long-term. Most of the systems would be deployed on the roofs of buildings or in arid regions. The raw materials (mostly silicon and glass) are neither in short supply nor toxic. The operational time required to recover the energy used in the fabrication of advanced PV systems (eg based on Sliver cells) is one year, compared with an expected lifetime of 30-50 years. The environmental and health impacts of solar cell factories are minimal.

Photovoltaics has many social advantages over competing energy technologies. There are few avenues for the diversion of the technology to military and terrorist uses. The PV industry would provide a decentralised, democratising energy source, allowing individuals and groups to control their own energy production and to make the national energy supply less vulnerable to war or terrorist activity. Furthermore, the solar resource is ubiquitous. In fact, poorer regions of the world tend to have good solar resources.

The global PV industry is booming. Not only has growth been sustained since the industry was established, but global annual growth rates in the PV industry are accelerating. Global PV industry exponential growth rates were 24%, 31% and 37% averaged over the last 15, 10 and 5 years respectively.

Crystalline silicon solar cells are used in 95% of PV modules. Silicon, which is the second most abundant element in the Earth’s crust, has many advantages, including the abundance of raw material, non-toxicity, high and stable cell efficiencies, market dominance, and the ability to share infrastructure and development costs with the well-established integrated circuit industry.

For many reasons, wafer-based silicon solar cells cannot be a long-term solution to large-scale energy production. Indeed, a major challenge presently facing the PV industry is a critical shortage of hyperpure silicon at an affordable price. The silicon used to make solar cells must be purified in very expensive facilities. The PV industry used to consume 10% of the world’s hyperpure silicon (off-spec silicon from the integrated circuit industry), but this figure is now 50%.

Possible solutions to this problem are thin crystalline silicon solar cells such as Sliver technology, non-silicon thin film cells such as CdTe, CuInGaSe, dye-sensitised and organics, and hypothetical advanced high efficiency cells based on quantum wells or engineered materials. The high efficiency potential and low cost potential of Sliver technology confers a major advantage over alternatives.

Sliver solar cell technology

The invention of Sliver solar cell technology in 2000 by Dr Klaus Weber and Professor Andrew Blakers of the Australian National University is a fundamental breakthrough. Sliver cell technology uses standard materials and conventional techniques in novel ways to create thin single crystalline solar cells with superior performance at significantly reduced cost.

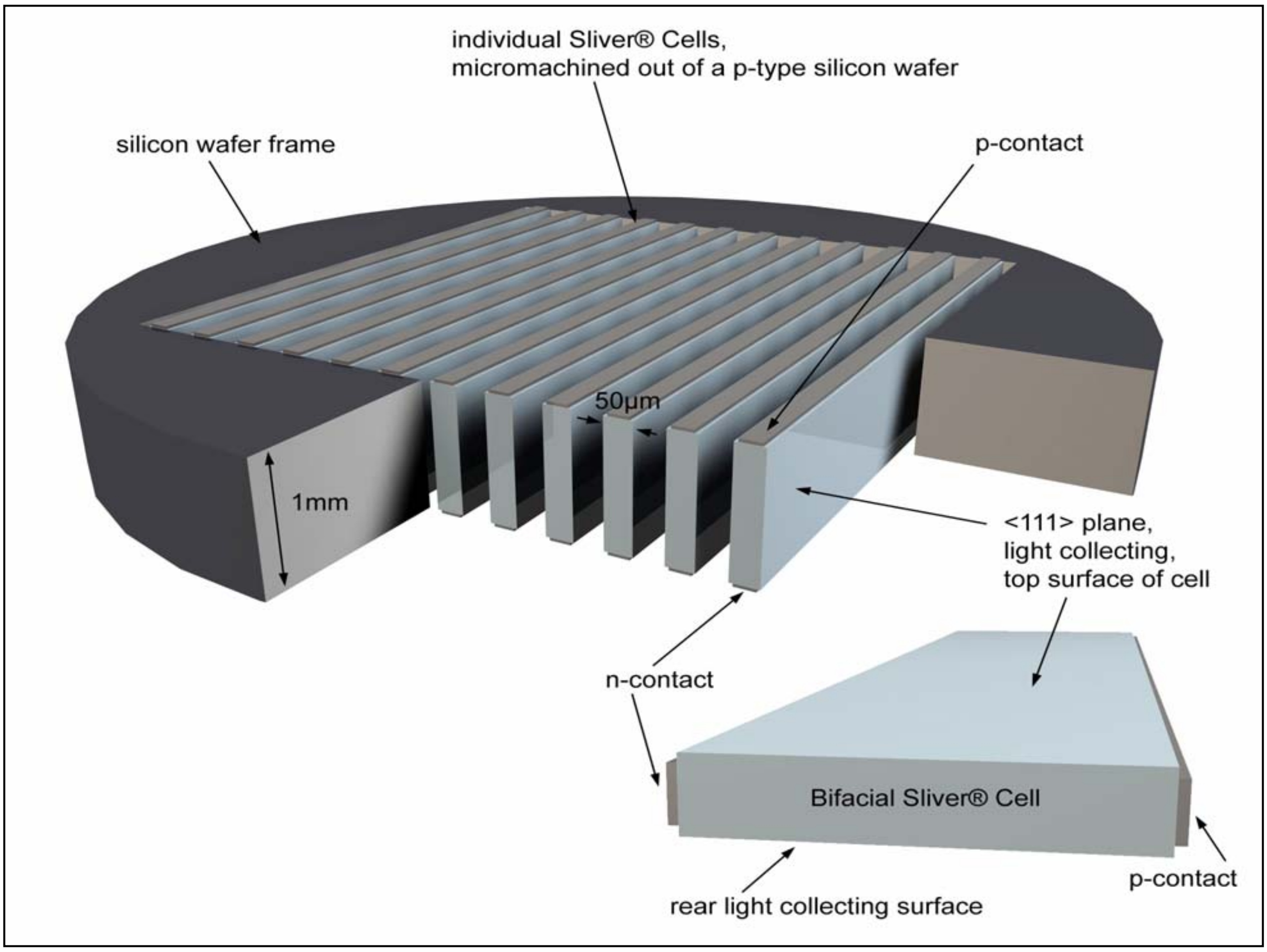
Sliver cells are fabricated on single crystal silicon – the gold standard of the PV industry. Sliver modules are manufactured using techniques adapted from conventional module manufacture. Mature Sliver modules will use only conventional materials. Sliver modules can be efficient, low cost, bifacial, transparent, flexible, shadow-tolerant and light-weight. Sliver technology has the potential to be a comprehensive long-term solution for PV.

