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Mass Utilization of Solar Thermal Energy

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Summary

Recent developments in the science, technology and application of solar thermal energy have underlined the advantage of this form of energy for mass utilization, providing the potential for eventually supplying most, if not all, of our energy from the sun. Immediate viable application for electricity and process heat provision could, within a relatively few years, be expanded to the supply of solar-modified fossil and biomass fuels, non-hydrocarbon fuels, chemicals and other materials, to give an increasingly benign and sustainable energy supply over the next decades.

The key to much of the developments discussed and the potential for further advances into new applications, has been the advent of large cost-effective paraboloidal dish collectors for producing high temperature solar heat and concentrated solar flux, combined with the use of commercially available heat transport network technology and heat-to-work conversion machinery (turbo generators) and combined cycle plant. These techniques can be utilized now in small to very large systems and there already exists industry which can manufacture and install such systems.

Research and development should be biassed in favour of those areas which can lead to rapid mass utilization and which can achieve substantial performance and/or economic improvements in technology; those technologies which can be applied cost-effectively on a large scale the earliest, should receive highest priority and greatest funding, but always maintaining funds for longer-term projects which hold obvious promise, including those still at a fundamental stage of research. The following order of priority is accordingly suggested:

Solar thermal electricity and heat production (immediate application and continuing R&D).

Thermochemical/photonchemical-based systems, including solar gasification (commercial within this decade).

Solar-driven catalytic conversion of toxic materials (commercial within this decade).

Utilization of photochemistry, photosynthesis and photoelectrochemistry (longer term).

Thermochemical systems permit the installation of very large solar plant, collecting energy from large areas and enabling effective storage and transport of solar energy. Solar thermal energy for solar gasifying biomass materials (bagasse, wood chips, straw from rice and wheat, rice hulls and many others) and producing methanol (by further solar-driven processing) will eliminate all nett carbon emissions from transport fuels and most of such emissions resulting from chemical processes employing syngas or methanol as a feedstock, as well as from normal syngas applications including town gas, process heat and powering gas turbines for electricity generation.

In the case of fossil fuels, solar gasification provides energy for the process without generating greenhouse gases; increases the energy content of the original fuel; provides fuels in gaseous or liquid form allowing ready storage or transport (in the process, storing and transporting solar energy), and reduces the potential polluting effects after modification has been achieved. For example, solar gasification doubles the effective energy content of brown coal and thus gives

a 50% reduction in CO_2. Brown coal normally produces some 67% more CO_2 emissions per tonne of carbon than natural gas. If the effective energy content of coal were doubled, then solar gasified brown coal will generate only 83% of the CO_2 from natural gas.

We are now in the position whereby major solar energy additions can be made to our energy systems, even in their currently developed forms. Many additional advances are, however, apparent and much R&D in the 1990s should be directed to make solar thermal electricity generating systems the clear contender for any new increase in generating capacity: this goal is attainable both technologically and economically. Indeed, our view is that the stage has now been reached whereby it is no longer necessary or appropriate to build any further coal-fired power stations, but to employ solar thermal power — which can be implemented rapidly, cost effectively, and with excellent energy profit ratio (payback periods of approximately 9 months). While natural gas-driven electricity has advantages over coal, this can be only a stopgap measure, allowing time to develop more-benign systems.

Policy makers usually propose solar energy systems but assume that it will take a very long time for installation on a large scale. But rapid growth has been demonstrated when there are strong economic incentives, environmental legislation mandating change, or concerted public or private effort, by employing wellknown industrial mass production, construction and installation techniques. In the case of the ANU/ANUTECH solar technology, only a small change is needed to be competitive with baseload power.

Finally and most significantly, a major impetus for the implementation of substantial solar thermal power concerns economic factors. A rapidly growing realisation of the unacceptability of further environmental damage caused by continued fossil and nuclear fuel use, has led to detailed studies of the costs of preventing such damage. While figures are still only approximate, the general conclusions are that some 25% to 50% or more needs to be added to the average Australian electricity tariff (now approximately 8 to 9¢/kWh) to include these externalities. Incorporating total costs to society similar to those legally established in many industrialized countries dramatically changes relative economies of solar thermal systems, making them cost competitive with fossil fuels now.

This report considers the many aspects of solar thermal energy supply already available, or potentially available.

1. Introduction

Solar energy provides the only foreseeable means for achieving a benign sustainable energy future[1]. Used directly or in derived form (wind, wave, precipitation and biomass), this source is characterised by great richness and diversity of utilizable effects and processes, allowing widespread application in one form or another, thereby permitting most areas to establish at least some degree of energy independence.

The greater part of our energy at present is supplied from chemical processes based on coal, oil and natural gas, whose polluting nature is becoming increasingly recognized, as is the urgent need to redress these problems. Concentrated solar energy can, as a result of research and development in recent years, now provide a viable replacement source for both heat and electricity, employing existing thermal processes, materials and production technologies. With a relatively modest R&D effort and without requiring major *breakthroughs*, concentrated solar flux can also take advantage of known means for driving the chemical processes which allow existing fossil fuels to be used with substantially reduced polluting effects, at the same time permitting the solar energy to be stored and transported. Solar-driven gasification can, in this way, be applied (for example) to coal and natural gas, producing synthetic gas (CO, H_2) which can be used as a town gas, for process heat and electricity generation, and as the starting point for major chemical industries as well as the production, via a further solar-driven reaction, of methanol — an excellent motor fuel and chemical feedstock. The same solar gasification processes, when employing biomass, result in particularly low polluting effects due to the recycling of the product carbon dioxide as a result of plant regrowth.

Accordingly, the production of solar modified fossil and biomass fuels could, over the next 30 to 40 years or so, bridge the gap between current energy supply of all forms and the utilization of mainly solar sources. This would allow a gradual transition which employs current infrastructures without causing dislocation of the energy industry which could thereby adjust gradually to lesser and lesser polluting sources; at the same time the resulting breathing space would permit the development and installation of increasingly effective purely solar supply to the massive degree required for changeover of systems. [Even for replacing only present electricity generation plant by solar-driven systems — or for that matter by any other kind of electricity generating system — would need, worldwide, the commissioning of some 150 units each of 1000 MWe, each year for the next 40 years or so; and electricity accounts for less than 40% of total primary energy used for all purposes and some 20% of energy in the forms actually used.]

There are now well appreciated means for employing solar thermal/thermochemical energy for a vast range of applications apart from those already mentioned. These include the increasingly important needs of land reclamation, water desalination, water detoxification and toxic waste conversion. In one way or another, solar thermal and concentrated photon energy (requiring the same concentrating collectors as thermal systems) can, with further research and development and the use of thermochemical and photonchemical processes, provide fuels, chemicals, energy storage and most if not all of our energy needs, as well as energy in the wellknown forms of process heat and electricity, already available.

Misconceptions abound in relation to the development and use of solar energy. For example, Australian perceptions about total solar energy use per annum as a percentage of primary energy for all purposes, downplay the over 30% actually used [see Hagen and Kaneff (1991), Section 3]. A much more common misconception relates to the total land area required for realization of various energy sources; solar energy is often thought to require much more land area than fossil and nuclear energy. Yet, when all aspects are

[1] Unless nuclear energy can eventually be developed to be far less problematic and much less expensive than is the case at present, solar energy in its many forms is the only realistic alternative.

considered, it emerges that **by and large all energy sources require much the same total land area for their implementation**, as shown by the Meridian Corporation [1989] Study, summarized in Table I.

2. Advantages of Solar Thermal Systems

Even though we are still in the early stages of developing solar energy utilization, benefits can start flowing immediately if attention is paid to those technologies — especially solar thermal systems for electric power generation in sizes from tens of kilowatts to hundreds of megawatts and larger — which are now ready or almost ready for economic application. A further reason for favouring concentrating solar thermal systems stems from their applicability, as already mentioned, to the production of fuels and chemicals via thermochemical and photonchemical processes and their realization of mass energy storage systems. It is to be noted that other valuable solar-based energy sources, for example hydro, wind and photovoltaics (and the nuclear energies), produce electricity only and have economic difficulty in providing the non-electric energy needs (which require secondary conversions).

Table II summarizes some features of solar thermal systems.

To implement more-benign sustainable energy supply clearly presents massive problems, but the worthiness and significance of the goals demand urgent attention and increasing support from all sectors — government, research communities, industry, commerce and the public at large — in keeping with the benefits which will flow to all.

3. Comparison of Solar Thermal Technologies

In the past 20 to 30 years, three technologies have gained most credence for the supply of concentrated solar heat: parabolic trough, central receiver and paraboloidal dish-based systems, the most development having occurred with troughs. Figure 1(a) illustrates the wellknown basic configurations of each technology; Figure 1(b) portrays common functional aspects.

It is therefore unsurprising that LUZ International Ltd chose trough technology to establish the first commercial systems even though this is potentially the least promising solar thermal technology [Kearney 1986; Jaffe et al 1987; LUZ International 1990; Kearney et al 1991]. Over the period 1984 to 1991, nine power systems with a total output of 354 MWe have been connected to and are now operating on the California grid. As illustrated in Figure 2, LUZ generation costs [LUZ 1990] have dropped from US 24¢/kWh to about 8¢/kWh within 5 years, due to continual improvement on excellent engineering concepts, including reliance on the economy of size.

These costs include up to 25% use of natural gas as backup to provide reliable peaking power and are cost effective with standard peaking electricity contracts in California. LUZ have projected 1994 technology to use direct boiling receivers and advanced combined cycle turbines. Because of absence of published data, the solar-only costs for LUZ systems is difficult to ascertain. Kaneff [1991a] has assessed, on the basis of 25% gas utilization, a solar-only generation cost of about US 12¢/kWh for the best 1991 technology; and an expected US 7.5¢/kWh for the next generation units in approximately 1994. These figures can serve as benchmarks when considering other technologies.

From time to time, studies have been carried out comparing trough, central receiver and dish-based power systems, in each case showing that all things considered, trough systems are potentially the least, while dish systems are the most cost effective, with

TABLE I — LAND UTILIZATION FOR POWER GENERATING SYSTEMS

[From Meridian Corporation 1989]

Type of Plant♯	Conventional Coal	AFBC	IGCC	Nuclear*	Photo Voltaics	Solar Thermal Power$^{\phi}$
Land Area Required Hectares/GWh^{+}						
Extraction and Processing of Fuel	.033	.033	.026	.006	NA	NA
Operation and Continuation of Plant	.003	.003	.003	.005	.032	.018
Total ha/GWh	.036	.036	.029	.011	.032	.018

+ Basis for comparison is the land area in hectares required per GWh of electricity generated over the total plant lifetime in each case. [GWh = GigaWatt hour]

ϕ Added for comparison by S. Kaneff. Based on insolation of 2500 kWh/m^2/year; 85% overall energy intercepted; 36% overall generation efficiency; collector spacing factor of 0.25, plant availability 95% [Kaneff 1989]. (1 m^2 land provides $2500 \times 0.85 \times 0.36 \times 0.25 \times 0.95 \times 30$ year plant life = 5450 kWhe over 30 years = 0.00545 GWhe ie a land area of $\frac{1}{.00545}$m^2/GWhe = 0.018 ha/GWhe)

* Not including land use for enrichment facility, waste reprocessing, permanent waste storage and plant decommissioning; nor land taken out of service due to contamination from nuclear accidents. These factors may well increase nuclear land requirements well above all others in the table.

♯ Plant Compared

- A 500 MWe Conventional Coal Plant with Scrubber — Conventional.
- A 500 MWe Atmospheric Fluidised Bed Combustion Plant — AFBC.
- A 1000 MWe Integrated Gasification Combined Cycle Plant — IGCC.
- A 1000 MWe Boiling Water Nuclear Reactor — Nuclear.
- A 100 MWe Central Station Photovoltaic Plant — PV.
- A 100 MWe Solar Thermal Electric Plant — STP.

Table II — Features of Solar Thermal Energy Systems

- Utilize local solar resources.
- Need produce no permanent deleterious effect on land employed.
- In the case of dish systems, 75% of the land occupied can still be farmed or grazed (if suitable).
- Little pollution or waste management problems occur.
- Systems can be provided in small, large or massive scale.
- Can utilize much existing technology within these systems, as well as existing factory production for their implementation. For example, electricity generating systems can use existing turbine generator sets and heat transport technology, while collectors depend on steel, concrete and glass, or plastic-forming processes.
- Many storage means are becoming available.
- Fossil fuel backup and solar/fossil combined systems are practicable.
- Energy payback time is short, allowing rapid deployment and fast *breeding* compared to other energy systems.
- In relation to electricity generation, multi-megawatt systems are already employed on the California grid and have demonstrated practicability.
- Systems can be produced in modular form and assembled quickly on site.
- Cost competitiveness compared with fossil-fuelled systems already exists in some situations; costs are well below those for photovoltaic and nuclear energy.
- Solar thermal systems can potentially provide many forms of energy — heat, electricity, solar fuels, solar-modified fuels, chemicals, and most other energy forms required.
- Solar-modified fossil fuels and solar fuels can form a major industry, with great export potential.
- System costs are falling rapidly; many further innovations are becoming available to reduce costs much further.
- Major implementations of new technologies are occuring. The potential, both technological and economic, exists for rapid and massive growth in this decade.

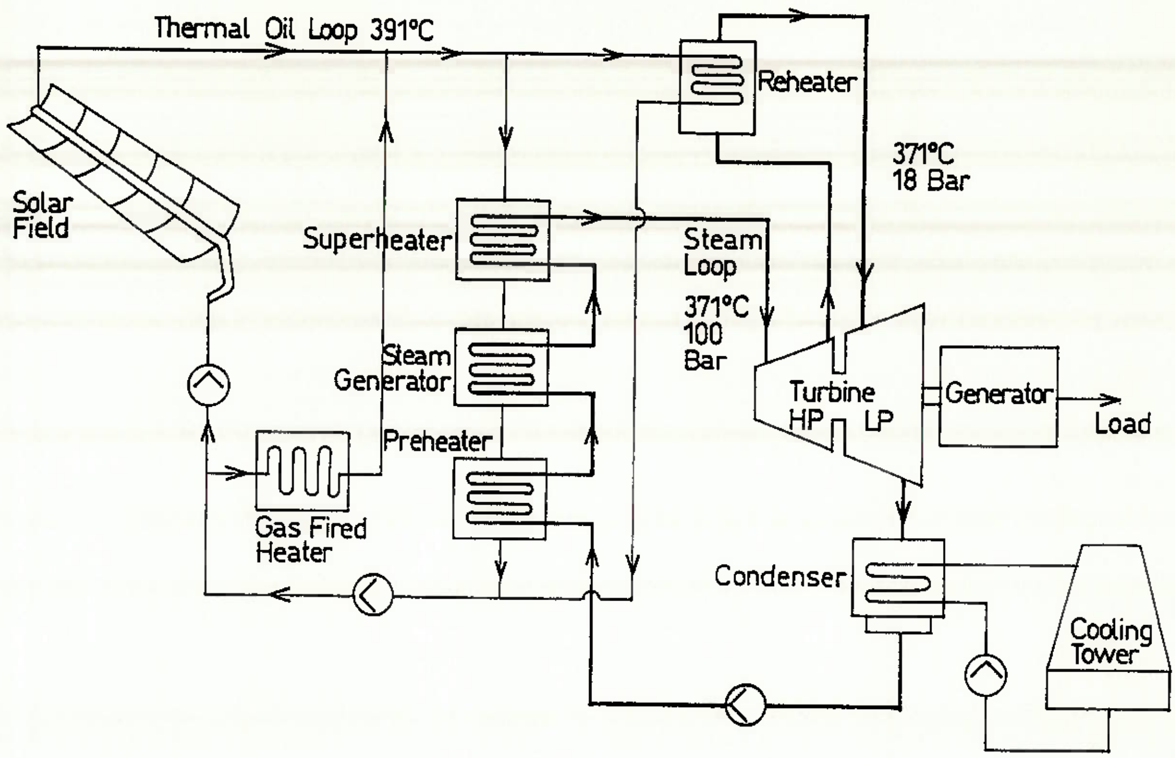


Figure 1(a)(i) — Typical Parabolic Trough System (LUZ 80 MWe Plant).

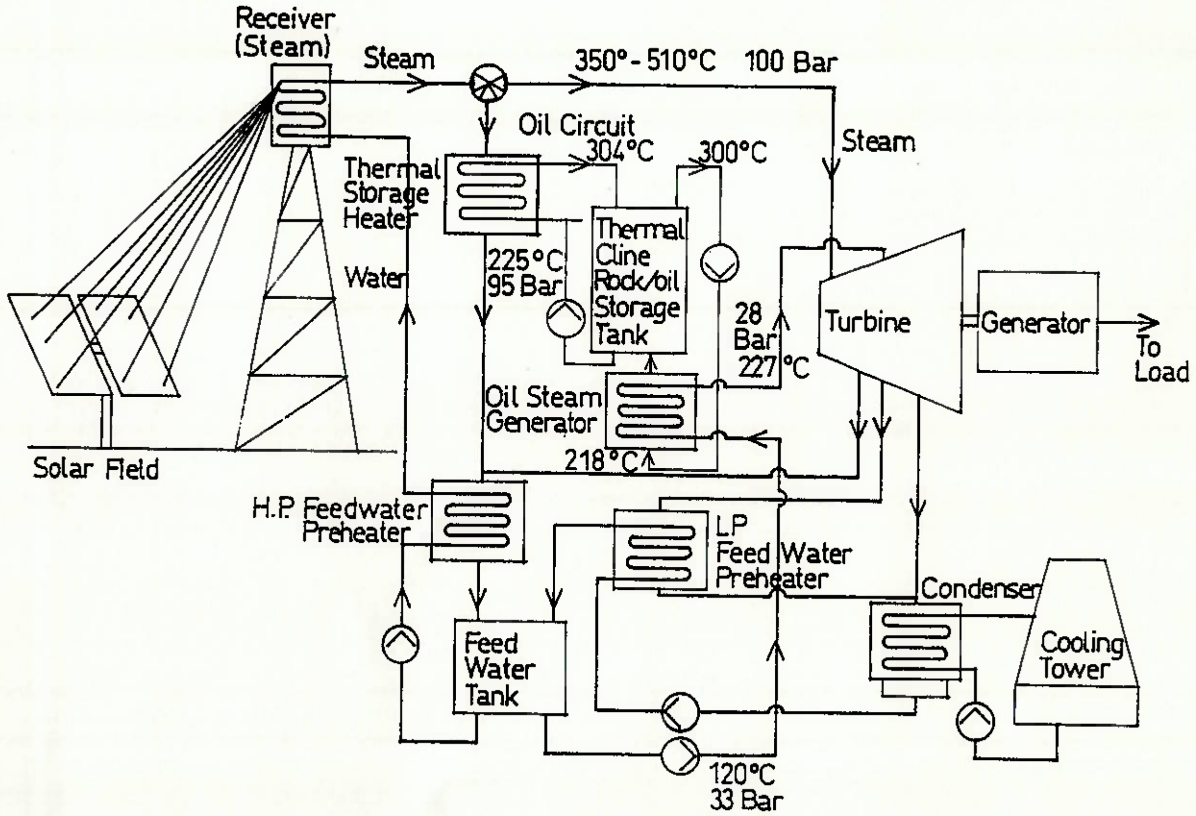


Figure 1(a)(ii) — Typical Central Receiver System (Barstow 10 MWe Plant).

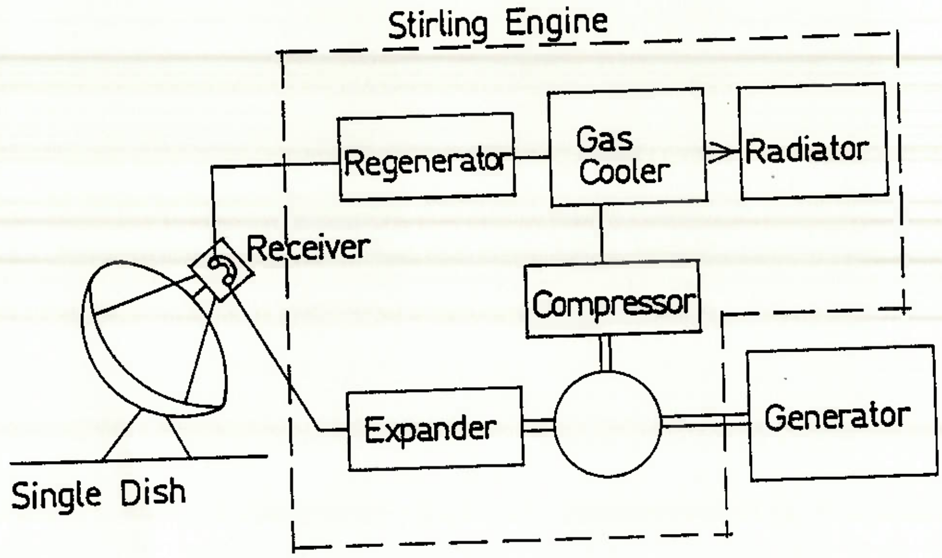


Figure 1(a)(iii) —Typical Dish/Stirling Engine System. (5-25kWe)

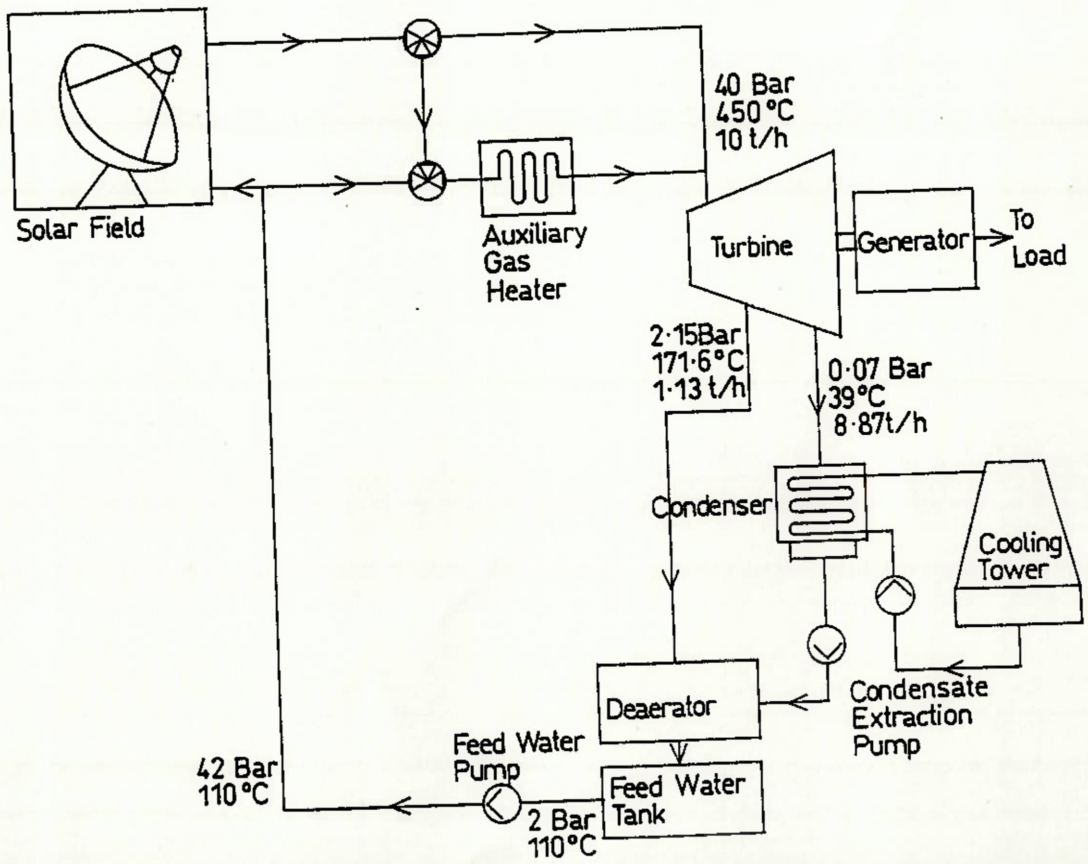


Figure 1(a)(iv) —Typical Dish/Central Plant System (Tennant Creek 2 MWe Plant).

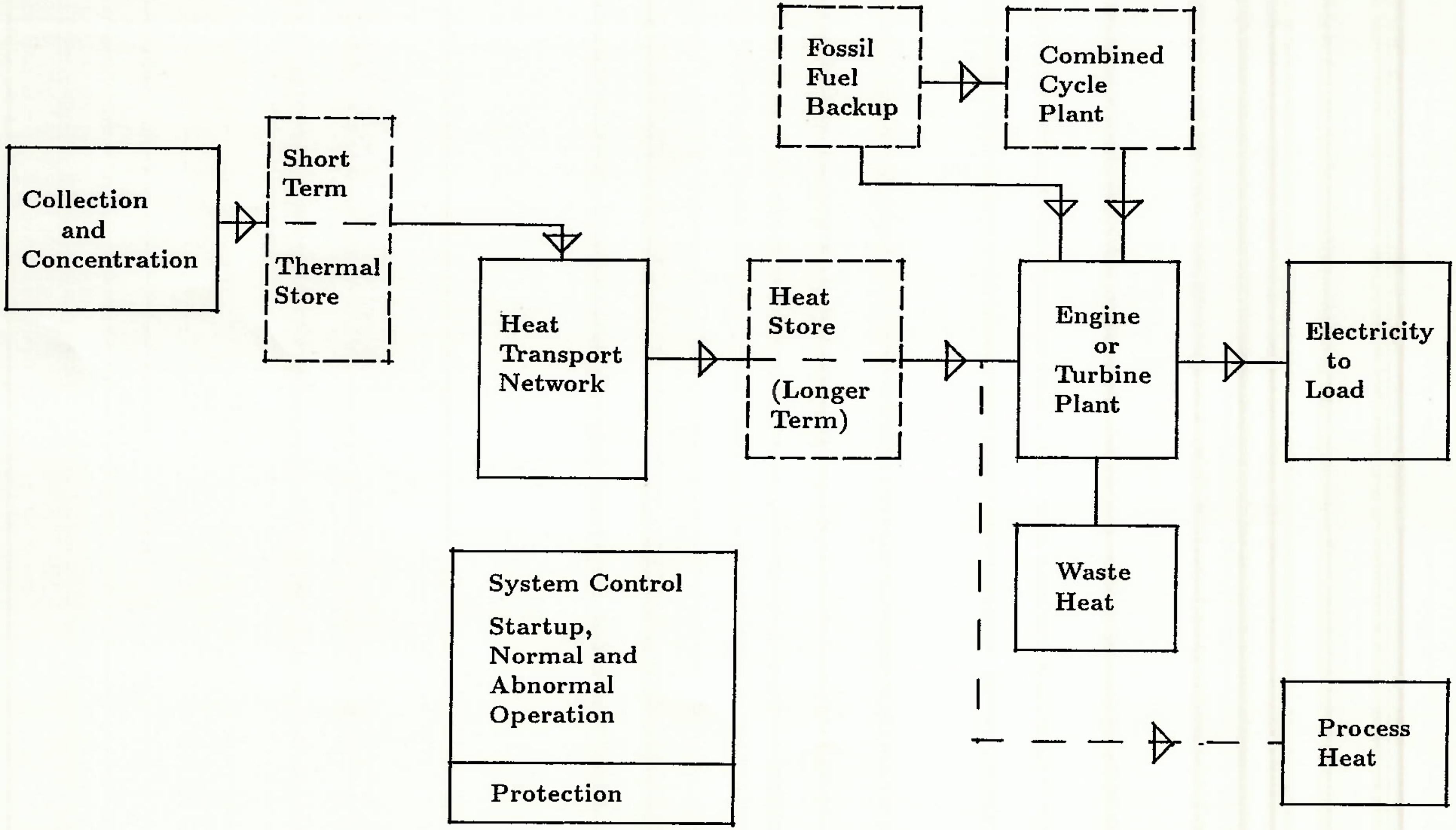


Figure 1(b) — Common Functional Aspects of Solar Thermal Systems.

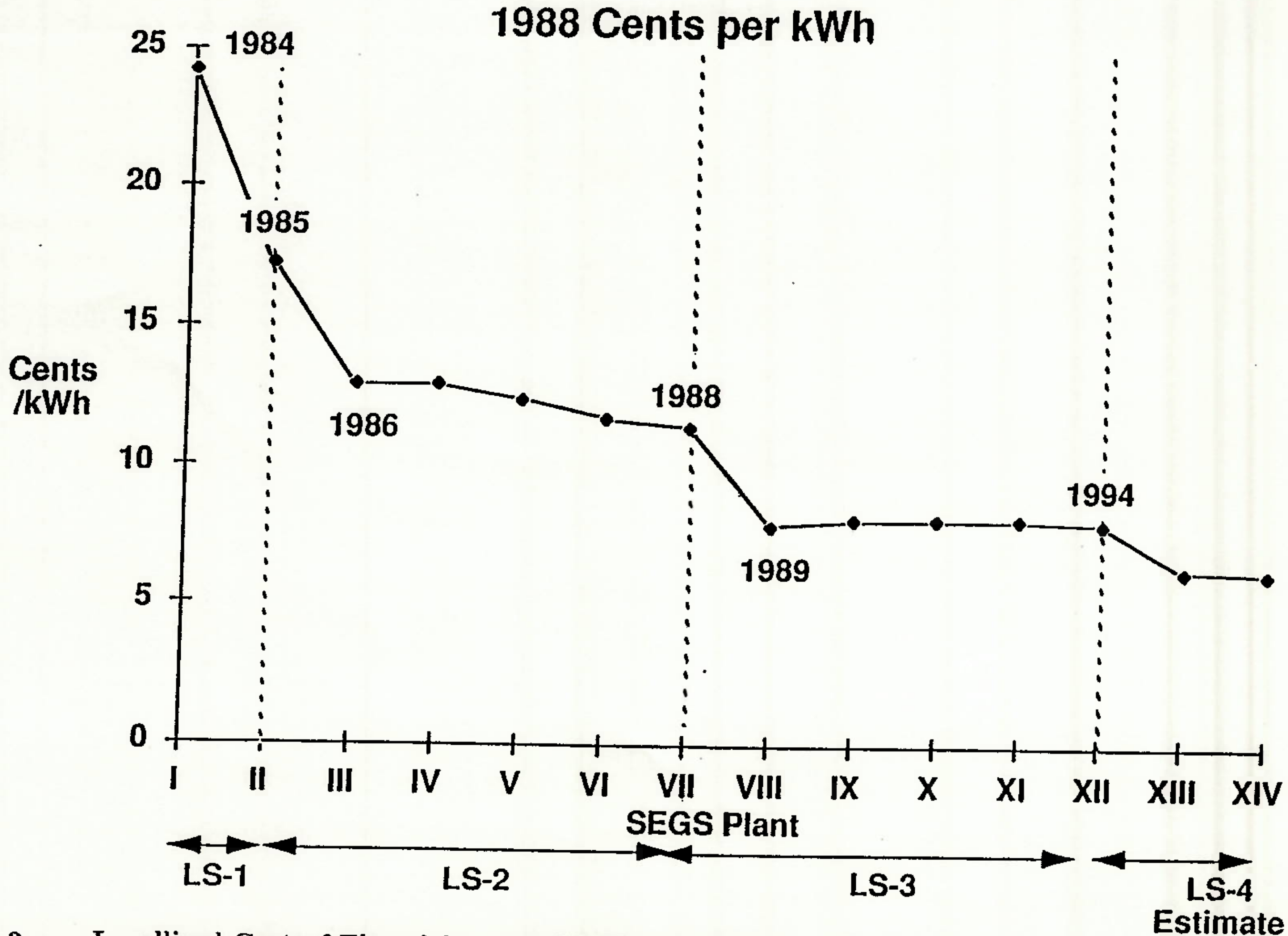


Figure 2 — Levellised Cost of Electricity — LUZ Plants.

central receivers in between. For example, this relativity is indicated in Figure 3 from Williams et al [1987] for electricity generating plant in the range 0 to 100 MWe.

Figure 3 indicates that in all aspects, except O&M, dish systems are superior. But Figure 3(c) indicates higher O&M costs for dish systems only because in this USA study, dishes are assumed to carry focal region engines, a feature which carries with it increased O&M costs. Were dish systems (except for very small units) to feed central plant — as we have always advocated — the dish curve in Figure 3(c) would be (as indicated) very similar to the central receiver and trough characteristics, both of which employ central plant. A further consequence of the focal region engines in the case of dishes is to cause the dish curve to level off in all cases for systems of increasing size, instead of rising in Figure 3(a), and falling in Figures 3(b), (c) and (d) (as shown dotted), which they would do as a result of the increasing efficiency with size of steam turbines, to an extent not overcome by the greater accompanying heat transport network losses.

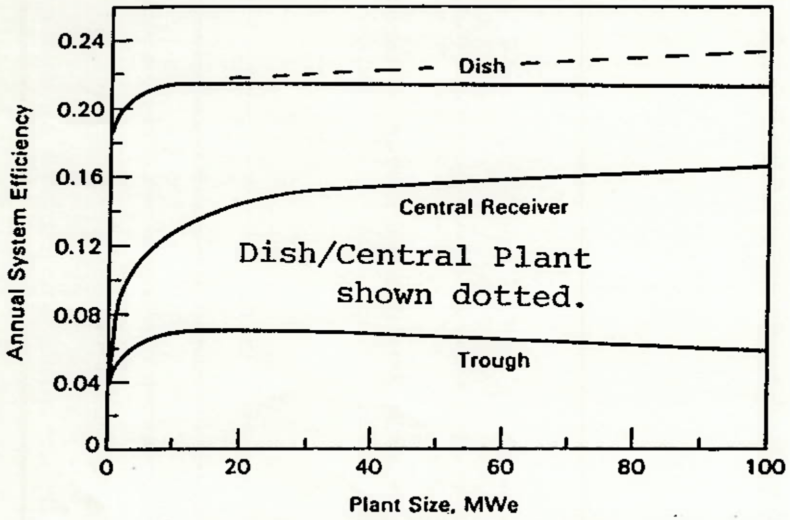
The relativity indicated in Williams et al [1987], which applies certain basic principles and the technology as appreciated in 1987, does not preclude a given technology surpassing another for a period of time due to new developments; but expectedly all technologies will generally improve together and considerably, in time, probably maintaining their basic relativity overall and each having preferred applications areas.

The parabolic trough characteristics of Figure 3 represent the LUZ systems of 1987 (for solar-only generation), but later LUZ developments surpass the Williams et al figures. The concept of employing troughs with relatively low concentration ratio (<10), with line focus oriented on the polar axis, while tracking from east to west and employing newly developed selective surfaces of particularly high absorptivity and low emissivity as proposed by Mills [Monger and Mills 1991; Mills 1992], promises also to produce more cost effective parabolic trough systems than indicated in Figure 3, in this case employing small trough units oriented along the polar axis and tracking from east to west each day. That the approach projected by Mills can result in very economical systems, is still to be demonstrated.

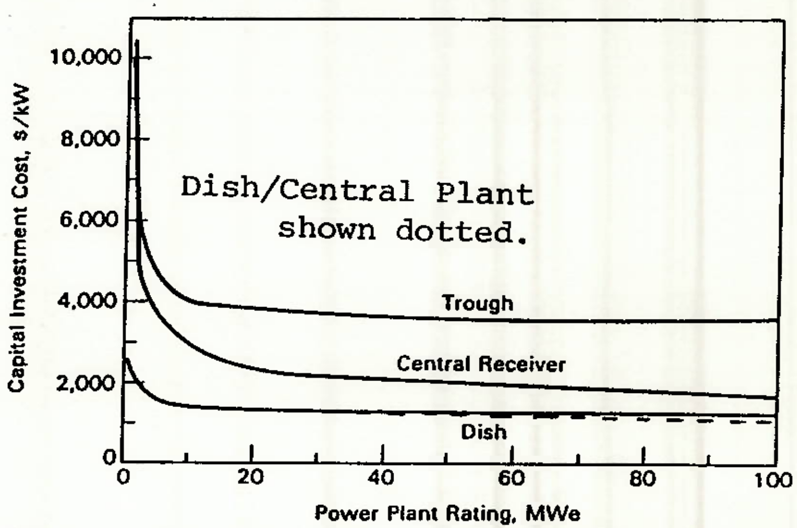
Fundamental limitations of troughs include the losses from line foci, high fluid pumping effort and, unless 2-axis tracking is employed, reduced energy collection; central receivers make less effective use of heliostats due to variable aperture throughout the day; while dishes, by facing the sun squarely at all times, gather the most energy per collector aperture, as well as possessing very high potential conversion efficiency — they also can produce the highest absorber temperatures. Typically, present realizable useful temperatures are approximately 400°C to 500°C for troughs; over 1000°C for central receivers, and over 2000°C for dishes, effectively delineating their fields of application — Carnot efficiency considerations favour central receivers and dishes and most thermochemical reactions require temperatures above 400°C, in most cases precluding the use of troughs, which nevertheless have an important role to play in many applications, especially those involving individual enterprises particularly where rooftop collection is practicable. Further comments are appropriate.

3.1 Current Status of Solar Thermal Technologies

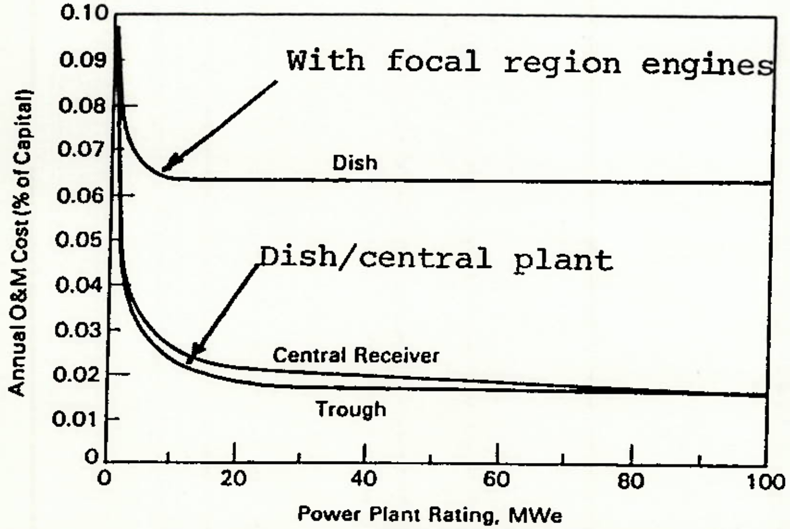
In terms of resources expended and time elapsed, most effort has so far been applied to the development of parabolic troughs; central receivers have also received substantial attention and resources, while dishes have received the least actual support and have been developing over a shorter period of time. Nevertheless, as a result of very recent advances in dish technology, especially in relation to size and economics, dishes are now the most cost-effective means for providing solar thermal concentrated energy, suitable for a wide range of immediate applications (providing electricity and heat) and have a great potential



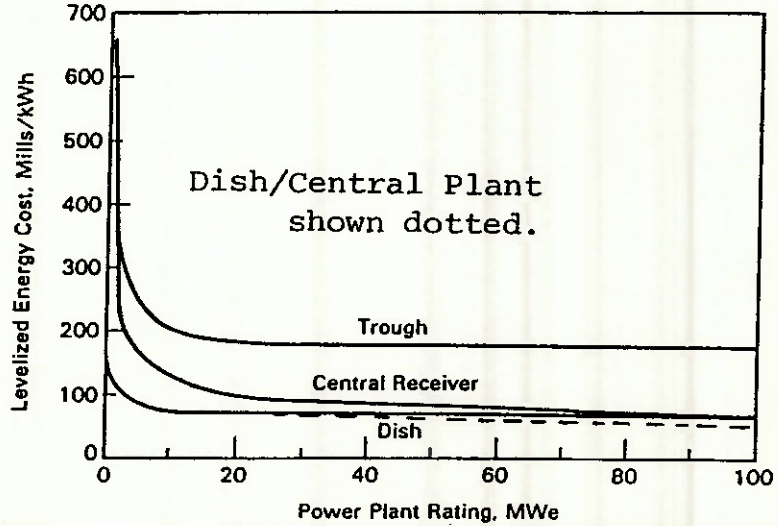
(a) — System Annual Efficiency (no storage systems).



(b) — Initial Capital Investment Costs (no storage systems).



(c) — Operation and Maintenance Costs as Percentage of Capital Costs (no storage system).



(d) — Levellised Energy Cost versus Plant Size (no storage system).