Standard single crystal silicon wafers around 1 mm thick are used as the starting material for the Sliver cell process. Low cost micromachining methods are used to create many narrow parallel grooves that extend vertically through the wafer but do not extend to the wafer edge. The grooves lead to the creation of an array of thin, parallel, silicon strips, referred to as "Slivers", confined in the wafer, and held in place at their ends by the un-grooved part of the wafer, referred to as the wafer frame. The entire wafer, containing up to several thousand Slivers, is then processed using standard techniques to turn each of the Slivers into a solar cell.

At the end of the process, the Slivers are cut out of the wafer frame, laid flat, and electrically connected. The rotation of each Sliver through 90 degrees generates a large gain in the active surface area – "area multiplication" – compared with the starting wafer.

Area multiplication is a valuable attribute of Sliver technology, allowing a single wafer containing the equivalent solar cell surface area of around thirty conventional wafers to be processed at not much greater handling cost than a single conventional wafer.

The key to understanding the significance of Sliver technology from the cell processing perspective is to recognise the fundamental difference between conventional cell processing and Sliver cell processing. In the conventional cell process, cells are formed on the wafer surface – essentially a 2-dimensional process. In the Sliver cell process, cells are formed in the wafer volume – essentially a 3-dimensional process, which produces a dramatic increase in the active surface area of solar cells per unit volume of silicon consumed and per wafer that is processed.



By using the Sliver process a large increase is obtained in the active surface area of solar cells, compared to the surface area of the starting wafer, of the order of 10-30 times. Thus the cost of cell processing is greatly reduced by the dramatic reduction in the number of wafer starts required for an equivalent energy output compared with conventional cell processing.

Sliver technology allows for large reductions in the consumption of expensive hyperpure silicon, by 90-95%, compared with conventional silicon solar cells. This solves the hyperpure silicon supply problem.