Figure 3 — Comparison of Solar Thermal Systems.

for expanded use — via solar-driven thermochemical and photon chemical reactions — in providing solar-modified fossil and biomass fuels (for example by solar gasification); solar fuels and chemicals, as well as allowing the mass storage of solar energy (and other forms of energy). The relativity, suggested in Figure 3 between the various solar thermal technologies, which favours dishes, can now be demonstrated by commercial reality, as important dish developments are proceeding.

Many of the most recent applications, developments, potential and forward planning concepts are reported in the Proceedings of the Sixth International Symposium on Solar Thermal Concentrating Technologies, held at Mojacar, Spain, 28 September to 2 October 1992 [sponsored by: Centro de Investigaciones Energeticas Medioambientales y Technológicas (CIEMAT); Plataforma Solar de Almeria; International Energy Agency; Commission of the European Communities, Ministry of Industry, Commerce and Tourism, City of Mojacar, Electricity Commission of Seville and others]. This symposium, together with much other recent evidence and thinking in solar thermal circles, confirmed the rapid progress achieved and the potential and scope for generally far more substantial developments overall in the science, technology and economics of solar thermal systems. More importantly, the commercialization of systems is either already at hand or is expected shortly, depending on the technology concerned. The following is our assessment of four developing technologies; based on current evidence, viewpoints and on our own experience:

Parabolic Trough Systems: [Illustrated in Figure 1(a)(i)] As already wellknown, LUZ have led in the development of troughs for power system installations, using natural gas backup. This technology has received much resource support which has brought it to commercial utilization on the Californian grid as a result of special incentives and approaches.

Further progress is possible but, due to the already developed nature of the technology, is much more difficult to achieve. To obviate high oil transport pumping requirements and other problems, LUZ had been considering direct steam generation. This has also been considered more recently by other groups in Europe and USA, but the problems involved are not unsubstantial and success may carry too high an economic penalty. As already mentioned above, better selective surfaces are being studied and could improve troughs further [Mills 1992], even in small sizes, combined with polar axis orientation to gather more annual energy. The expectation by LUZ and Mills is the achievement of lower generation costs in due course. [LUZ solar-only costs were targeted at about 7.5¢/kWh for 1994; Mills expects even lower costs.] These costs (yet to be demonstrated) are still above the already-realizable dish system generation costs using central plant [Kaneff 1991a, 1992].

Central Receiver Systems: [Portrayed in Figure 1(a)(ii)] Central receiver technology is being revived in USA as a result of funds becoming available to convert Solar 1 (Barstow) to a liquid metal heat absorption and transport systems, an experiment expected to become operational in 5 or so years (designated Solar 2). If successful, a 100 MWe central receiver would be planned for operation after 2000, with generation costs approximately 10¢/kWh or lower (down to 6¢/kWh eventually). The European Community is also continuing central receiver studies at the Plataforma Solar de Almeria (PSA) in Spain, focussing on air volumetric receivers with air heat transport to storage and central plant, following recent work on such systems at PSA. Similar generation costs to the Solar 2 and subsequent 100 MWe plant are projected. It is clear that, even with major effort (and Solar 2 alone is expected to cost approximately $US 45 million) progress in central receiver systems will be slow and is not expected to come to commercial fruition before 2000.

Dish/Stirling Systems: [eg Figure 1(a)(iii)] Much effort has been expended since the late 1970s, especially in USA, on the attractive concept of dishes powering very efficient Stirling engines placed in the focal region of the dish, thereby reducing heat transport losses and allowing the high temperatures required to efficiently reach the engine. Had this concept been easy to realise, the major effort already expended would have achieved success. The problems of producing robust, reliable, highly efficient and economical Sitrling engines, are daunting and have taken major resources from several organizations over 50 years and more. To lessen the task, relatively small engines (5 kW to 50 kW) have received most attention; more recently 5 kW to 25 kW. There is clearly a long way to go before technologically successful, commercially viable units will emerge, whether kinematic or free piston systems.

Although very long term projections of costs are not lacking, immediate true costs are not available, although experimental systems are now in evidence. The most successful of these is the Schlaich, Begermann and Partner (SBP) 7–9 kWe unit mounted on a stretched steel membrane collector [Schweitzer et al 1992, Schiel et al 1992] with polar axis tracking. Such systems are viewed as meeting a niche market — competing eventually with photovoltaic systems in relatively small sizes for remote areas.

This is the European and USA perspective, predicated on the relegation of solar electricity to relatively small sizes, a view generated earlier when solar electricity was perceived as involving an expensive technology. So long as such small systems figure prominently in plans and actions, the approach may be fulfilled and economical systems for larger sizes will not emerge because the philosophy does not support them. To produce such large systems by dish/Stirling units, will require massive numbers of small size units with their attendant disadvantages. Development of large units is not being pursued and, while-ever small systems remain non-perfected, are unlikely even to be attempted. Moreover, even if attempted, their economic viability is subject to considerable question as discussed in Section 4.1, 4.2, 4.3.

One further point needs to be made. Dish/Rankine Cycle units (which are now available to produce electricity via steam cycles — even in small sizes — with acceptable economics in many areas [Kaneff 1991a]) lend themself to the utilization of waste heat and to the utilization of backup fossil-fuel-generated steam for continuous operation, if required, whereas neither facility exists with Stirling engines and would need to be developed as a new venture.

Dish/Stirling units therefore remain to be proved commercially and cost effectiveness has yet to be revealed. They will most likely remain a technology viable in small size units — after suitable development — and do not seem potential candidates for producing substantial amounts of electricity before 2000.

Dish/Central Plant Systems: [Refer for example, Figure 1(a)(iv)] In a comparatively short space of time (only a decade or so), paraboloidal dish systems have revealed themselves as having major potential for providing, with good economics, most if not all of our energy requirements. By considering overall factors which promote cost-effectiveness in engineering: including the economy of size, the achievement of relatively small step advances based on use of as much existing technology and infrastructure as is relevant, and by employing materials whose industrial processing is already well advanced — for example steel, glass and concrete — paraboloidal dishes have been developed with increasingly attractive cost-effectiveness [Kaneff 1991a, 1992; Rogers et al 1988]. When these are matched to optimized heat transport networks (based on existing technology) [Carden and Bansal 1987, 1992] and existing heat/work conversion machinery, plus fossil backup fuel for direct steam generation or for combined cycle systems, cost-competitive solar thermal electric power systems can emerge [Kaneff 1990, 1991a, 1992]. The first commercial demonstration project based on these approaches is now ongoing [Kaneff 1992].

Electricity generation costs of dish-based central plant systems are one-half those of LUZ and are expected to fall further as system size is increased [Kaneff 1991a, 1992]. These advances are bringing the solar thermal dish technology to the point of most economical generation costs in many parts of Australia — in areas of good insolation; at the ends of transmission lines and for the supply of offgrid power. Adding concepts already appreciated, is expected to reduce costs further. The Tennant Creek 2 MWe Solar Thermal Power Station is intended to demonstrate the various conceptual advances via a practical power system, as a forerunner to much larger systems (see Section 5.8).

3.2 Superiority of Dish/Central Plant Systems

While the LUZ parabolic troughs provided the only immediate commercial prospects for solar thermal electric systems in the early 1980s as a result of prior R&D in many countries, this technology was only marginally effective, requiring subsidy and other benefits to enable early development and is currently still marginal. Progress in dish technology has well surpassed that of troughs with respect to installation and generation costs more recently, to the extent that the advantages of dish systems relative to troughs are now 2:1 in favour of dishes [Kaneff 1991a, 1992]. Central receivers are still well behind in economics and in stage of development.

Although the drive for dish/Stirling units has been extremely well supported and that for dish/central plant systems has been only slightly supported in Europe and USA, the latter systems now appear superior for the many reasons already mentioned in Section 3.1 and further discussed in Sections 4.1, 4.2, 4.3. This is not unexpected in view of the Williams et al [1987] assessment and similar studies, as well as a wide range of other factors which relate mainly to the matter of employing as much of existing technology and industry as possible (which dish/central plant systems do and dish/Stirling units do not).

As far as can be judged at this stage, it is not likely that dish/Stirling systems can be produced commercially to be cost-effective in the near term (perhaps not until the close of this century or later, except possibly in very small sizes). This leaves the provision of significant amounts of solar electricity in the hands of dish/central plant systems up to large sizes, the technology and production facilities for which are available <u>now</u> and the technology itself can be provided cost-effectively in many areas already: more widespread application will be practicable as innovations already appreciated are incorporated in commercial units.

There is every expectation that, in due course, the 4 technologies will establish regular areas of utilization which are complementary in nature. Energy Research Centre programmes have concentrated on dish technology because of high temperature capabilities in meeting, cost-effectively, the needs of high temperature process heat and efficient electricity generation in the first instance; and later in satisfying the requirements for solar production of fuels, chemicals, energy storage, and other applications. The following sections address these aspects.

4. Paraboloidal Dish Systems

The availability recently, for the first time, of large cost-effective paraboloidal solar concentrating collectors, has opened out a vast array of energy conversion processes — solar driven — which permit solar energy to supply most of our energy needs, including:

Process Heat
Electricity
Solar-Modified Fossil and Biomass Fuels
Solar Fuels
Chemicals
Materials
Energy Storage

Process heat and electricity can already be provided cost effectively at many locations and the rapidly decreasing costs of dish systems, together with the substantial scope for further major technological and economic advances, will ensure that within the relatively short term, other applications will become commercially viable.

As indicated in Section 3, LUZ have demonstrated that the apparently least effective solar thermal technology can be made successful and viable. Furthermore, they have been able to build and commission 80 MWe systems within some 9 months; this rapid rate can be repeated for dish-based systems.

Paraboloidal dish systems have received far less development than have troughs; nevertheless technologies have improved rapidly while costs have dropped equally rapidly. Figure 4 illustrates USA progress over a period of 12 years. Figure 5 provides another means for comparison of USA dishes with some Australian developments added. Comment on the nature and direction of dish system evolution is relevant, especially in relation to the form of dish construction and the configuration of systems for electricity generation.

4.1 'Lightweight' Dishes

The plausible view that effective practicable dishes of overall lighter weight per m^2 of collection area can be achieved by stretched membrane construction has yet to be demonstrated. The use of thin individual plastic mirrored membranes, as in the LaJet concept [McGlaun 1986] or large stretched metal/glass membranes as in new heliostat designs and as realised in similar dish systems [Schlaich et al 1983; Schertz 1991], have yet to show weight advantages; similarly for large stretched plastic membrane collectors [Mancini 1986]. The situation in this respect may be well summarized in Figure 5 by comparing the currently targeted USA stretched membrane designs with the achieved PKI Inc square dish [Bilodeau et al 1987; Rogers et al 1988] and ANU large dish designs [Kaneff 1990], both of which employ glass mirrors and steel supporting structures — in the latter case, of great rigidity with lightweight. Nor does there seem to be the substantial opportunity with stretched membrane units to call on the economy of size to reduce costs per m^2, except possibly for multi-faceted configurations. If very lightweight dishes are successful, they will benefit dish/central plant systems as well as dish/Stirling units.

This aspect of dish development may still be considered as very much in a state of flux.

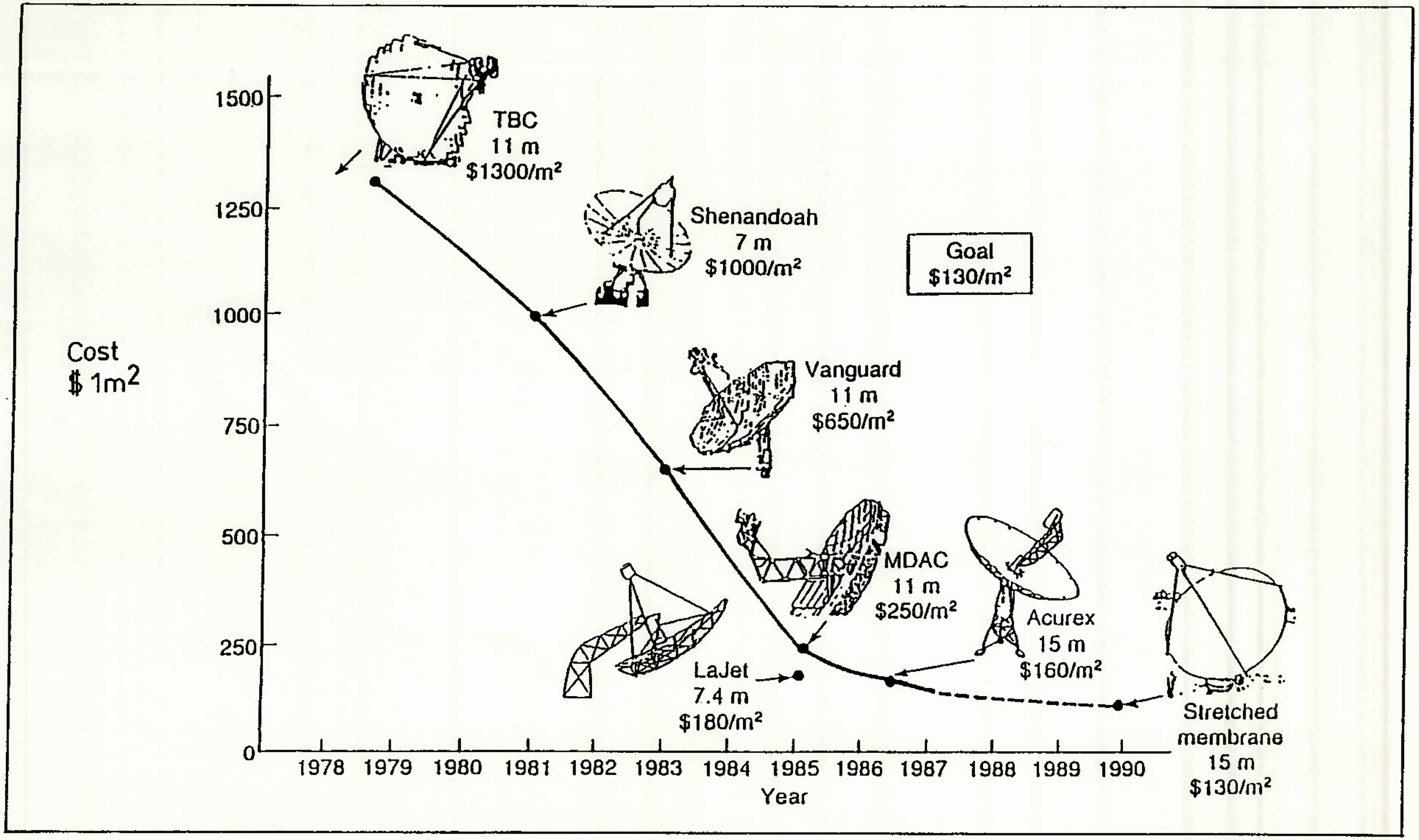


Figure 4 — Cost Reduction of USA Paraboloidal Dishes over the Period 1978 – 1987 (from W.B. Stine (1989) SERI/SP-220-3237, p4).

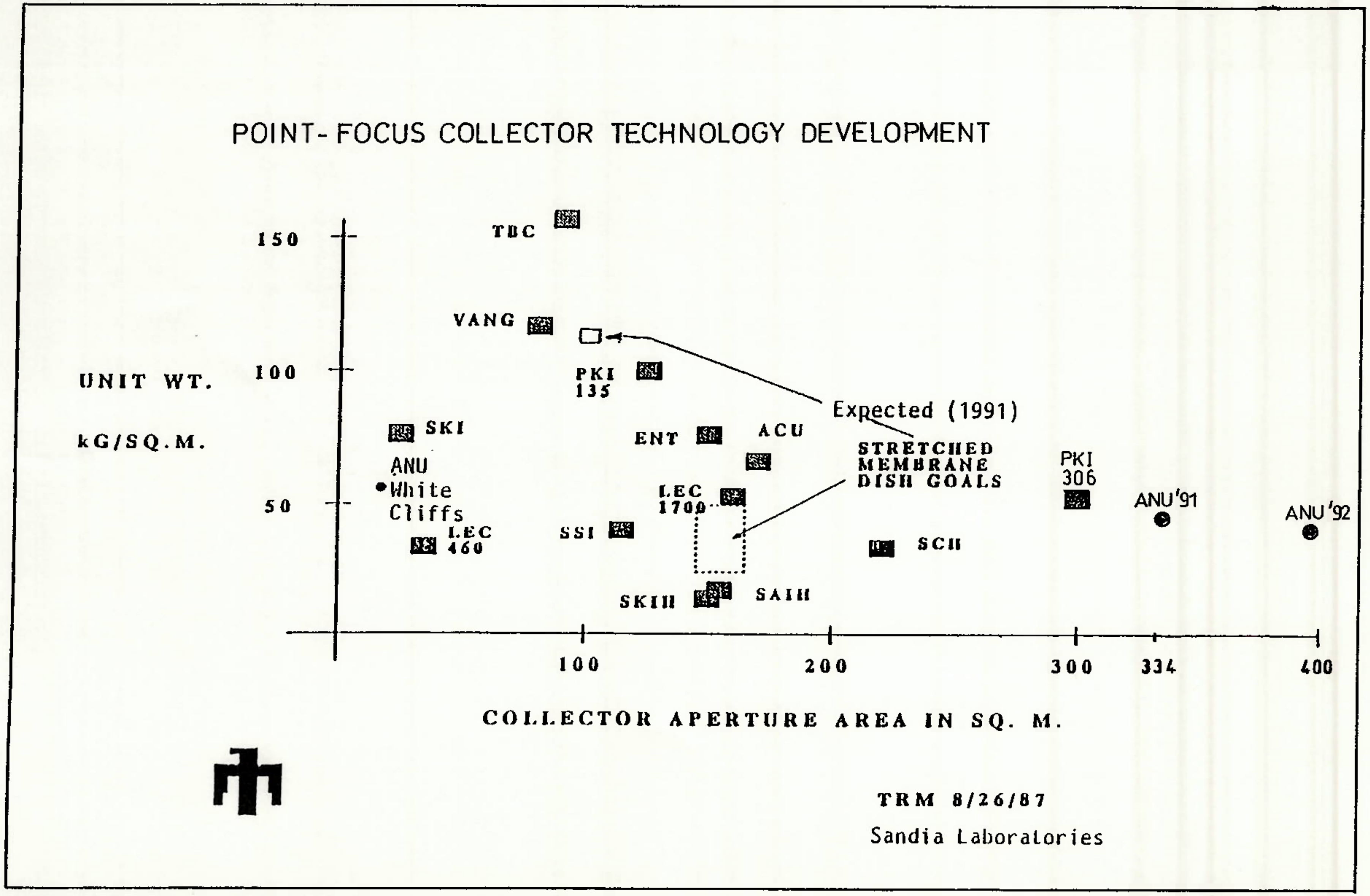


Figure 5 — Collector Weight per Unit Area versus Gross Collector Aperture Area.

4.2 Focal Region Engines versus Central Plant

Our studies over the past 20 years have always revealed that, all things considered, dish array/central plant systems are more cost-effective and appropriate than focal region engines or dishes with individual engines, except for systems of less than about 2 MWe. Even in dish/engine systems, however, engines can be located on the ground; as the apparent advantages of high performance dish-mounted Stirling engines carry with them various disadvantages, especially when the larger systems are considered. The 2 MWe size arises due to the significantly lower steam turbine efficiencies in units below 2 MWe, allowing individual dish/engine units to compete on an efficiency basis, particularly as higher temperatures are able to be employed with lower heat transport losses. But above 2 MWe, turbine central plant rapidly surpass even the best Stirling engine system developments, as well as carrying other important advantages discussed below. Moreover, the use of more effective heat transport systems following further development (for example, the use of vacuum-based insulating lines) will allow higher efficiency ground-based engines — with all their advantages — to be employed.

Grounds for requiring each dish to carry a focal region heat engine, include statements such as:

[See for example "Status of Solar-Thermal Electric Technology", prepared for Electric Power Research Institute, Palo Alto California, by HGH Enterprises, December 1989.]

(a) Distributed power generation can achieve higher energy production per unit concentrator area than the potential of systems with central plant generation.

(b) High thermal inertia with warmup and cooldown of pipe networks and distributed receivers can be a significant limit on annual collection capability of central plant systems.

(c) High temperature (and so high conversion efficiency) operation of central plant systems is limited by the heat absorption and transport fluids (for example steam) available.

(d) Distributed power generation systems are modular.

(e) The dish/Stirling concept is preferred because

- There have been systems which have achieved high performance.
- Unattended operation has been demonstrated.
- Rapid warmup, startup and good response to cloud transients have been achieved.
- Part load efficiency is high.

We comment on the above points as follows:

(a) This has not been subject to comparative study on systems designed to optimize each approach nor to relate this to system size. We suspect that many of the comments may apply to a particular unsuccessful dish/central plant system, but do not apply generally nor to properly designed systems; the statement is untrue except for small systems. Indeed, such views miss the point that dish/Stirling units seem limited in size until first, Stirling engines are available as relatively cost-effective units, and then can be produced in larger sizes — say 100 kW to 500 kW and higher, to take advantage of the economy of size of large dishes (and probably of larger Stirling engines).

(b) High thermal inertia is not an essential feature of heat transport networks between dish arrays and central plant (Figure 3, p 16 of Kaneff [1991a] shows the PKI/ANU system following the solar variations well for an engine mounted on the ground). Actual thermal inertia (including the effects of the *soakage* of heat into insulation) is a matter for proper design. Advanced heat transport networks need have little thermal inertia — if so desired — and can take advantage of new developments in vacuum insulation if deemed appropriate. Moreover, it is not at all clear why electrical output of a solar thermal station should follow transient variations in insolation.

What effect, for example, would a 1000 MWe solar power station comprising 40 000 Stirling engines each of 25 kWe output have on a power system in the presence of intermittent sunshine with rapid variations — a not uncommon phenomenon? Does the concept of energy storage have no relevance?

(c) Carden and Bansal [1992] have shown that overall heat transport costs for large central plant systems (100 MWe) using steam can be less than 5% of the value of the annual energy throughput (when including actual heat losses plus capital costs/annum in the overall heat transmission network, applying normal power system discount rates).

By careful grading of heat quality produced by an array of paraboloidal dishes, losses can be reduced further and steam quality at central plant can allow high conversion efficiences to mechanical/electrical output. In these circumstances, gross turbine cycle efficiencies of over 40% can be realised. When combined with the advantages of higher efficiency collection and conversion from larger dishes and the relatively low-loss heat transport notworks, paraboloidal dish central plant systems have overall advantages, not disadvantages, even efficiency-wise, when compared with relatively small dish/Stirling engine units combined into large power systems.

O&M requirements for the dish/central plant systems are likely to be less than for dish/Stirling units [indicated by Williams et al 1987 and Figure 3(c) herein].

(d) Distributed dish/central plant systems are modular also; dish/Stirling units have no monopoly in this attribute. Moreover, the solar array generally has the least O&M requirements; engines the greatest, and the fact that steam turbines are produced in great numbers as a well-proven technology, does confer a degree of advantage in these also.

(e) The achievement of high performance, unattended operation, rapid warmup and startup and high part load efficiencies in dish/Stirling units have counterpart solutions in dish/central plant systems. The matter of storage of energy is usually left out in the consideration of dish/Stirling units but does need to be addressed. It is worth noting that central plants can more readily take advantage of topping and bottoming cycles, utilization of waste heat for various purposes (including water desalination) and the provision of industrial process heat either as a main or subsidiary output. The capability to use fossil fuel backup in simple or complex form, for example with combined cycle gas turbine plant, conveys a major advantage to central plant systems, particularly in achieving high overall conversion efficiencies, as well as operating convenience.

For all these reasons we consider dish/central plant systems to be superior in cost effectiveness and in variety of outputs, to dish/Stirling plant. This advantage increases with size of the solar thermal system. [This is not to condemn dish/Stirling systems which, when available as viable cost-effective units in the future, should play a role in providing electric power; first in sizes of 5 kWe to 25 kWe as current developments come to eventual fruition, probably competing with photovoltaic systems. Combinations of such systems to produce megawatts would then become possible but, due to the factors already discussed, we do not expect such multi-megawatt dish/Stirling systems to have advantages over dish/central plant systems into the foreseeable future. Larger individual dish/Stirling units greater than 25 kWe await suitable Stirling engine development.]

Accordingly we consider dish/central turbine plant to be the most appropriate and effective above 2 MWe, and smaller dish/engine units based on steam to be appropriate where waste heat utilization is important. Moreover, these technologies are available, are cost-effective now and can be implemented rapidly without requiring the establishment of substantially new industries or significant new industrial skills.

Finally, it is important to stress that the drive to realise dish/Stirling systems is having an extremely constraining influence on dish development generally — in nature, configuration and size. The foreseeable appearance of cost-effective Stirling engines in relatively small sizes only — 5 kW to 25 kW — is, in many quarters, forcing the development of matching dishes. This does not facilitate the realisation of economy of size for dishes (which, by this philosophy, must await the appearance of larger Stirling engines). Dish applications far transcend simply electricity generation — including process heat, thermochemical and photonchemical applications producing fuels and chemicals — and ought not to be inhibited by one area of utilization which also tends to limit overall system size.

The realisation of dish/central plant-electric systems facilitates the development of cost-effective dishes for other applications, as well, thereby expediting all development and, by expanding the potential market, reducing costs more rapidly. Therein resides a major advantage which is the greater because cost targets are also set in relation to mainline electrical systems (not to relatively expensive smaller systems).

4.3 Paraboloidal Dish System Development and Installations

Paraboloidal dish system developments have been of comparatively recent origin, although a conical-type concentrator was constructed and ran a printing press at the Paris Exhibition of 1878. The forerunners to present dishes, however, were first produced some 100 years later. Most of these individual units, employing cumbersome costly technology, did not lead to actual systems, which arose instead as a result of developments directed towards systems rather than units. All such paraboloidal systems employed dishes supplying central plant, contrary to much current thinking in some quarters which seems bogged down in the development of economical dish/Stirling engine systems directed to relatively small scale units and installations and largely ignoring the more technologically effective and financially attractive dish/central plant options which can take advantage of the economies and efficiencies of size and scale — both in relation to dishes and heat-to-work conversion systems (as mentioned in Section 4.2) and can be implemented now. Dish/Stirling units (with focal region engines) are not further discussed here, in accordance with our views on large systems (and on the restricted output repertoire of such systems) already expressed in Section 4.2. A comprehensive up-to-date account of such units is presented in the Proceedings of the Sixth International Symposium on Solar Thermal Concentrating Technologies, September 28 to October 2 1992, Mojacar (Almeria) Spain, organized by CIEMAT (Spanish Ministry for Industry) and sponsored by the International Energy Agency et al; Sessions 1.3; 2.7 and, more specifically, in Stine [1992].

Three relatively small multi-dish systems were developed and installed at about the same time (1979–1982): the White Cliffs plant in western New South Wales, Australia [eg Kaneff 1982; 1991b]; the MBB system in Kuwait [Zewen et al 1982, 1983; Moustafa et al 1984]; and the Shenandoah USA plant [Ney and King 1984; Fair 1985; Ney 1988]. Power Kinetics Inc of Troy NY, also contributed an array of 18 *square dish* collectors providing heat for the Soleras water desalination plant in Saudi Arabia in the mid-1980s [Krepchin et al 1987]. All systems have contributed much to knowledge about solar thermal collection and power generation, especially under harsh environmental conditions. A somewhat larger plant (5 MWe) was developed by LaJet at Warner Springs CA and tested in 1984/1985 [Schefter 1985; McGlaun 1986, 1987]. Because basic design concepts were poorly implemented, the LaJet plant could not be considered a success; the innovative lightweight collectors however have been improved from the original designs and form one option which is receiving further development.

Of the above systems, the White Cliffs plant has operated continually for over a decade [Kaneff 1991b] and is still operational, but temporarily disconnected from the town supply, pending a town grid connection and modification of the solar-driven electrical system to match the new electric distribution network. The Shenandoah plant operated for several years, as has the Soleras desalination system. The MBB and LaJet systems were closed down after relatively short experimental running periods.

A commercial 2 MWe 25-dish demonstration project has commenced (1 August 1992) using ANU/ANUTECH paraboloidal big dish technology to supply power to Tennant Creek NT, Australia (with natural gas augmentation), scheduled to be operational in 1994 and is considered a forerunner for larger systems of 10 to 100 MWe.

5. Energy Research Centre (ANU/ANUTECH) Solar Power System Development

The Energy Research Centre (prior to 1988 known as the Department of Engineering Physics) has pursued studies in solar thermal/thermochemical energy since 1971.

5.1 Research and Development Programmes

Early research in 1971 addressed the identification of areas which would be most appropriate to achieving early mass utilization of solar energy. As a result, it was assessed that solar thermal energy and its derivatives provided the best alternative, especially as means could be seen whereby all or most required energy forms could be provided, given the requisite R&D attention. Knowledge gaps were identified and served as a basis for research programmes. The major problems to be overcome were, evidently, those relating to the low energy density and intermittency of the solar resource; accordingly, these were addressed and led to the establishment of programmes for studying thermochemical systems which were seen then — and even more clearly now — as vital means for gathering, storing and transporting large amounts of solar energy. Basic theoretical and experimental studies in the requisite thermochemistry and thermodynamics were initiated, as were also programmes to conceive and develop effective solar collector and concentration means for providing the driving energy. This work has continued and broadened to include solar gasification and the production of gaseous and liquid fuels — so far on a theoretical basis only but, with the advent of large dishes and the consequent potential for solar-driven reactors of useful size, experimental studies are now being initiated.

In 1976/1977, reducing university funding forced a more immediately practical approach which necessitated external funds being gained; this biassed much of the R&D into relatively short term objectives which could attract outside support. The first such assistance of any consequence came from the New South Wales Government in 1979, via their Department of Energy and its successors, founding and supporting the White Cliffs Project (Section 5.3) which also resulted in the Australian National University (ANU) establishing ANUTECH Pty Ltd, a wholly-owned ANU commercial company which could carry forward such projects in a more flexible and effective manner than normal university practices allowed. Since 1979, New South Wales Government support has been continuous and important to our development of solar thermal systems and developments mentioned in Sections 5.3 to 5.10 (except Section 5.4 which relates to a joint ANU/Power Kinetics Inc Project funded by the US Department of Energy as a result of a successful bid in competition with US solar R&D and manufacturing organizations). Currently this support flows from the NSW Office of Energy.

5.2 Nature and Scope of ERC R,D and D Programmes in Solar Thermal Systems

It has always been our view that, where completely new technology is involved, there should be no initial bias imposed on the *shape* of this technology and on configurations and processes required to realise the objectives to be met. In the case of solar thermal systems, it has turned out that applying normal manufacturing and construction concepts and practices from some industries has often led to almost overwhelmingly uneconomic systems. New thinking is essential and usually emerges when imagination is given free rein. Invention of the highest order is required to achieve economically, as well as technologically, successful solar thermal systems which have their own peculiar attributes and constraints and do not necessarily gain directly from other technologies. [This does not preclude existing industries from participating in the manufacture and installation of newly-developed systems, so long as inappropriate manufacturing and work practices are not employed. Industry can, of course, also be inventive and contribute much to the further development of systems and components.]

An important aspect in the development process is the need to consider complete systems *ab initio*, rather than to first develop components which might later form parts of systems as yet undefined. Accordingly, we have been involved in system development first and foremost, in a drive to ensure that economical integrated systems emerge; components have then followed in response to the needs of the systems. Thus, referring to Figure 6 which records in simplified form the various functional aspects of solar thermal electric systems (thermal and thermochemical), we have given attention to every functional process and have developed theoretical and practical experience in every necessary area (except for combined cycle systems which have only now become practicable and are receiving our current attention).

Figure 6 illustrates the scope of our involvement in solar thermal systems. As indicated earlier, the most important advances over recent years have involved the development of large cost-effective paraboloidal dishes which have opened out an array of solar-driven applications. Fortunately, the great repertoire of technology required to assemble solar thermal systems is assisted by much previous development, so that receivers, dish arrays, heat transport networks and storage can all be implemented to varying degrees of effectiveness; and central plant and heat transport networks can call on much commercially-available equipment. Nevertheless, continual R&D over many years is still required to bring to fruition the many improvements, the nature and benefits of which are well appreciated (and others not yet envisaged), to ensure unimpeded progress.

Direct involvement with practical systems from conception to commissioning and subsequent operation, has provided a unique knowledge and experience base which is now extending to larger commercial megawatt systems. Invaluable information so obtained has, as a result of continuity of involvement, allowed us to proceed through the difficulties which most other groups have encountered and not overcome. A significant contribution has accordingly been made to the realisation of cost-effective solar thermal electric and process heat systems [Kaneff 1991a; 1991b; Hagen and Kaneff 1991]. Increasing collaboration is now occurring between ourselves, power utilities and industry in Australia in furthering this field, which is currently arousing much interest in user and potential user organizations.

The losers in this situation have been the relevant areas of fundamental research which have received decreased funding since 1978 from Federal Government sources and from universities. [We have been, only with considerable difficulty, able to maintain basic research programmes in energy storage and transport involving thermochemical systems (especially employing ammonia) and heat storage in phase change materials. With the developments indicated in Section 7, interest in solar/fossil combined systems may change this picture.]

Valuable collaboration has been ongoing over the years between the ERC and several other groups. The most extensive has involved our colleagues PKI Inc, Troy NY USA, especially since 1984. Significant collaboration exists with Dr David Mills, University of Sydney, Professor W.W.S. Charters, University of Melbourne, and lately with Dr A. Blakers of the ANU Engineering Programme of the Faculties.

Over the past year we have been involved with members of the Solar Energy Centre of the Indian Department of Non-Conventional Energy Sources and with Professor H.P. Garg and (over several years) with Dr N.D. Kaushika, Indian Institute of Technology, New Delhi. This has given an appreciation of major problems to be solved in India. Collaboration in this respect is being set up with a view to assisting developing suitable systems for solving the many outstanding and very evident energy problems. The use of solar energy via the thermal path clearly has a major role to play in these endeavours.

5.3 The White Cliffs Project

Conceived, researched, designed, built, installed and commissioned over the period August 1979 to December 1981, the White Cliffs solar thermal paraboloidal dish system was intended to ascertain the feasibility of solar thermal systems operating in remote areas; the intention being eventually to produce systems over a wide range of sizes for both on-grid and off-grid application. Originally intended as an experimental system running for a short period to gain experience and information, it was found that the system could continue effective operation indefinitely provided appropriate maintenance requirements were satisfied. Accordingly, the township of White Cliffs continued to be supplied with solar power (with diesel backup) for a decade.

The 10-year operating experience with the White Cliffs plant has demonstrated the feasibility of small stand-alone solar thermal systems in remote areas, including the practicability of automatic units to work unattended, successfully calling on local assistance (whose skills do not extend beyond motor vehicle maintenance) as and when required. White Cliffs has provided invaluable lessons for subsequent system advances which have influenced R&D directions in a manner not practicable with testbed systems in the laboratory. Details of a decade of White Cliffs experience are reported in Kaneff [1991b].

Among the many lessons learned include:

- Practices and strategies for operating in extremely demanding environmental conditions.
- Means for achieving robust, reliable, cost-effective operation.
- The fact that very small systems suffer economically; large systems are potentially more cost effective.
- Equipment can successfully be made dustproof or dust tolerant.
- Robustness and reliability are far more valuable attributes than high efficiency performance and contribute more readily to annual collection efficiency.
- It is imperative that overall system considerations be given prime importance in R&D; component characteristics must follow system needs. System optimization is an important operating aspect which must be achieved by design and by automatic control based on effective operating strategies.

The solar array of 14 dishes and associated systems have been extremely successful and troublefree. Mirror degradation has been slight on average, with some mirror segments suffering less than 2 to 3% loss in reflectivity; others have shown 10% — this latter could have been avoided with better inspection of the mirror silvering quality at the construction stage. There is every reason to expect the well-silvered mirrors to last well beyond a further 10 or more years. Collectors have turned out to be robust, reliable and practicable: they have given confidence that much larger paraboloidal dishes can be successfully built and operated with good economic viability.

The heat transport network has also proved eminently successful and trouble-free. Heat losses at rated insolation amount to less than 3% of throughput and, given early morning sunshine, heat capacity and *soakage* typically cause only a few minutes' delay before useful generated power is available.

Most of the plant problems occurred with the developmental engine and the receivers; both sets of problems have been solved over the years, the most onerous being to achieve long-life receivers (which are subject to extremely traumatic heat flux conditions). Nevertheless, it is still an open question as to the realistic useful operating life of receivers, since tests have not as yet been able to be conducted over the requisite number of years (and acquiring of definitive information will need another decade of operation). Further R&D in relation to receivers is bound to continue for many years to come. Realistic testing will be facilitated on commercial systems, which offer the only practicable means for long term validation of improvements — as for any new technology. The stage of development is now such that practicable cost-effective systems can be built and advances will be incorporated from time to time as they appear; again, as happens with any evolutionary technology — this process does not hold up application and utilization, but simply means succeeding systems are better.

White Cliffs has illustrated our dish/central plant preferences, in this case employing a high performance reciprocating steam engine. But while we advocate ground-based engines for systems of less than 2 MWe and (in appropriate applications) dish/Stirling units when these have been adequately developed, turbines become attractive at 2 MWe and larger. They are well developed and satisfactory so long as their operation is carefully controlled in accordance with their characteristics; that is, the frequent variability and intermittancy of solar input must be properly handled. This aspect is receiving attention in the Tennant Creek Plant (Section 5.8).

5.4 Joint ANU/PKI Project (SCSE No 2)

Following an invitation from Power Kinetics Inc (PKI) of Troy NY, USA, an ANU/PKI collaborative tender was submitted to the US Department of Energy (DOE) in competition with other tenders in response to a DOE Statement of Opportunity. The programme involved 250 kWe in 5 units, each with a ground-based engine; the submission was successful and the project was conducted over the period 1985 to 1988.

Under the US Department of Energy's Small Community Solar Experiment No 2, this collaboration between the ANU and PKI facilitated the design and building of a solar thermal electric power module of nominal 50 kWe, employing a PKI *square* dish of 295 m^2 aperture and receiver/steam system/engine room based on ANU White Cliffs experience. The philosophy required modular units, each having a power conversion module/point focussing collector. Tests of the first unit were completed at Albuquerque NM in August 1988 [Cameron and Harvey 1991] and made clear the fact that improvements then under way would permit the next systems to meet or exceed design specifications; PKI have subsequently made substantial modifications towards commercialization and larger scale systems. The main lessons emerging from this project have come in relation to the feasibility of realising much larger dish systems than employed at White Cliffs and the Albuquerque unit, and pointing to how these can be achieved cost-effectively, thus giving confidence and data to assist the ERC Third Generation Systems [Kaneff 1990]. For the first time, a credible technology pointing to how very large systems might be realised in practice, became evident as a result of practical demonstration of a key element — the collector.

5.5 Size of Dishes — Solar Generator 3 (SG3)

White Cliffs made it abundantly clear that arrays of 5m-diameter dishes were far from optimal, but were implemented in that situation as a result of inadequate information on climatic conditions and on the potential for increased size while establishing economic viability. Since 1980, several studies have been made by ERC to ascertain what limits exist to dish size. Figure 7 shows earlier results in relation to projecting dish sizes [Kaneff 1987].

Such considerations must be very strongly qualified by the fact that each costing needs detailed design, which in turn requires a specific configuration: changing configuration and other details can change any optimum factor dependent on size. Eventually, it is only specific practicable designs, built and tested, which can give a truly realistic picture of dish cost versus size. This stage has not yet been reached. Nevertheless, there are good grounds for expecting that large dishes can be viable.

The SG3 big dish programme was initiated in 1986, during a visit to White Cliffs by Mr Peter Cox, NSW Minister for Energy, who was impressed by the potential of White Cliffs as a forerunner to producing much larger grid-connected systems. This gave us the opportunity to develop designs of dishes which were not only large, but were potentially more cost-effective as a result of a new configuration; and being parked — and operating for most of the time — close to the ground, unlike most other designs (including White Cliffs and the SCSE No 2 design), thereby assisting with reduced wind loading problems and enabling the construction of lighter weight collectors. Other attributes which suggested themselves as a result of much in-field experience and new conceptual thinking, were also able to be introduced into the SG3 concepts and detailed designs.