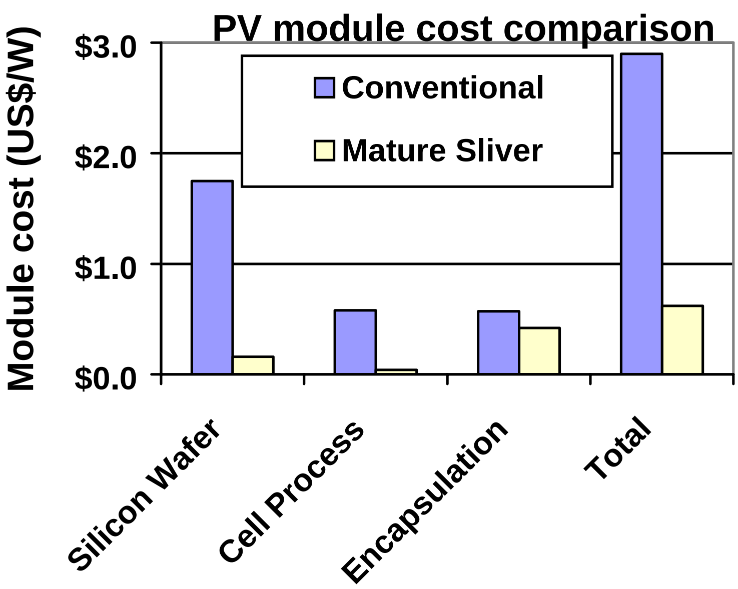
Mature Sliver solar cell technology

Sliver technology has the potential, over the next few years, to reach very low costs per square metre for the crystalline silicon energy-converting material. This will happen as the technology matures. Costs may become so low that the cost of encapsulation, which is much the same for any PV technology, dominates the finished module price. Sliver technology has a decisive advantage over competing low cost technologies because it is likely to be 50-100% more efficient in commercial production than alternatives.

There are three distinct phases in PV module manufacturing: (i) the production of silicon wafers (ii) the processing of the wafers to form solar cells and (iii) the electrical interconnection and packaging of the solar cells to form PV modules. The ratio of costs for each of the above manufacturing phases using conventional solar cell technology is roughly 50%, 25% and 25% respectively. Essentially a mature Sliver technology reduces the 50% cost of the silicon wafers and the 25% cost of the wafer processing to very small values. This leaves only the 25% cost of interconnection and packaging, which is roughly comparable to conventional solar cell technology cost.

In the long term, as cost structures for various technologies converge to the packaging cost, PV choices will ultimately be made on the basis of efficiency alone. Efficiency MUST be high for a PV technology to be competitive in the future. Sliver technology already has demonstrated a clear lead in the efficiency stakes, holding the world record for thin film efficiency. The efficiency of mature Sliver cells in commercial production is likely to be around 20%.

The chart shows our estimates of the cost of mature Sliver technology in the medium term. Heroic assumptions are not required to reach low electricity generation costs. There is no fundamentally new technology required for mature Sliver technology. What is required is careful silicon processing, micromachining and packaging engineering to transfer laboratory-based mature Sliver technology into methods and processes for the commercial manufacture of Sliver cell PV modules. The high efficiency and low cost expected of mature Sliver solar cell technology means that Sliver technology has an excellent chance of dominating the worldwide PV industry.



Applications for Sliver technology span the PV industry, as shown in the Table below.

Application	**Salient features of Sliver technology**
Power modules	Low cost, efficient
Architectural applications	Bifacial, low-cost flexible, efficient, shadow-tolerant, semi-transparent
Small power supplies (eg toys, phones)	Flexible, efficient, high voltage from small area module
Parabolic trough concentrators	Low cost, efficient, shadow-tolerant
Line-focus microconcentrators	Bifacial, low cost, efficient, shadow-tolerant, suitable cell shape
Transportable panels	Flexible, efficient, light weight, shadow-tolerant
Aerospace	Bifacial, lightweight, radiation tolerant, shadow-tolerant

Applications for Sliver cells span the PV industry

It appears that energy costs in the range of 10 c/kWh will be possible with Sliver technology. This would put solar electricity technology in the same price range as wind energy and projections for "zero emission" coal electricity.

Facilities available to the Centre of Excellence for Solar Energy Systems

The Centre of Excellence for Solar Energy Systems has full access to the resources of the Centre for Sustainable Energy Systems within the Department of Engineering, as well as facilities elsewhere in the University. The resources include:

E125 Gingera Laboratory: clean room used for production of high efficiency cells. 3 fume cupboards, 6 furnaces, photolithographic facilities (resist spinner, HMDS & baking ovens, 2 mask aligners, laminar flow HEPA units).

E126 Gudgenby Laboratory: clean room for metal deposition under high vacuum conditions. Two cryopumped Varian deposition systems.

E127 Ginini Laboratory: used for device characterisation activities. IV curves, Suns-Voc.

Building housing the Centre of Excellence in the Department of Engineering

- E124 Bimberi Laboratory: clean room device fabrication. 3 furnaces, 2 fume cupboards, spin rinsers, silicon etching station
- E123 Tidbinbilla Laboratory: general purpose lab. 2 fume cupboards, Ag plating, APCVD deposition system

E122 Piccadilly Laboratory: clean room for device processing. 2 fume cupboards, silicon etching, laser machining workstation, furnaces, LPCVD deposition system, microscopes, rapid thermal annealing furnace

Bimberi Laboratory

Tidbinbilla Laboratory

E131: Franklin Laboratory – downstream processing and module/receiver assembly: 2 dicing saws, soldering jigs, IV characterisation workstation, screen printer, workbenches, glass cutting table, vacuum chambers, accelerated life testing.

E114: Mechanical Workshop: Full workshop facilities with metal fabrication facilities shared with Department of Engineering

E138: Characterisation Laboratory. Several minority carrier lifetime systems

E129: Electronics Workshop. Used for fabrication of electronic components and as a maintenance resource for all other equipment

E128: Maintenance Office. Used for workbench maintenance of equipment

Faculties Teaching Centre at building 42 (separate from PV Laboratories). Rooftop used for installation of prototype and demonstration systems – clear sky access from large flat roof area. $16m^2$ of parabolic troughs delivering solar intensities of 30-40 kW/m^2 for testing and prototyping.

Bruce Hall: $300m^2$ of parabolic troughs.

Other facilities at ANU: Access to extensive facilities in other Departments, including good microscopes, PECVD, RIE, lasers, ion implanters, MOCVD and an extensive array of characterisation facilities.

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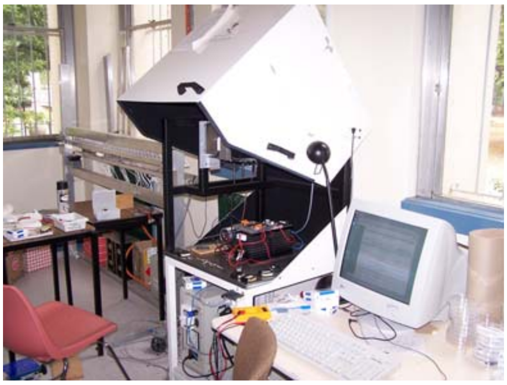

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Advisory Board of the ARC Centre of Excellence for Solar Energy Systems

Mr Drew Clarke

Drew Clarke commenced as Head of the Energy and Environment Division in the Australian Government Department of Industry, Tourism and Resources in April 2003. His previous position was Executive General Manager of AusIndustry, the Department's business assistance agency. Drew has worked in Australian Government science and business agencies for 25 years, including national and international representative roles. His professional background is in the spatial sciences.

The Energy and Environment Division comprises four Branches:

- Energy Futures: focussing on economic and policy research, energy data and forecasts, technology RD&D, fuel mix, and energy efficiency.
- National Energy Market: focussing on the policy, development and regulation of the wholesale, network and retail elements of the national electricity and gas market.
- International: focussing on Australia's interest in the International Energy Agency, APEC Energy Working Group, bilateral energy cooperation arrangements, energy security policy and energy security risk assessments.
- Environment: focussing on greenhouse policy, sustainable development, and development of the environment and renewable energy industries.

The Division provides the Secretariat for the Australian Ministerial Council on Energy, comprising Energy Ministers from the Commonwealth, State and Territory governments.

Professor Lawrence Cram

Professor Lawrence Cram is Deputy Vice-Chancellor (Research) at the Australian National University. His career spans more than 30 years of research in engineering, mathematics, astronomy, physics and computing. He has a track record of involvement in successful commercialization of research, through experience at CSIRO and the University of Sydney as well as the ANU. Professor Cram also has extensive experience in research management and public sector research funding, having worked for three years as Executive Director in the Australian Research Council. He is currently a non-executive Director on four companies involved in the commercialization of research.

He is a Fellow of the Australian Institute of Physics, and the Royal Astronomical Society, as well as a member of the American Astronomical Society, the International Astronomical Union and the Astronomical Society of Australia.

Mr Merv Johnston

Merv Johnston (**B.Eng (Syd), FIEAust)** has more than thirty years experience in industry, including, multinational private sector organisations; management consulting; as founder and principal shareholder of a small computer sales and service company; and in the public sector. He is currently Managing Director of CVC REEF Limited, which specialises in providing Venture Capital to businesses which are commercialising innovative Renewable Energy technologies, Managing Director of Magma Pty Limited, a management consultancy, specialising in the innovation and commercialisation processes, and early stage businesses, and a Director of Windcorp Australia Limited.

Ms Susan Neill

Susan Neill has a tertiary background in mathematics and modern languages.