Kaneff [1990, 1991a] has reported on the initial 334 m^2 aperture dishes and their economic properties (see Table III and Figure 8). Paraboloidal dishes with apertures of

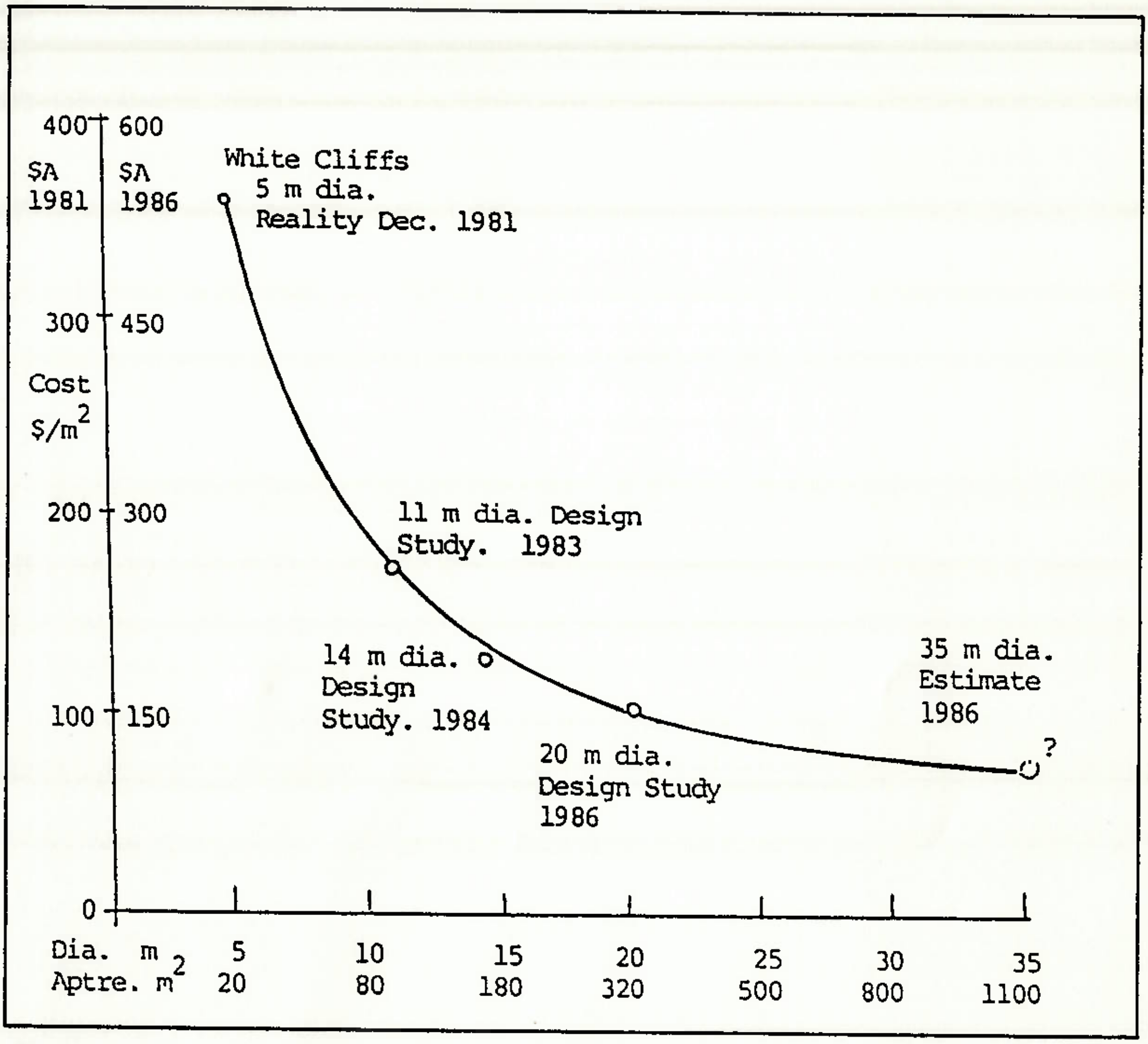


Figure 7 — Size versus Cost for ANU Dishes (1980 – 1986).

TABLE III — SUMMARY OF ANU DISH-BASED SYSTEMS — PARAMETERS AND COSTS

Site Insolation:	2 360 kWh/m²/annum	
Dish Parameters:	Aperture Area	334 m²
	Reflectivity	0.94
	Rated Insolation (to gain nett rated output)	950 W/m²
	Receiver absorptivity at rated insolation	0.94
	Energy collection and transport efficiency (to fixed base of dish) at rated insolation	0.88
	Annual heat supplied at fixed base of dish	660 $MWh_{thermal}$/annum

System Rated Output at 950 W/m²		50 kWe Demo Plant	50 kWe	200 kWe	1 MWe	10 MWe	100 MWe
Assessed Output at 950 W/m²		52.9 kW	52.9 kW	241 kW	1.02 MWe	10.5 MWe	100.4 MWe
Collector Aperture	m²	334	334	1 336	5 680	42 420	316 630
Number of Collectors		1	1	4	17	127	948
Nett Annual Heat Energy delivered to engine or turbine (a)	MWh_{th} per annum	660	660	2 640	11 220	83 840	619 400
Number of engines (e)/turbines (t)		1e	1e	1e	5e*	1t	1t
Nett enthalpy to engine/turbine at rated output (950 W/m²)		279.5 kW	279.5 kW	1 118 kW	4.74 MW	35.3 MW	262 MW
Gross engine/turbine efficiency of conversion at rated output	%	21.5	21.5	23.5	23.5	32.5	42.0
Auxiliary Power at rated output	kWe	2–4.2	2–4.2	4–8	20–42	700	8 000
Nett Electrical Output		52.9 kWe	52.9 kWe	241 kWe	1.02 MWe	10.5 MWe	100.4 MWe
Engine/Turbine-Alternator Efficiency at rated output	%	18.9	18.9	21.6	21.6	29.7	38.8
Efficiency of Overall System Nett electrical output/solar input at rated output	%	16.7	16.7	19.0	19.0	26.1	33.4
Nett Annual Electrical Output (b)	MWhe per annum	124	124	558	2 360	24 140	234 800
Annual Average Overall Collection and Conversion Efficiency solar to electricity	%	15.7	15.7	17.7	17.6	24.1	31.4
<u>Process Heat</u>							
System Installed Costs	$million	0.1649	0.1132	0.439	1.848	11.74	76.61
Heat supplied/annum [see (a)]							
Life Cycle Cost at 8% nett interest rate	¢/kWh_{th}	2.74	1.86	1.77	1.77	1.42	1.27
<u>Electricity Generation</u>							
System Installed Costs (total)	$million	0.2362	0.1775	0.6556	2.398	20.1	136.06
Installed Costs	$/kWe	4 465	3 355	2 720	2 350	1 910	1 355
Nett Electricity Produced per annum [see (b)]	MWh_e per annum	124	124	558	2 360	24 140	234 800
Life Cycle Cost at 8% nett interest rate	¢/kWhe	23.0	16.5	13.7	11.7	9.5	6.6

* Alternatively a 1 MW turbine could be employed instead of 5 engines.

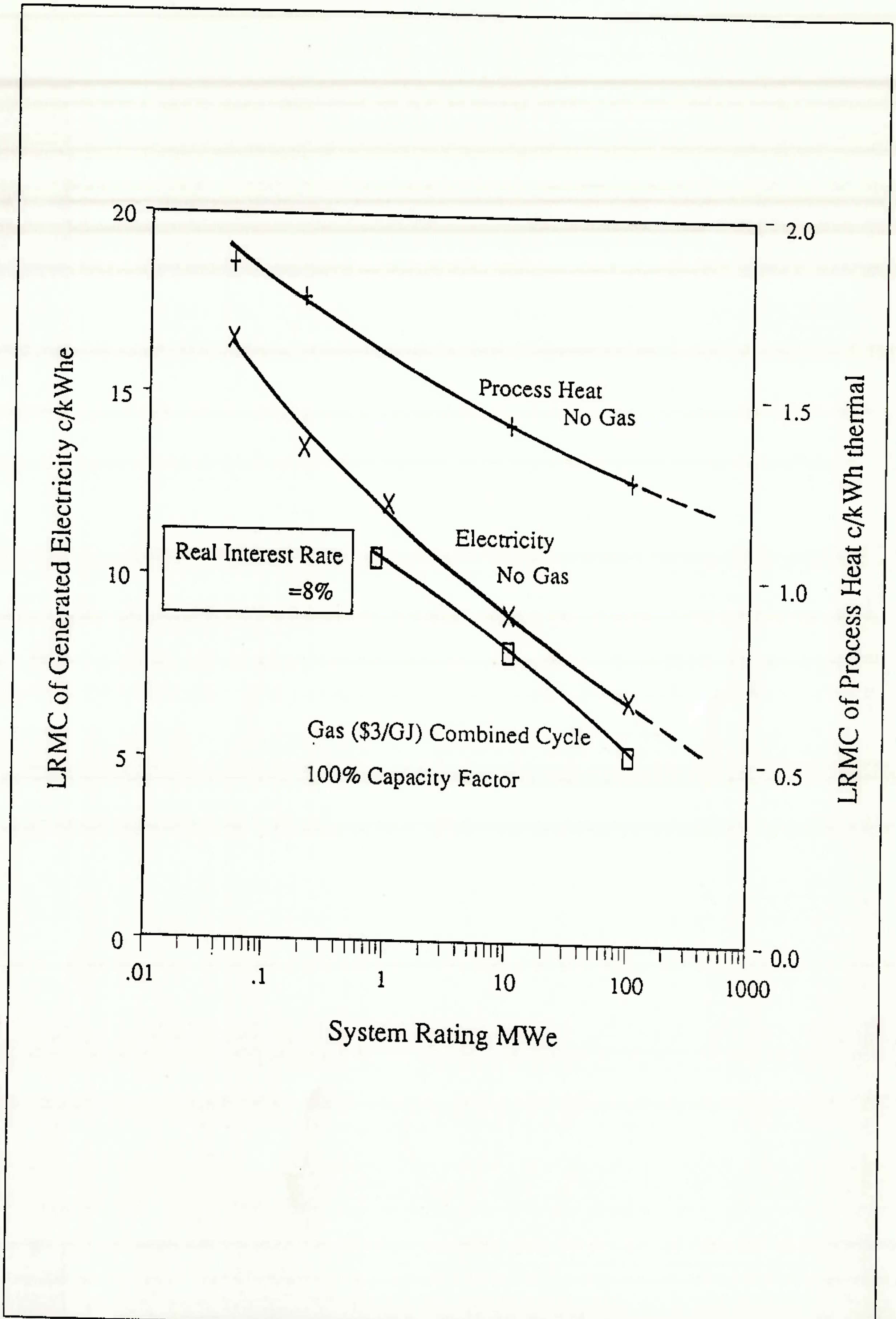


Figure 8 — Cost of Electricity and Heat from ANU 334m² Aperture Paraboloidal Dish Systems.

400 m^2 are now practicable (Figure 5) but definitive costing estimates await completion of the first unit being built in Canberra, to validate actual costs: Evidence to date suggests a 20% reduction in costs/m^2 aperture. SG3, although first considered in 1986 and outlined in detail in 1988, was not funded until August 1990, with support from the New South Wales Government and Allco Steel Corporation. The configuration eventually evolved, as a result of several detailed iterations, to a 400 m^2 aperture dish with novel features and the potential for commercialization, especially in relation to modular factory mass production and relatively simple and undemanding installation. Automated production and accurate construction has allowed assembly in the field with no required adjustment of dish alignment. A feature of the technology involves great rigidity combined with light weight.

The SG3 collectors are intended for solar thermal systems of any size, with each collector module adding approximately 400 $kW_{thermal}$. In the case of the first unit, the single collector drives a reciprocating steam expander providing 50 kWe nett at an insolation of 950 W/m^2. Figure 9 shows the functional arrangement of the single dish system. [To achieve water desalination from the waste heat of this system, the air-cooled section of the condensing system is replaced by a supply of saline water (to be purified) to the condenser, running the engine exhaust at approximately 100°C (causing a loss of electrical output of only $\simeq$ 1 kW) and employing vacuum evaporation and subsequent condensing of the collected vapour (which thereby preheats the incoming saline cooling water). The remaining concentrated saline solution is allowed to evaporate completely in a small pond from which the salts are removed as a product.] For larger systems, the dishes supply one or more larger engines: at 2 MWe and above, steam turbines form the central plant, together with heat storage and/or fossil backup, including combined cycle plant based on natural gas — depending on system requirements.

We are investigating much larger dish units; at this stage up to 2000 m^2 aperture. The major trade-offs involved are wind load, mass of materials, production and erection costs, glazing concepts including cleaning of mirrors, receiver efficiency and degree of sophistication. There is little doubt that quite large dishes can be built and, as size increases, labour costs per m^2 decrease but material costs increase, while collection and conversion efficiencies also increase. However, a more elusive aspect also intrudes — that of inventiveness in relation to configuration — and whereas it is not difficult to optimize dish aperture area for a given configuration, it is not practicable to determine an absolute optimum, as suggested earlier.

A further factor relating to a completed dish, which involves labour and materials, should take account of the level of initial processing of the basic raw materials. A more fundamental consideration of design can involve taking the basic raw materials (which, in the case of the 400 m^2 ANU big dish, are worth less than $3000) and imposing on them a different set of manufacturing processes which could reduce their costs, as at present applying, by up to one order of magnitude, with corresponding benefits to overall labour costs [see Hagen and Kaneff 1991, Section 4].

5.6 Commercial 'Big Dishes' — Solar Generator 4 (SG4)

The final stage of the SG3 project involves incorporating lessons and emerging data from this demonstration plant in order to produce more cost-effective commercial units suitable for quantity production, resulting in a modified system, SG4. As many means are now clear for achieving further commercial advantages in these units, it is expected that the costs identified in Figure 8 and Table III will be improved. Utility and industrial involvement in this phase is under way, in recognition of the potential to establish cost-

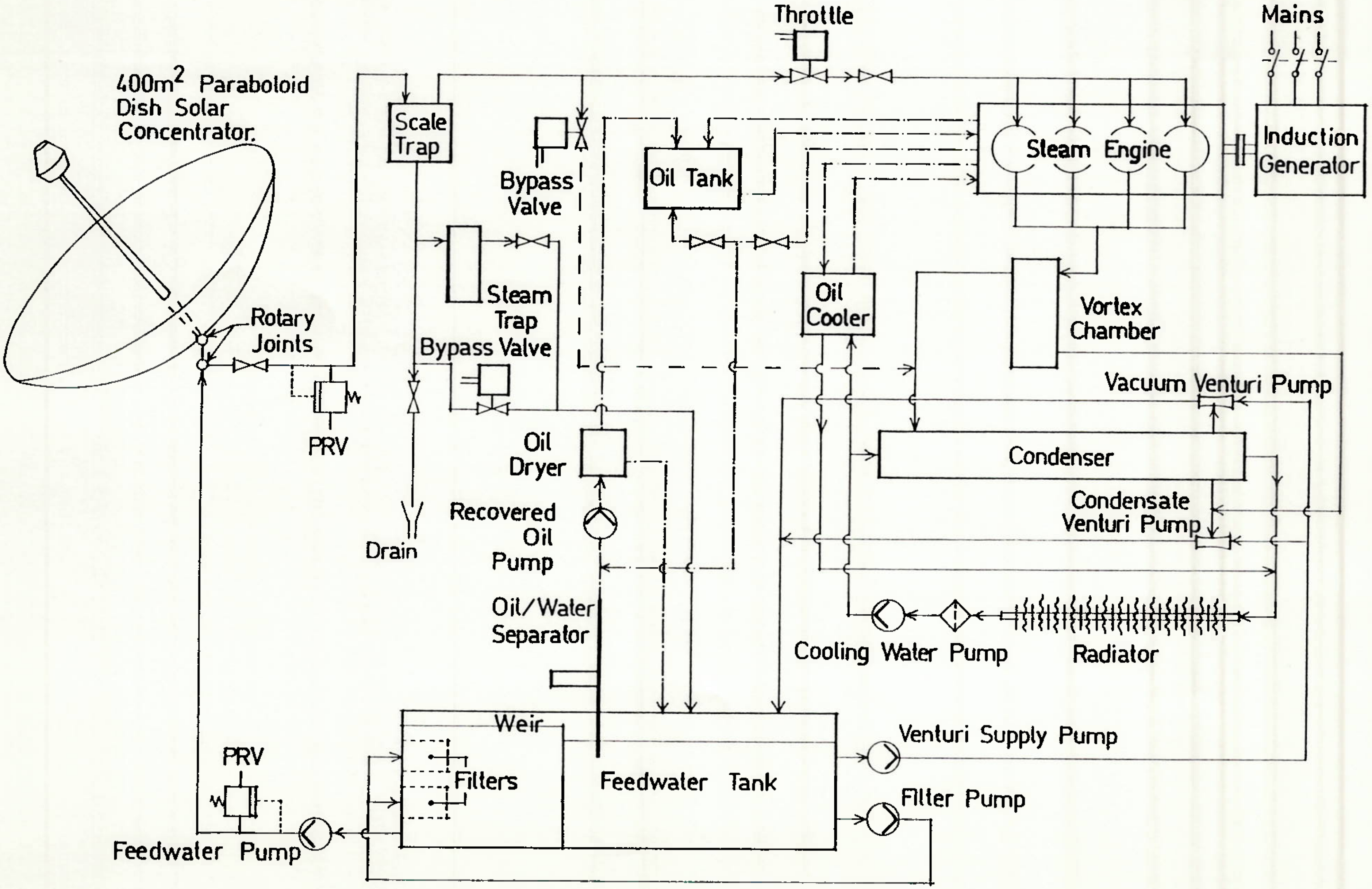


Figure 9 - Functional Diagram for 50 kWe Dish Engine System.

effective large multi-dish commercial solar power systems based on SG4, without the need for further development to achieve viability in many areas. This is not to deny the advantages of further improvements, as indicated in Section 5.5, but merely to state that SG4 designs are considered commercially viable already in many situations and can form the basis of many useful systems over the coming years, while further advances (which may take time to demonstrate) are brought to fruition.

5.7 Size and Cost of Dish Systems

That paraboloidal dish systems have so far been realized in sizes from 25 kWe to 5 MWe, has produced a perception that dishes are more appropriate for small power levels only. This is illusory, having arisen partly because, unlike central receivers (for example), they can be built successfully in small sizes to demonstrate effectiveness, in the process placing only relatively small resources at risk.

The only major apparent technological barrier to large dish systems is the matter of losses in and cost of the required heat transport network connection to a central plant. The use of individual dish engine systems is ruled out at this stage generally for the reasons outlined in Section 4.2, because of their economic unavailability and the fact that units being developed are small (a 1000 MWe dish/Stirling system of 25 kWe units needs 40 000 collectors and engines, the O&M aspects of which are difficult to contemplate). Less than 800 dishes of 400 m^2 each are required for a 100 MWe plant and the heat network losses can be less than 5% of the value of annual throughput energy, when taking account of both actual heat lost and total annual costs of the insulated heat transport network itself [Carden and Bansal 1987, 1992]. There are several concepts, such as graded temperature production at the extremities to the array, which are not included by Carden and Bansal and which, together with superheating dishes close to the central plant, could improve this aspect further.

Table III and Figure 8 [both from Kaneff 1991a] give assessed costs for paraboloidal dish systems of 50 kWe up to 100 MWe, revealing close cost competitiveness with other energy sources. We expect such systems of up to 200 MWe or so to be practicable. [Much larger systems (eg 1000 MWe) using thermochemical energy transport (and storage) can be envisaged over the next few years, employing less than 2000 very large paraboloidal dish collectors.]

The 400 m^2 dish designs have already overtaken the values in Table III and Figure 8, giving encouragement that in the next 2 to 3 years, generation costs lower than those of new coal-fired power stations in Australia will be realised without relying on the inclusion of external costs to achieve this competitive position.

Much R&D in the 1990s should be directed to make solar thermal electricity generating systems the clear contender for any new increase in generating capacity: This goal is attainable both technologically and economically.

5.8 Tennant Creek NT 2 MWe Solar Power Station — Solar 5

Realisation that solar thermal power systems could compete favourably with natural gas generated electricity in the Northern Territory of Australia, led the NT Power and Water Authority (NT PAWA) to an agreement with ANUTECH Pty Ltd for the development and installation of a 2 MWe demonstration plant at Tennant Creek NT. With project commencement on 1 August 1992, a 3-year programme involves completion of the plant in mid-1994, after stages involving feasibility study, design and construction. Figure 1(a)(iv) gives the simplified functional diagram for the station.

That the Northern Territory enjoys excellent direct beam insolation even in tropical coastal areas (such as Darwin) is evident from Figure 10. This works in favour of the applicability of dish systems. Further determining factors are the relatively small existing installed capacity of 15 to 20 MWe at Tennant Creek, based on 1 gas turbine, 2 dual fuel units and 6 diesel sets, and the relatively high cost of natural gas at that site. Even for areas with larger installed capacities and lower natural gas prices, current solar thermal designs would now be cost-effective — eg over the whole Northern Territory and in many parts of Western Australia, South Australia and Queensland.

The project is a joint venture between NT PAWA and the Energy Research Centre/ANUTECH with involvement of industry; and likely participation of other electric utilities and the Federal Energy Research and Development Corporation, at the second and later stages of the project (early in 1993). System configuration, parameters and costs will emerge later in 1992, with presentation of the first report. This plant will be the first commercial demonstration of the big dish solar thermal technology.

5.9 Further Developments

The 'Big Dish' development has caused, in the past year, a number of individual associations between the ERC/ANUTECH and respectively Pacific Power and the Electricity Trust of South Australia — the former relating to the detailed study of solar thermal power systems in sizes ranging from 2 MWe to 100 MWe; the latter involving an R&D programme to develop the dish technology further while installing a small number of dishes to demonstrate various applications, including electricity generation and water pumping, water desalination and solar modification of landfill gas.

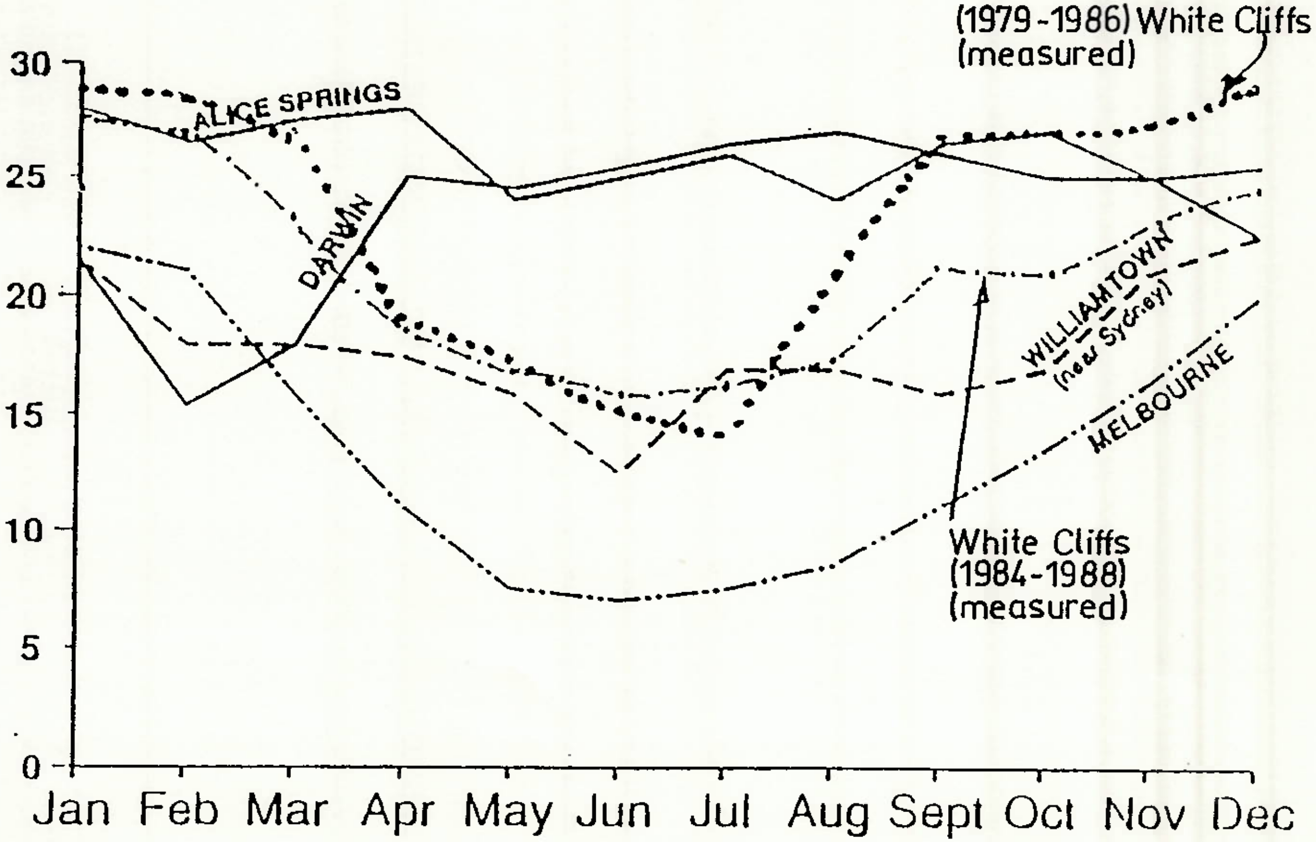
Recently, arising from the Northern Territory decision to install solar thermal power, the concept of an Australia-wide consortium of interested organizations has grown and has led to establishment of a mechanism for joint participation with ERC/ANUTECH in the further integrated development of solar thermal power systems based on dishes, providing both funding and direction for R,D&D as well as commercialization directions.

Organizations involved are:

Northern Territory Power and Water Authority (NT PAWA)
Electricity Trust of South Australia (ETSA)
NSW Office of Energy (NSWOE)
Pacific Power (PP) (formerly the NSW Electricity Commission)
State Electricity Commission of Victoria (SECV)
State Electricity Commission of Western Australia (SECWA)
Queensland Electricity Commission (QEC)
Electricity Supply Association of Australia (ESAA)
Energy Research and Development Corporation (ERDC)
Energy Research Centre (ERC)/ANUTECH

A first meeting in Adelaide in September, following an ERDC invitation, set up the collaboration; detailed arrangements for participation are to be determined at a meeting in December 1992. It is possible that others (including industry) will take part. A project already involving collaboration of the participating groups had been initiated earlier to obtain detailed insolation, wind and other climatic parameters at 14 Australia-wide stations, to facilitate the design and installation of solar energy systems.

Figure 10 — Direct Irradiance Normal to Solar Beam (MJ m^{-2} day^{-1}).



Source: "Data Handbook for Australian Solar Energy Designers" by GG Roy and SG Miller University of Western Australia,

5.10 Commercialization

A major objective of the ERC has been the following through of all aspects of developing new energy sources and technology — from conception to establishment of R&D programmes; and construction, installation and commissioning in practical environments, carrying on O&M and carrying forward the lessons learned to enable requisite improvements to be made. As this process has progressed in any one activity, so an increasing collaboration has been established with industrial and other relevant groups whose composition varies from time to time as required. Continuity of expertise is all-important.

Currently the collaboration with Spacetech of Moorabbin (Victoria) is an important element in establishing the structural aspects of the big dish technology on a commercial basis; this has been facilitated by direct assistance from Palmers' (Steel Tube Manufacturers) of Brisbane and Dulux Australia (Protective Coatings). Allco Steel of Tomago (NSW) have previously provided funds, together with the NSW Office of Energy, to assist the project. Several other industries have been involved in the manufacture and supply of components.

The transition from SG3 to SG4 to produce a commercial dish technology is being based on many developments which have already become apparent from SG3 — largely configurational aspects directed to simplification and cost reductions without performance degradation. The obvious economies of scale of production run can be assessed following confirmation of final SG4 details.

But there are many other means for facilitating construction and commercialization, based on wellknown engineering principles and practices, which can be invoked in the drive for commercial realisation [see Hagen and Kaneff 1991].

(a) **We note that in any event:**

- Solar Thermal Power is Competitive Now —
  In remote locations.
  For summer peaking power.
  For hybrid peaking power.
  For solar process heat.

- And is more competitive —
  When real increases in fuel costs are included.
  When full life cycle costs are included and
  When the same interest rates are charged as for other energy systems.

- Solar Thermal Power could be more widely used and be very competitive —
  When subsidies on other energy sources are accounted for.
  When external costs and resource depletion are included.

(b) **Applying Wellknown Principles and Practices, to Reduce Solar Thermal Costs:**

- Volume of Production —
  Sell, Produce, Purchase in Large Volumes.
  Obtain Lower Interest Rates.

- Technology Improvement —
  Devise and Select the most Effective Technology.
  Optimize Structural Design, Material Selection and Material Use.

- Reduction of Production Costs —
  Use Local Materials.
  Maximize Production to Minimize Capital Cost.
  Automate Production to Minimize Labour Cost.
  Minimize System Transport Cost.
  Automate Assembly and Installation.

- Optimization of All Aspects —
  Schedule Maintenance at Night.
  Provide Optimum Spare Parts.
  Minimize Marketing Costs.
  Streamline Administration.
  Optimize Quality.

(c) **The Further Development of Solar Thermal Electricity Generation:**
Can be assisted by commercially available technologies which can be applied directly to enhance the performance and/or output continuity of current solar thermal power systems, including:

i. Natural gas backup for solar steam (boilers, etc are available).
ii. Solar steam-injected gas turbines (turbines are available).
iii. Solar steam feeding the steam turbine section of a combined gas turbine/steam turbine plant in which waste heat from the gas turbine drives the steam turbine (combined cycle plant is available).
iv. As in i, ii and iii, but with the gas supply-syngas ($CO + H_2$) coming from solar gasification of coal, natural gas or biomass. [Plant is commercially available except for the solar-driven gasification reactor which can employ well developed reactions but needs development of the solar aspects — the dishes are now available.]
Natural gas pipelines could reticulate the syngas.

5.11 Development and Cost Targets

Given appropriate development over the next few years, solar thermal electricity may be produced for less than 5¢/kWh on a life cycle basis. This may fall as target overall system efficiencies of some 60% and installed costs as low as $500 per kWe are attained for electricity generation and efficiencies of approximately 90% are reached for high temperature process heat. Addition of economical heat storage and fossil/combined cycle augmentation and/or backup, will assist this process. Improvements have been rapid in the past 5 years and can still rely on known but undeveloped concepts to effect considerable further technological and economic benefits. Not the least of the latter is in the development of the employment and industrial sector. [Discussed further in Hagen and Kaneff 1991, 1992.]

6. Potential Penetration and Growth Rates

Solar thermal systems are already viable and cost-competitive in areas of inland, central and northern parts of Australia, where electricity generation costs tend to be higher than mainline power grids near large cities [see for example Table IV from Hagen and Kaneff 1991]. When ongoing improvements are incorporated into existing solar system details and configurations, cost effectiveness will be widespread.

TABLE IV - COSTS OF POWER IN REMOTE GRIDS IN WESTERN AUSTRALIA							
Location	Total Cost c/kWh	Capacity Site Rating kW	Marginal Fuel Cost c/kWh	Peak Demand kW	% Over Peak	Proj Growth %/year	% Safe Over Peak
Broome	11.81	13720	8.69	8200	67	4	18
Camballin	22.02	893	17.90	270	230	2	85
Carnarvon*	9.56	16506	5.20	8830	87	2	33
Cue	12.60	1152	12.16	530	117	4	40
Denham	17.49	1465	14.33	760	93	4	0
Derby	15.46	11100	9.11	5300	109	2	41
Esperance	12.43	14406	10.29	10190	41	4	-1
Exmouth	13.92	8776	8.75	4300	105	2	44
Fitzroy	15.65	2564	12.10	1230	108	5	37
Gascoyne		240	26.77	60	300	2	100
Halls Creek	15.46	2668	12.19	1130	136	2	56
Hopetoun	16.20	1014	12.00	390	160	3	59
Kununurra	15.56	12400	10.73	6620	87	5	32
Argyle	23.86	570	18.45	130	338	2	100
Leonora	16.16	3389	11.48	1730	95	5	38
Marble Bar	24.20	1386	14.77	490	182	1	67
Meekatharra	14.46	3740	11.88	2020	85	3	21
Menzies	23.61	350	17.37	80	337	5	113
Mt Magnet	13.52	3360	12.47	1770	89	3	-3
Nullagine	24.42	370	14.95	190	94	4	0
Onslow	17.45	2064	13.88	910	126	2	33
Ravensthrope	16.02	2024	11.65	730	177	4	66
Sandstone	26.85	235	23.29	70	235	3	71
Wiluna	11.48	1014	10.65	340	198	3	82
Wittenoom	23.78	800	16.57	210	280	2	124
Wyndham	17.56	4336	11.04	1850	134	0	28
Yalgoo	19.58	285	17.22	120	137	3	25
Total	18.xx	110,832	13.74	58,455	190	3.2	49

Data from State Electricity Commission of Western Australia 1991.
Excluding Pilbara Grid, and Norseman, Laverton. * on gas

There are more than 500 MWe at remote Australian sites where electricity costs are 10¢/kWh to 30¢/kWh and higher and where hybrid solar thermal plant can be implemented immediately, reducing present life cycle costs to utilities, mining companies and small communities. Installing solar thermal systems in these sites now will give the initial volume required to establish a competitive solar thermal power industry.

Indeed, our view is that the stage has now been reached whereby it is no longer necessary or appropriate to build any further coal-fired power stations, but to employ solar thermal power — which can be implemented rapidly, cost effectively, and with excellent energy profit ratio (payback periods of approximately 9 months). While natural gas-driven electricity has advantages over coal, this can be only a stopgap measure, allowing time to develop more-benign systems. [Further consideration is given to these aspects in Sections 7 and 8.]

Policy makers usually propose solar energy systems but assume that it will take a very long time for installation on a large scale. But rapid growth has been demonstrated when there are strong economic incentives, environmental legislation mandating change, or concerted public or private effort, by employing wellknown industrial mass production, construction and installation techniques. Solar salt production demonstrates this situation, discussed in Hagen and Kaneff [1991, 1992].

6.1 Economically-Driven Growth of Solar Evaporative Ponds

The reality and potential for very large scale solar energy use, once it is competitive, is demonstrated by Australia's solar salt industry.

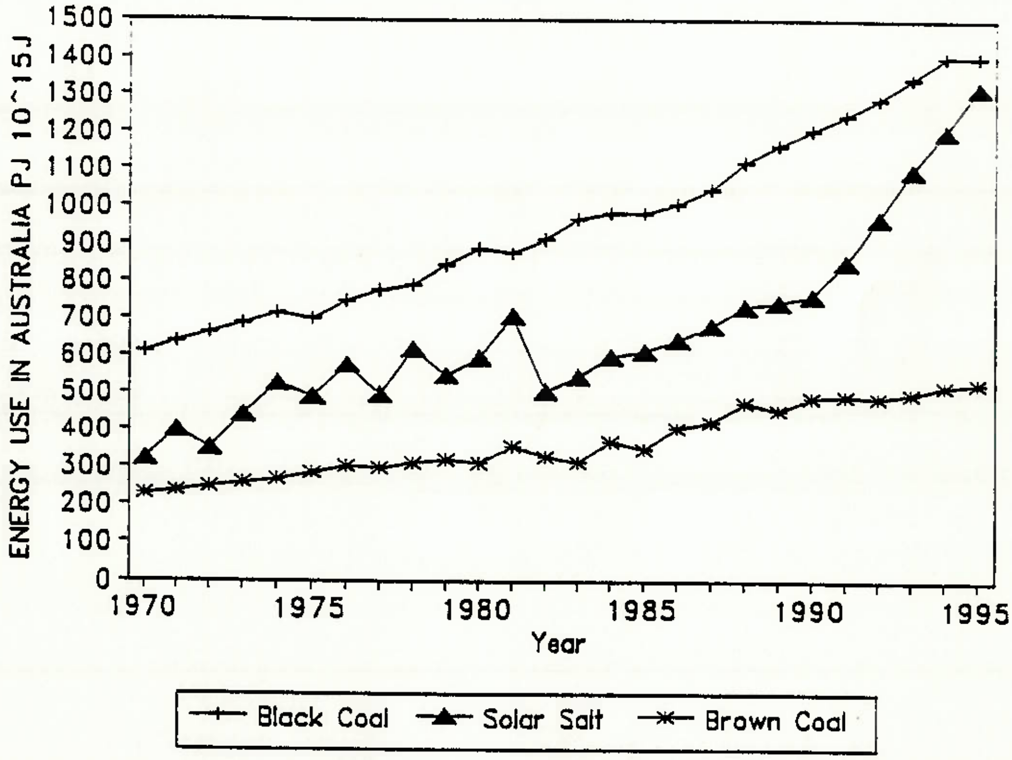
- Australian solar salt companies currently operate over 28 000 hectares of evaporative solar ponds and are expanding to over 45 000 hectares. They are adding 3 000 to 5 000 hectares per year or growing at more than 10% per annum.
- They currently produce about 8 million metric tons (t) of salt per year and evaporate about 344 million m^3 of water.
- Solar evaporative ponds collect about 840 PJ per year nett (or 1 600 PJ gross) equal to 20% nett (or 39% gross) of *total primary energy use* in Australia. Present expansion is increasing this to 1 300 PJ per year nett solar collection.

England previously used coal to produce salt for export. Solar energy has now effectively displaced all such coal used in making salt. Nett solar energy commercially collected to make solar salt already exceeds total brown coal use in Australia and is projected to soon exceed total black coal use, as illustrated in Figure 11!

This massive solar use of 20% of total primary commercial energy is not reported in official statistics, while the 0.1% used in domestic solar water heaters is so recorded, as a result of incorrectly assuming that salt production is *passive* and does not displace conventional fuels, while solar domestic water is *active* and does. But both involve the construction of solar collectors for the purpose of gaining the solar energy, and both have alternative processes for gaining their product.

In the case of the ANU/ANUTECH solar technology, only a small change is needed to be competitive with baseload power.

Figure 11 — Australian Coal and Solar Salt Energy Use (from Hagen and Kaneff 1992).



6.2 Potential Solar Thermal Growth and Installation Rates

As discussed in Hagen and Kaneff [1991, 1992] and in Section 6 (above), rapid change and growth can occur when there are strong economic incentives, appropriate legislation or strong private or public effort. The case of Australian solar salt production has already been mentioned.

Some countries have achieved substantial and rapid changes with focussed policies and actions in achieving energy supply conversion, for example after the 1973 OPEC oil crisis. As reported in Hagen and Kaneff [1992], Denmark converted its electricity generation from 66% coal-based in 1966 to 78% oil-based by 1972 — or a conversion rate of 8% per year. Following the oil shock of 1973, Denmark then reversed its fuel dependency to achieve 87% coal-based by 1981; that is, involving a conversion rate of some 8% per annum. By 1988, Denmark's energy was 88% coal-based and oil usage had dropped to 6.6%. France achieved similar major changes between 1979 and 1989 by changing its electricity dependence from oil-based to nuclear-based, increasing nuclear electricity generation by 270 TWh_e per year.

Similar major developments have occurred in recent years with respect to energy efficiency and structural change. From 1972 to 1987, Danish total energy consumption remained sensibly constant while Gross National Product (GNP) increased 30%, with a reduction in energy intensity of 1.7% per annum. Other countries have achieved similar results: by strongly encouraging energy efficiency and structural change, and providing large low interest loans to install efficient equipment, Japan's ratio of energy/GNP dropped 40% from 1973 to 1990 — a reduction of 2.2% per annum. A major additional benefit has been the resulting economic competitive advantages on international markets.

The above aspects of energy developments give strong encouragement that rapid change and growth can occur with new systems, so long as conditions are appropriate. ABARE [1991] has shown that **conventional efficiency efforts, coupled with changeover of all electricity generation to natural gas, still would achieve only one-half the Toronto reductions of carbon dioxide or only about 2.3% per annum.**

Nor can the often quoted statement that a small country's carbon dioxide emissions do not amount to much on a global scale, be taken at face value: for example, in Australia the Business as Usual (BAU) growth to 2050 would result in Australia alone producing 23% of *globally allowable* emissions, assuming all other countries achieved carbon dioxide stabilization levels [Hagen and Kaneff 1992]. These factors provide further drive for the rapid implementation of solar thermal systems.

Finally and most significantly, a major impetus for the implementation of substantial solar thermal power concerns economic factors. A rapidly growing realisation of the unacceptability of further environmental damage caused by continued fossil and nuclear fuel use, has led to detailed studies of the costs of preventing such damage. While figures are still only approximate, the general conclusions [Hagen and Kaneff 1991, 1992] are that some 25% to 50% or more needs to be added to the average Australian electricity tariff (now approximately 8 to 9¢/kWh) to include these externalities.

Incorporating total costs to society similar to those legally established in many industrialized countries dramatically changes relative economies of solar thermal systems, making them cost competitive with fossil fuels now.