Susan commenced working in the renewable energy industry at a wholesale level in 1986, obtained PV System Design Accreditation and completed postgraduate Applied PV certificate from UNSW. She became involved in the development of the Solar Energy Industry Association of Australia (SEIAA) in 1990 through to its present status as part of the Business Council for Sustainable Energy, fulfilling the role as national president of SEIAA through the mid 1990s. Susan is currently a member of the PV Directorate for BCSE.

Susan is currently Managing Director of Quirk's Victory Light Co. Pty. Ltd. - Energy Today. This company specialises in stand-alone and grid-connected wind and solar systems for which Quirk's is a major wholesaler of system components. Susan's company also works on the development and manufacture of power efficient low voltage refrigeration.

Susan has broad experience in industry development issues and a wide network of contacts at industry level.

Mr Peter Ottesen

Peter Ottesen is Executive Director of the Office of Sustainability within the Chief Minister's Department of the Australian Capital Territory government. The Office is responsible for driving implementation of the Government's sustainability agenda and has whole-of-government policy responsibility for water, energy and greenhouse.

He has more than 20 years senior level policy and management experience in the public and private sectors within the environment, protected areas, commercial fisheries, tourism, agricultural, transport, waste management, sport and event management industries, within Australia and Canada.

A personal career highlight was his five years with the Sydney Organising Committee for the Olympic Games (SOCOG) where he established and led its Environment Program. In 2001 the United Nations Environment Program elected SOCOG to its Global 500 Roll of Honour. He was subsequently an adviser to the successful Beijing 2008 Olympic Games Bid team on environmental matters and the London 2012 Bid.

He has been an adviser to a senior cabinet minister in the Australian Government and held positions in the Australian Government's Department of Primary Industry and the Great Barrier Reef Marine Park Authority, and Environment Canada.

Peter is Chair of the Banksia Environmental Foundation, a leading Australian NGO that identifies and rewards environmental excellence, an Executive Member of the ACT Division of the Environment Institute of Australia and New Zealand and an "Honorary Ambassador" to the ACT for his contribution to the Canberra-Beijing sister-city relationship.

Peter has a BSc, with Honours (Marine Ecology) from the James Cook University and a MSc (Natural Resource Management) from the University of Western Australia.

Professor John Richards

Professor John Richards is the director of the ANU Institute for Information Sciences and Engineering.

He is also Master of University House, and Graduate House

Professor Richards was formerly Deputy Vice-Chancellor and Vice-President of the Australian National University from October 1998 to October 2003.

From 1987 to 1998 he was at the University College, Australian Defence Force Academy, where he served as Head of School of Electrical Engineering, Deputy Rector and Rector.

He graduated from the University of New South Wales with the degrees of Bachelor of Engineering (Hons1) and Doctor of Philosophy, both in Electrical Engineering, in 1968 and 1972 respectively. He is a Fellow of the Australian Academy of Technological Sciences and Engineering, and a Fellow of the Institute of Electrical and Electronics Engineers, NY.

Mr Denis Smedley

Denis Smedley, MIE Aust

Manager Renewable Energy Technologies

Department of Environment and Heritage

Australian Greenhouse Office

Denis Smedley joined the Australian Greenhouse Office in 2001 and is responsible for the Australian Government's renewable energy commercialisation, deployment and industry development programs that are administered through the Office. Prior to this, Denis worked for the Western Australian Government's Office of Energy, looking after energy efficiency and renewable energy programs for the State. This followed a 24 year engineering career in the Royal Australian Air Force. Denis is an electrical engineer.

Hugh Saddler

Hugh Saddler BSc, PhD, Managing Director, Energy Strategies Pty Ltd

Dr. Saddler is the Managing Director of Energy Strategies, a consultancy company he established in 1982, specialising in the fields of energy, environment and technology economics and policy. He has a training in science, with degrees from Adelaide and Cambridge Universities, but since 1973, which was the year of the first oil shock, has been fully engaged in the analysis of major national energy policy issues in the UK and Australia, as an academic, government employee and consultant. Over the past decade or so the main focus of his work has been on issues relating to energy and greenhouse policy. While most of his professional output takes the form of consultancy reports, he is the author of a book on Australian energy policy and of over 70 scientific papers, monographs and articles on energy technology and environmental policy. He is currently a member of an ACT government advisory committee on environmental pollution and from its establishment in 2002 until April 2005 was a member of the ACT Sustainability Expert Reference Group. He is also a former board member of ACT Electricity and Water. He is a Fellow of the Australian Institute of Company Directors and of the Australian Institute of Energy.