Furthermore, with the advent of the ERC/ANUTECH SG4 collectors, costs (as yet unvalidated however) are expected to fall below those of Figure 8 and Table III, to the values indicated in Figure 12 (please note $US). This may be a most influential reason for accepting solar thermal power for mass utilization.

Growth and installation rates are determined by factors such as those discussed; but also depend on the physical resources and capacity to achieve rapid installation rates. In this respect, favourable factors include:

(a) The well-developed nature of the dish technology and the lack of need for significant in-field adjustments.

(b) The ability to use existing industry based on steel, glass and concrete, together with spare factory space and facilities from the motor industry.

(c) The availability of commercial turbo generator, heat transport network, and other plant required.

(d) The current involvement of industry (in the ERC projects) with a strong desire and capacity to move ahead rapidly.

(e) The interest within Australian electric utilities, NSW Office of Energy, the Electric Supply Association of Australia, and the Federal Energy Research and Development Corporation.

(f) The modular nature of solar thermal systems, which means that they can be very rapidly deployed once a commitment is made to installation.

(g) The already demonstrated fact of rapid solar thermal system installation.

   - LUZ International has already installed plants with 354 MWe solar thermal power in California. LUZ financed and installed one 80 MW solar thermal plant in 7.5 months.

Given similar management and productivity, businesses could very rapidly build and install hybrid solar thermal systems of Australian design once a commitment is made to do so, and the government implements policies and utility reforms to remove barriers and correct market distortions.

- One 100 MWe solar thermal plant per year per installation crew is achievable and one 400 MWe solar thermal plant per year per installation crew with the next generation technology should be practical. This is illustrated in Table V.

The 2 MWe Tennant Creek plant is seen as a preliminary to the commercial demonstration of much larger systems, but is still of adequate size to demonstrate the technology.

6.3 Commercial Installation Rates

Crews to install solar thermal systems would be similar to those working on large commercial buildings, hotels or civil works, but much more automated, streamlined and efficient due to the repetitive tasks involved, especially with modular factory-based production. Based on demonstrated LUZ installation rates:

- A solar thermal crew of about 200 men could install 4 dishes per day or one 100 MWe solar thermal system with 800 dishes per year (eg within 10 months).

Extending this to further teams provides the features illustrated in Table V, which indicates that any reasonable need for fast provision of systems could be met, given the commitment and resources.

Figure 12 — ANU Big Dish Solar Thermal Target Electricity Costs (Note $US).

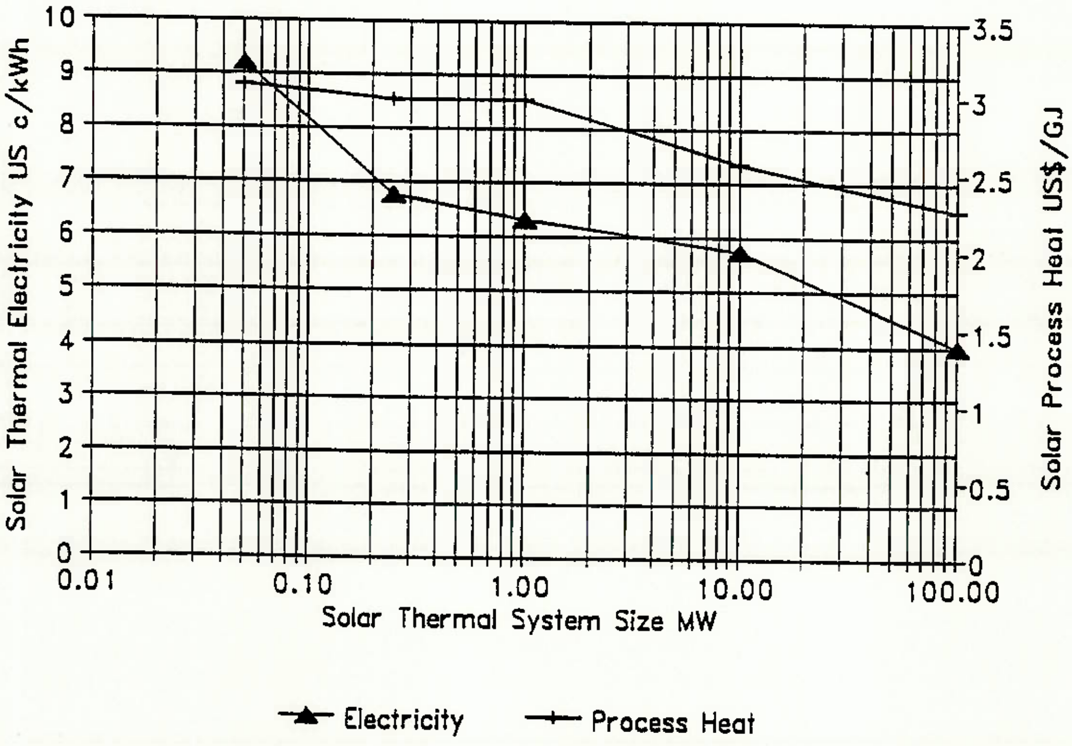


TABLE V(a)- POTENTIAL SOLAR THERMAL CREWS AND INSTALLATION RATES

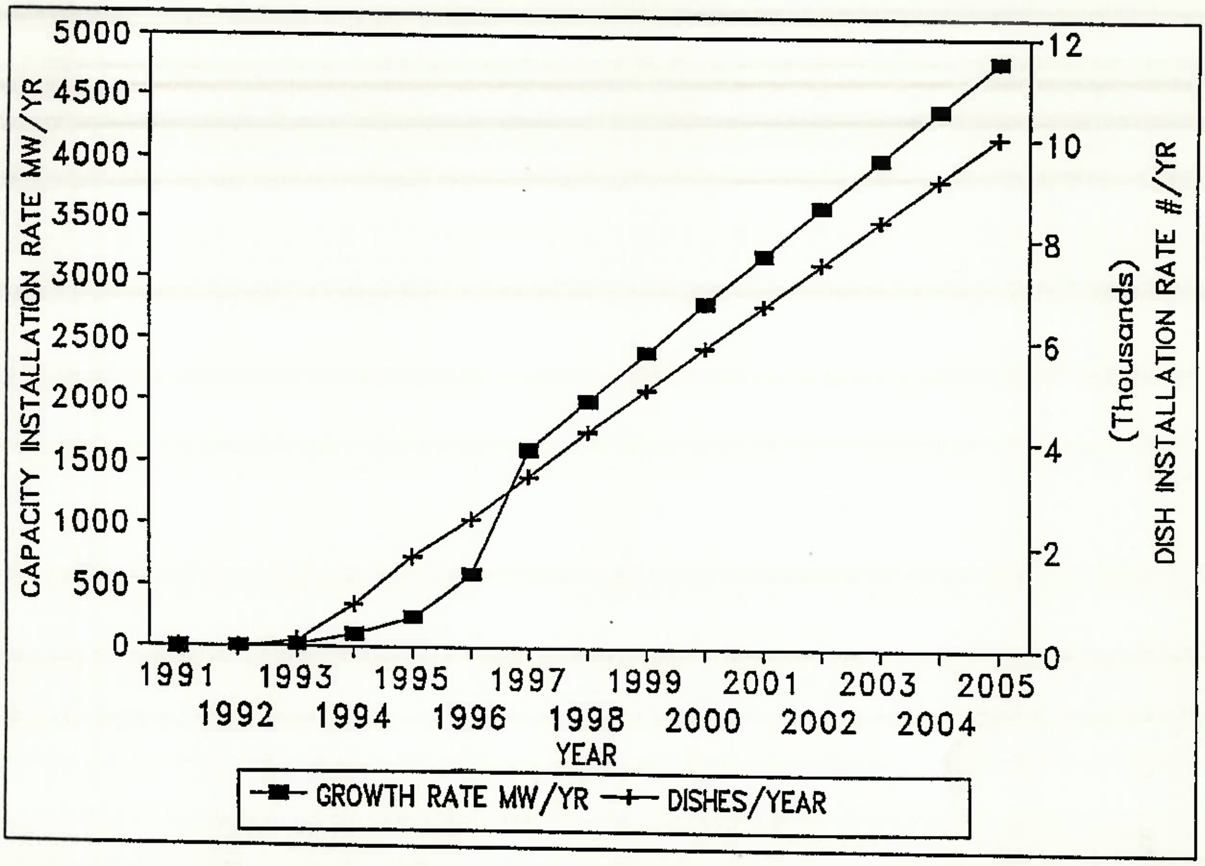


TABLE V(b)- POTENTIAL SOLAR GENERATION AND CO_2 SAVINGS

Year	Solar Power			Solar Electricity PJ	Coal Displaced PJ	CO_2 Displaced Mt
	No of Teams	No of Dishes	Capacity MW			
1992	1	1	0.05	0.000424	0.001	0.0001
1993	1	18	1.05	0.009	0.024	0.003
1994	1	146*	11.3	0.10	0.26	0.03
1995	1	997*	115	0.97	2.6	0.28
1996	2	2767*	355	3.00	8.1	0.86
1997	3	5272*	955	8.07	21.8	2.32
1998	4	8612	2555	21.6	58.4	6.32
2001	7	23642	9755	82.5	222.8	23.66
2006	12	65392	29755	251.5	679.6	72.16

Base rate 835 dishes/team/yr, @ 100 MW/yr/team then 400 MW/yr/team.
* changing from 3rd to 4th generation dishes. Adapted from Hagen & Kaneff 1991

7. Major Dish Application Areas

The following are attainable either immediately or in the next few years:

7.1 Electricity and Process Heat

Electricity and process heat provision have already been considered in Sections 5 and 6. Generally, installations can be implemented now if based on dish/engines (ground-based engines) and dish/central plant in the case of electricity generation, or single or multi dish systems for provision of process heat.

Waste heat from dish/steam systems (whether single or multi-engine and turbine plant) can be used for various low temperature applications, for example desalination and building heating. Dish/Stirling units, which produce electricity only, are not at this stage available as cost-effective units.

Very Large Solar Thermal/Thermochemical Systems

The 400 m^2 aperture paraboloidal dishes outlined in Sections 5.5 to 5.8 and Section 6, allow individual solar thermal electricity and process heat generating systems of up to some 200 MWe to be viable, using water/steam as a heat transport medium. Such systems may need storage options which can be selected from, for example, technologies outlined in Section 7.2 — some of these options are not yet commercially available.

The efficient collection of solar energy from very much larger areas and energy transport over long distances are, in principle, practicable via the conversion of concentrated solar heat into chemical energy by thermochemical reactions carried on in a focal region reactor. While several thermochemical reactions appear favourable, that most appropriate for the purpose due to its simplicity and cost effectiveness is based on the dissociation and resynthesis of ammonia, as studied by the Energy Research Centre over a number of years [Carden 1977, 1987; Lovegrove 1992].

The thermochemical approach depends on converting solar heat energy (at high temperature and pressure in the presence of a catalyst) into chemical energy in a solar-driven reactor, transferring the sensible heat to the incoming ambient-temperature material (for example ammonia – NH_3) which is heated to a temperature near the reactor temperature as a result of heat from the outgoing dissociated components (for example N_2 and H_2). This allows both dissociated and non-dissociated materials to be transported at ambient temperatures (in the case of an ammonia system, transport can be effected in mild steel tubes at pressures of 100 to 300 atmospheres with very small pumping losses $\approx 0.1\%$ throughput energy). Efficiency of conversion at the collectors can be arranged to be over 95%; storage over long periods is effected at ambient temperature and at normal system pressure; and synthesis can occur whenever the heat energy is required, again being conducted at high temperatures and pressures in the presence of a catalyst.

Overall collection transport and synthesis efficiency of over 60% can be attained (for high quality heat) but the rest of the collected solar heat is also largely available at lower quality and still suitable for use for desalination or similar lower-temperature applications. Using direct work output from such an ammonia thermochemical system allows overall solar input to electricity efficiencies of 26% to 33% (depending on whether non-isobaric or isobaric systems are used). A feature of this approach is the capability of long-term storage (months or longer if required). [A further advantage allows the output from the plant to produce hydrogen from water and nitrogen from the air, with the production of extra ammonia by the synthesis, and the availability of various valuable gases — oxygen, neon, xenon, krypton, etc — as additional products.]

Other thermochemical reactions, for example the steam or carbon dioxide reforming of methane, can also be employed for energy storage and transport (Section 7.3) but the ammonia-based approach has a number of advantages in producing very large solar systems with storage. These technologies are currently at the laboratory stage. Natural gas-type pipelines could carry the N_2, H_2 mixtures from solar collecting arrays to central plant, a feature of this approach being the ability to decouple the solar collector arrays from point of energy use and of storage — considerable energy storage being also available in the transmission pipelines.

7.2 Energy Storage

Means, at various levels of development, are practicable for achieving energy storage, including:

Pumped storage.
Sensible heat storage.
Heat storage in phase change materials.
Thermochemical storage (can be very long term).
Biomass production and storage.
Storage by converting renewable energy into various fuels and energy-rich products, for example

- Hydrogen, Ammonia, Methanol, Ethanol — via various solar-driven processes
- Solar gasification of coal, natural gas and biomass — the solar energy is then stored in the syngas gas ($CO + H_2$) so produced.
- Solar/fossil combinations in general,
- Others.

7.3 Production of Solar Modified Fuels

Natural gas is being hailed as the replacement fuel for coal in the drive to reduce carbon dioxide emissions. As a substitute for oil and coal, natural gas can rapidly reduce air pollution over the decades but by itself cannot solve the problems of global warming. As already noted in Section 6.2, changeover of all electricity generation to natural gas still would achieve only one-half the Toronto goal for carbon dioxide reduction and, consequently, can be considered only a stepping stone towards a sustainable energy future.

To solve the long term energy problems, we must achieve an appropriate transition to an energy efficient economy founded on renewable energy, over the next few decades. During this transition period, solar/fossil combined systems can moderate emissions from fossil fuels — gas, oil and coal — by employing solar-driven gasification processes which are already wellknown commercially, except for the solar drive, which is now becoming practicable as a result of the development of suitable large solar concentrating collectors.

Employing solar/fossil combined systems for a period of several decades, will allow a largely renewable energy-based energy infrastructure to evolve and to be established without serious dislocation of present energy systems, while providing substantial and increasing improvement in emissions.

The use of solar energy to modify hydrocarbon-based fuels to allow more-benign utilization and to produce new hydrocarbon-based fuels, is now potentially practicable, requiring R&D to produce appropriate solar-driven reactors, and can form the basis of massive new industrial developments. [Items (c), (d), (e) and (f) below are developed further in Hagen and Kaneff, 1991.]

(a) Rationale and Benefits

As a result of research carried out in various laboratories over the past 12 years, fossil fuels can be modified by processes driven by high temperature solar heat and/or photon flux from recently developed concentrating collectors — allowing more energy to be available when using coal, natural gas, bagasse and biomass in general, with less overall pollution.

This approach:

- Provides energy for the process without the generation of greenhouse gases.
- Increases the energy content of the original fuels (eg natural gas, coal, bagasse or biomass in general), with less overall pollution as a result of storing a large fraction of the applied solar energy in the product gas or liquid.
- Provides fuels in gaseous or liquid form, allowing ready storage and/or transport and utilization (and in the process, effecting storage and transport of solar energy).
- Reduces the potential polluting effects after modification has been achieved.
- In the case of natural gas modification, the product gases (CO, H_2) are far less greenhouse influential than the original natural gas in the event of leakage into the atmosphere.
- Provides syngas (CO, H_2) from a range of hydrocarbon-based feedstocks — for example (apart from natural gas), all coals, oil shale, bagasse and biomass in general.
- Can provide:
  - Fuels for burning, eg for
    Town Gas
    Process Heat
    Electricity Generation via gas turbines (especially steam injected gas turbines and gas turbine/steam turbine combined systems with superior efficiency).
  - A starting point for a large part of the chemical industry including the synthesis of ammonia, methanol, various monomers of plastics, and others.
  - A means for producing methanol (or petrol) for transportation.
- Provides an approach for utilizing solar energy on a continuous basis — the solar modified fuels being used to supplement the solar energy when required; much of this supplementary energy is stored solar energy.
- Relies on the use of already largely-available technology and can be implemented with relatively small R&D effort; can therefore take effect rapidly.

- Is now practicable due to the development of suitable large cost-effective high temperature concentrating solar collectors (hitherto not available) by the Energy Research Centre of the Australian National University and related developments by Power Kinetics Inc (of Troy NY USA); as well as the progress in central receiver solar technology in USA and Europe.
- Solar gasification of fossil fuels and biomass and other thermochemical reactions provide the greatest long term potential for storing solar energy indefinitely.

(b) **Thermochemical Reactions**

The following wellknown thermochemical reactions (among many others) may be utilized, the endothermic energy requirements being provided by high temperature solar heat, driving an appropriate reactor:

Steam Reforming of Methane

$$CH_4 + H_2O + 206 \text{ kJ/mol} \longrightarrow 3H_2 + CO \quad (1)$$

$$CH_4 + 2H_2O + 163 \text{ kJ/mol} \longrightarrow 4H_2 + CO_2 \quad (2)$$

Temperature range 450° - 1000°C
Pressure range 1–50 Bar

Carbon Dioxide Reforming of Methane

$$CH_4 + CO_2 + 250 \text{ kJ/mol} \longrightarrow 2H_2 + 2CO \quad (3)$$

Temperature range 700°C — 1000°C
Pressure range 1–3 Bar

This process increases energy content by 44% or equivalently reduces CO_2 emissions by 30%.

Gasification of Carbon — Coal and Biomass

Water Gas Reaction

$$C + H_2O + 119 \text{ kJ/mol} \longrightarrow CO + H_2 \quad (4)$$

Boudouard Reaction

$$C + CO_2 + 162 \text{ kJ/mol} \longrightarrow 2CO \quad (5)$$

Solar gasification doubles the effective energy content of brown coal and thus gives a 50% reduction in CO_2. Brown coal normally produces some 67% more CO_2 emissions per tonne of carbon than natural gas. If the effective energy content of coal were doubled, then solar gasified brown coal will generate only 83% of the CO_2 from natural gas.

(c) **Solar Modification of Natural Gas and Recycling of Carbon Dioxide**

Natural gas refineries strip CO_2 and vent it to the atmosphere.

Recycling CO_2 by solar thermal-driven reaction with natural gas (methane — Equation 3 above) is 4 times as energy effective as displacing coal with natural gas.

The technology of storing heat energy by reacting CO_2 with methane to produce CO and H_2 is already proven (eg in Germany, Israel, USA) and is being applied to the storage of solar heat.

Solar concentrators now developed could recycle CO_2 from large scale natural gas combustion or coal-fired plants and displace a significant percentage of total CO_2 emissions.

i. **Methane**

Methane is 63 times as intense a greenhouse gas as is CO_2 in a 20-year time frame and 21 times as intense over 100 years [Houghton, Jenkins and Ephraums 1990]. Burning natural gas with a 3% system leak rate would thus generate more greenhouse effect than burning brown coal.

- Solar coal gas would thus have half the greenhouse impact of natural gas with a 3% leak rate.
- Correspondingly, recycling combustion gas from solar coal gas through gas turbines and combining it with natural gas through a solar gasifier would increase the energy content 44%.
- Solar gasifying methane in accordance with Equations 1 and 2 would thus reduce fuel use and carbon dioxide from methane by 30%. Solar gasified methane would further reduce greenhouse gas impact by 21% for each 1% leakage rate of methane.
- Solar-gasified brown coal (solar coal gas) or solar-gasified natural gas with recycled CO_2 (solar methane) could thus become the fuels of choice rather than normal natural gas, as having the least greenhouse impact.
- The solar gasification of methane could also be used to convert methane collected from coal fields, thus reducing emissions of this significant greenhouse gas.

ii. **Refining/Pumping Natural Gas**

Natural gas has the highest energy intensity in terms of the energy requirements for deliveries to final demand. Wilkenfeld and Associates [1991] estimate that in 1986/87, natural gas required 40 PJ in processing and pumping and leaked 10 PJ to deliver 496 PJ supply. This released 3.9 Mt[2] CO_2 and 0.2 Mt CH_4, or 8% of total natural gas delivered and 1.7% of total CO_2 emissions.

Pumping required 8 PJ while another 32 PJ were burned in wellhead production treatment. These released 0.4 Mt and 1.7 Mt CO_2 respectively. The wellhead treatment strips CO_2 from the methane. This process vented another 1.8 Mt CO_2 to the atmosphere in 1986/87 [Wilkenfeld et al Figure 3.2]. The pumping will steadily increase as the initial high pressure at wellheads subsides and demand increases.

The equipment and costs to strip CO_2 and vent it are already included in conventional natural gas processing. This provides an attractive situation to add solar thermal power to recycle the CO_2. The solar receiver/reactor is the primary technology that remains to be perfected and commercialised and added to these costs. [This is an area of research and development being studied by the Energy Research Centre.]

The 32 PJ at the wellhead processing is equivalent to 1000 MW of thermal power. At this scale, solar thermal paraboloidal dishes provide heat for less than \$3/GJ (1.1¢/kWht).[3] This is competitive with delivered costs of natural gas.

[2] Mt ≡ Million tonnes.

[3] kWht ≡ kilowatt hour thermal.

Most of the wellhead processing and pumping stations are in remote locations with excellent solar potential. Carbon dioxide is already being chemically stripped from the wellhead natural gas and is currently vented to the atmosphere.

- Solar gasification can eliminate venting CO_2 to the atmosphere from the wellhead gases as well as the emissions from burning natural gas to run the refinery.

Hybrid solar thermal systems are already cost competitive with future gas-fired peaking alternatives (eg less than 6.6¢/kWh). When externalities of about 2¢/kWh are included to account for pollution costs and depletion rents (charges or royalties), and when natural gas is priced at export or import parity, then solar thermal power in full scale production to pump natural gas is likely to be competitive with using the gas itself for pumping and in the refineries.

Locations along gas pipelines, by definition, have the gas available for hybrid solar thermal power. Conventional wisdom suggests that gas at such locations is too cheap to compete against. However, this is a matter of pricing and legislation regarding the externalities and resource depletion.

Gas is a valuable resource that is being rapidly depleted. Currently no rents (charges or royalties) are applied to gas usage to develop alternative renewable energy sources while present reserves are projected to be depleted in about 80 years.

The gas in NSW and South Australia contains 13% CO_2 by volume compared to 6% Australia-wide. These 2 states account for 38% of all gas consumed. These very high CO_2 contents suggest the greatest potential for major impact in a few locations.

iii. Carbon Dioxide Recycling from Natural Gas

High temperature solar heat could be commercialised to react natural gas with CO_2 (stripped from natural gas or combustion systems) at temperatures between 700°C and 1000°C at only 1 to 3 atmospheres pressure (as in Equation 3) [Levitan, Rosin and Levy 1989]. Assuming 70% nett efficiency, this gives 123 kg CO_2 recycled/GJ solar energy collected. This is better than displacing coal combustion.

- Even at 70% thermal efficiency, such solar CO_2 recycling would eliminate twice the carbon dioxide emissions compared to directly displacing natural gas emissions (and 130% of brown coal emissions).
- The cost of the solar heat to thus recycle CO_2 is effectively Au$24/tonne CO_2 (US$17/ton CO_2) at 70% efficiency with the ANU big dish. [Need to add the cost of chemical reactors to obtain full cost.]

The costs of the solar energy in such recycling are far below cost estimates to control CO_2 by conventional methods typically from US$200 to $300/ton (see Tables VI and VII).

Most of the energy input by the solar system is retained in the product gas. Solar gasification of methane by combining it with CO_2 and generating electricity by expanding the hot product gases increases the energy outputs by 28% compared to the input natural gas. This effectively stores solar energy in the natural gas stream for later use and reduces the amount of natural gas required to deliver a given amount of energy.

This reactor technology has been tested and is available now for commercialisation after developing appropriate solar-driven reactors. Current paraboloidal dish technology can handle the temperatures and pressures.

TABLE VI - CARBON CONTROL COSTS (1990$US)

Region	Target Year	% Reduction from Base	US$/Ton CO_2	Source
MACRO (Tax-Driven) Studies				
US	2030	57	300	Naill, Belanger and Petersen
US	2020	32	68	Jorgenson and Wilcoxen
US	?	42	119	Nordhaus
Japan	2005	16	6,480	World Wildlife Fund
MICRO (Technology-Driven) Studies				
US	2010	59	292	World Wildlife Fund
Canada	2005	55	2,488	World Wildlife Fund
Denmark	2030	68	208	Danish Ministry of Energy
NY State	2008	31-43	440	Sanghi (NY Energy Office)
California	2008	37	287	Spectrom Economics
Oregon	2005	32	111-296	Oregon Dept of Energy

Source: Chernick, Paul and Caverhill, Emily, "Methods of Valuing Environmental Externalities", The Electricity Journal, March 1991, p 46-53.

TABLE VII- GENERATION COSTS & COSTS OF AVOIDING CARBON EMISSIONS ASSOCIATED WITH ALTERNATIVES TO FOSSIL FUELS (1989 $US).

Fossil Fuel Alternative	Generating Cost[1]	Carbon Reduction	Estimated Pollution Cost	Carbon Avoidance Cost[2]
	(US cents/kWh)	(percent)	(US cents/kWh)	(US dollars/ton)
Improving Energy Efficiency	2.0-4.0	100	0.0	<0-16[3]
Wind Power	6.4	100	0.0	95
Solar Thermal Power (Dish)[4]	6.0	100	0.0	<100
Geothermal Energy	5.8	99	1.0	110
Wood Power	6.3	100	1.0	125
Solar Thermal Dish/Gas/Steam Turbine[4]	5.5	92	0.1	100-140
Steam-Injected Gas Turbine	4.8-6.3	61	0.5	97-178
Solar Thermal (Troughs with gas)[5]	7.9	84	0.2	180
Nuclear Power	12.5	86	5.0	535
Photovoltaics	28.4	100	0.0	819
Combined-Cycle Coal	5.4	10	1.0	954

[1]Levellized cost over the life of the plant, assuming current construction costs and a range of natural gas prices. [2]Compared with existing coal-fired power plant. [3]Some energy efficiency improvements cost less than operating a coal plant, so avoiding carbon emissions is actually a benefit not a cost. [4]Estimates based on paraboloidal dishes [Kaneff]. [5]Based on LUZ parabolic troughs and natural gas augmentation. SOURCE: Worldwatch Institute estimates [see Flavin C. "Slowing Global Warming", pp 17-38 in Brown (1990)]; except for items 4.

(d) Solar–Coal Gasification and Recycling Coal Carbon Dioxide

Using the water gas reaction (Equation 4) allows coal to be gasified with the aid of high temperature concentrating collectors.

When further developed, high temperature high pressure solar gasification of coal could effectively increase the energy content of coal by 43% [Fletcher 1991]. Generating electricity by expansion of the high temperature gases could potentially provide an additional 20% of the original energy as electricity (ie equivalent to 53% of the original primary energy for a 101% total increase in output).

Direct solar gasification reduces coal usage by 50%. Using such gas as backup for solar thermal systems would permit halving coal usage again. Using high efficiency aeroderivative turbines or combined gas/steam turbines instead of coal systems would require only 75% of what is left.

- **Solar gasifying with turbine expansion effectively doubles the energy available from coal or bagasse. It could give a 50% REDUCTION in fossil energy to make fuels compared to a 50% INCREASE in conventional fuel synthesis through coal gasification.**

Recycling Coal Carbon Dioxide

Carbon dioxide recycling technology could be applied to concentrated sources of CO_2, such as at coal-fired power plants or cement manufacturing facilities, using the Boudouard Reaction (Equation 5) or Equation 3 involving natural gas. Natural gas pipelines could be routed past such sites. The solar energy could recycle CO_2 by reacting it with natural gas and thus store the solar energy in the gas products returned to the natural gas pipeline.

Normally, recycling or sequestering the CO_2 produced during combustion is an expensive proposition. But solar coal gas is much cleaner than coal or conventionally gasified coal and there will be fewer problems with acid precipitation. The exhaust gases could thus be collected and the CO_2 stripped. This could in turn be reacted with methane or natural gas in a solar gasifier, increasing the energy in the input gases by 44% to displace up to 30% of natural gas.

By employing solar energy to dry brown coal, up to 14% less brown coal would be used; with gasification of any coal, usage could be reduced up to a further 50% and up to 75% to 80% by employing hybrid solar systems with efficient combined systems compared with conventional coal generation.

(e) Petroleum Refineries

The 8 petroleum refineries in Australia process some 33 million tonnes of crude petroleum per year and consume about 101 PJ or 2.6% of Australia's energy consumption in the process. The refineries purchase 4.3 PJ of electricity and 10 PJ of natural gas [ABARE 1991].

About 87 PJ of the refinery feedstock and petroleum products are used to heat and process the crude oil. This is equivalent to 9% of 975 PJ of fossil fuels used in electricity generation and is mostly in the form of byproduct light gases for which there is no other apparent market. About 67% of the energy used is at 350°C or below, while 33% is used at 500°C to 520°C.

From an energy quality (exergy) point of view, the light byproduct gases have much greater potential to generate electricity through a gas turbine than for direct process heat at 350°C. Correspondingly, solar thermal equipment could be used to generate part or all of the process heat required and displace this higher quality gas.

- When combined with solar thermal process heat, the consumed 101 PJ of energy (mentioned above) suggests the potential for generating well over 2000 MW of peaking or intermediate power (at 20% to 50% load factors) or over 250 MW in each of the 8 refineries in Australia.

(f) **Solar–Biomass Gasification**

As a source of carbon and carbon-based fuels, chemicals and other materials, biomass has the potential to almost wholly recycle carbon dioxide and, so long as the complete ecological cycle is understood and safeguarded, presents an attractive option for production of fuels and other products.

That careful attention needs to be directed to a sustainable overall cycle which does not result in deterioration of soil, water or air, cannot be stressed too strongly; but given such care, the use of biomass represents an extremely important resource, especially because much of the current availability of biomass — including crop 'residues' and 'wastes' — already represents a hardly utilized major resource, whose sensitive utilization will cause improvement, not deterioration, of the environment and needs no extra land commitments.

As in the case of coal, major future applications exist for solar gasification of biomass; and solar gasification represents the greatest long term potential to store solar energy for long periods.

In the same manner that coal can be gasified by high temperature solar energy to produce syngas (CO, H_2) giving a 50% reduction in fossil energy to make fuels, compared to a 50% increase in conventional fuel synthesis through coal gasification, so bagasse, wood chips, straw from wheat and rice, as well as many other biomass materials can be used as the carbon source material to produce syngas. Using these sources on a sustainable basis with solar gasification can provide town gas, process heat, fuel for gas turbine cycles and transport fuels which are almost completely renewable and produce recycling — not increase — of carbon dioxide.

Thus:

- **Solar thermal energy for solar gasifying biomass materials (bagasse, wood chips, straw from rice and wheat, rice hulls and many others) and producing methanol (by further solar-driven processing) will eliminate all nett carbon emissions from transport fuels and most of such emissions resulting from chemical processes employing syngas or methanol as a feedstock, as well as from normal syngas applications including town gas, process heat and powering gas turbines for electricity generation.**

These developments can prove substantial even in the comparatively near term.

7.4 Water Desalination and Land Reclamation

Australia, along with many other parts of the world, has much saline groundwater but is short of potable water; and has also, as a result of lack of prior knowledge, caused much soil degradation due to salinity problems which have arisen as a result of inappropriate landclearing and irrigation practices. Use of comparatively small numbers of dishes driving pumping machinery to lower watertables and purify the pumped saline water, provides a means for reclaiming land, lowering the watertable, and providing excellent water for valuable crops and human consumption; and producing salt as a saleable byproduct. In other areas, electricity generation and potable water can be simiarly produced (from saline groundwater).

Little technological development is required for such applications; only the commitment to do so. Initial studies of costs appear very promising.

7.5 Water Detoxification

A wide range of problems exists in relation to contaminated water, resulting from industrial, agricultural and other processes. Such water may be readily accessible as an output from industry or may already have entered the groundwater systems.

Typical problems include:

- Treatment of waters containing toxic metals and organic complexes of metals, occurring either separately or together. Both problems appear amenable to solution by the photocatalytic removal of the metals and, in the case of organic complexes, the process simultaneously reduces the metals while oxidising the organic materials [Prairie and Evans 1992].
- Destruction of organisms in aqueous solutions [Link and Anderson 1992].
- Solar detoxification of groundwater [Kelly and DeLaquil 1992].
- And many others.

Solar energy offers considerable advantages in all cases, particularly due to the provision of high energy photons in the near ultraviolet portion of the spectrum, which permits sunlight to accelerate the driven reactions which would otherwise be extremely slow. Much R&D is necessary before commercialization of processes can be achieved. Among the many advantages of solar detoxification is included the capacity to carry out the destruction processes where and when they occur by employing small local plant, eliminating the need for significant storage or transport of hazardous material.

The research of the ERC is developing suitable solar hardware, especially the concentrators and reactors, which could be applied to R&D in this increasingly important field, which has much to contribute to environmental improvement.

7.6 Solar Destruction of Hazardous Wastes

In recent years, concentrated solar energy has emerged as a highly promising and effective means for driving photocatalytic and photolytic hazardous waste destruction processes. A major problem with conventional waste disposal methods is that pollutants are rarely completely destroyed, causing significant toxic emissions from destruction equipment (for example from high temperature furnaces).

However, solar high temperature/high flux destruction can be carried out to completion in closed systems, powered by point focus collectors (central receivers and paraboloidal dishes) [Sanchez et al 1992, Link and Anderson 1992, Graham et al 1990, Alpert et al 1990]. A particularly attractive and convenient disposal means arises from the practicability of employing relatively small individual dish-based systems located at the point of toxic waste production, so obviating the need for transporting dangerous materials to central destruction plant.

The field of solar thermochemical/photonchemical destruction is still in its early stages of what promises to be a highly advantageous development area over the next few years. The ERC has worked in thermochemical systems since 1971 and, combined with current big dish development, is in an uniquely advantageous position in Australia to carry out R&D in solar destruction of hazardous waste (the solar power hardware is already available).

8. Research and Development Directions

Solar thermal power can be utilized now on an increasingly large scale. Moreover, many known innovative concepts can be applied to improve the technology and economics, towards the target overall efficiencies for electricity generation of over 60%, installed costs of $500/kWe and generation costs of less than 5¢/kWhe; other approaches which are apparent, but yet to be researched, can also be addressed.

The great scope for further improvement includes use of new fundamentals, new collector concepts with fixed ground level foci, substantial changes in processing materials to produce the necessary hardware; and means for coping with the ever-demanding climatic in-field conditions. But above all in the real world, cost and cost-effectiveness are paramount and need determined attention.

Research and development should be biassed in favour of those areas which can lead to rapid mass utilization and which can achieve substantial performance and/or economic improvements in technology and can be utilized to make a major contribution.

In this respect, those technologies which can clearly be applied cost-effectively on a large scale the earliest, should receive highest priority and the greatest funding; but always maintaining funds for longer term projects which hold obvious promise, including those still at a fundamental stage of research.

This philosophy suggests the following order of priority for funding and of development:

(a) **Solar Thermal Electricity and Heat Production — Immediate Applications Combined with Continuing Research and Development**

Technology for solar electricity and heat supply is already well developed and cost effective in many situations — and can be developed further very rapidly to considerably widen its scope and areas of viability.

Figure 6 suggests the many areas for continuing R&D, the main thrust for which should be:

- Further collector development to optimize configuration, size, cost, manufacture.
- System optimization, control strategies, protection, operation.
- Identification, by considerations of exergy, of system components which can be improved with significant gain.
- Study of best match between heat storage, backup, fossil fuel augmentation approaches, including combined cycle backup.
- Means for utilizing existing energy storage systems cost-effectively.
- Developing manufacturing processes which convert the basic raw materials more directly into the system components, thereby reducing costs.
- Encouraging industrial development via optimized processes of manufacture, administration and system installation.

(b) Thermochemical/Photonchemical-Based Systems — Commercial Within the Next Few Years

Development of solar-driven gasification of carbonaceous material:

- Study of solar gasification of coal, natural gas, biomass to produce syngas (CO, H_2) – solar-modified fuels (gaseous and liquid).
- Production of solar fuels.
- Production of solar chemicals and materials.

Development of solar energy storage and transport based on the above.

Development of suitable solar-driven reactors powered by large dishes — in the case of utilizing solar photon flux, need to develop suitable reactors and, when using ultraviolet light, may need special reflective materials.

Collaboration with the gas, oil and coal industry.

(c) Solar-Driven Catalytic Conversion of Toxic Materials — Commercial within This Decade

Closed cycle toxic waste conversion.

Water detoxification.

Development of suitable solar-driven reactors and materials, including more-effective catalysts.

(d) Utilization of Photochemistry, Photosynthesis and Photoelectrochemistry — Longer Term

Figure 13 lists (in ordered form) a selection of the many processes and products which may be solar-driven or solar-produced, separated into two main paths: thermoconversion and photoconversion. Combinations of the two paths is also possible. Apart from portraying the great richness and diversity of the associated science and technology, this diagram shows the still very early stage of development of solar energy utilization and the large potential yet to be studied, let alone developed. The potential imitating of photosynthesis is noted as probably leading to useful means for splitting water at ambient temperatures; absorbing carbon dioxide and forming carbohydrates; and absorbing photons (which drive the processes via electron action) as a direct conversion to electricity.

Herein is a vast potential for future development which has so far hardly been touched.

Figure 13(a) — Thermoconversion Path.

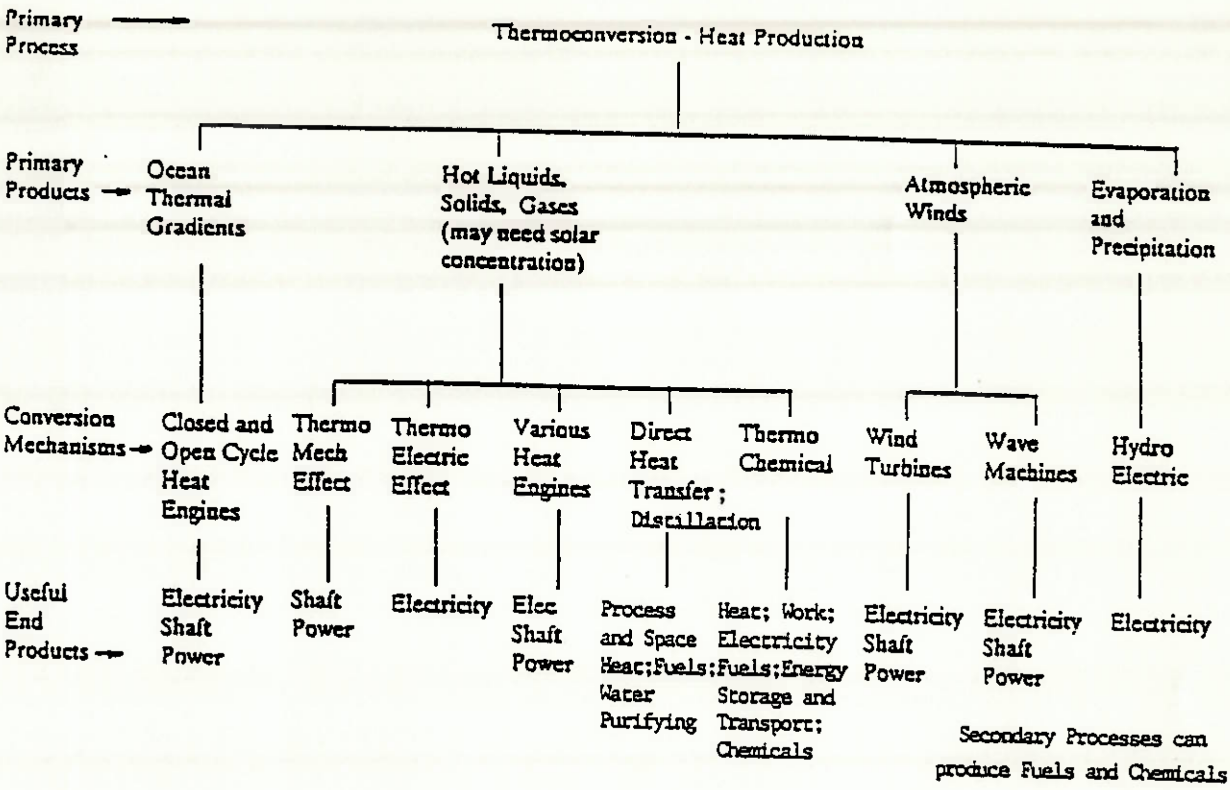
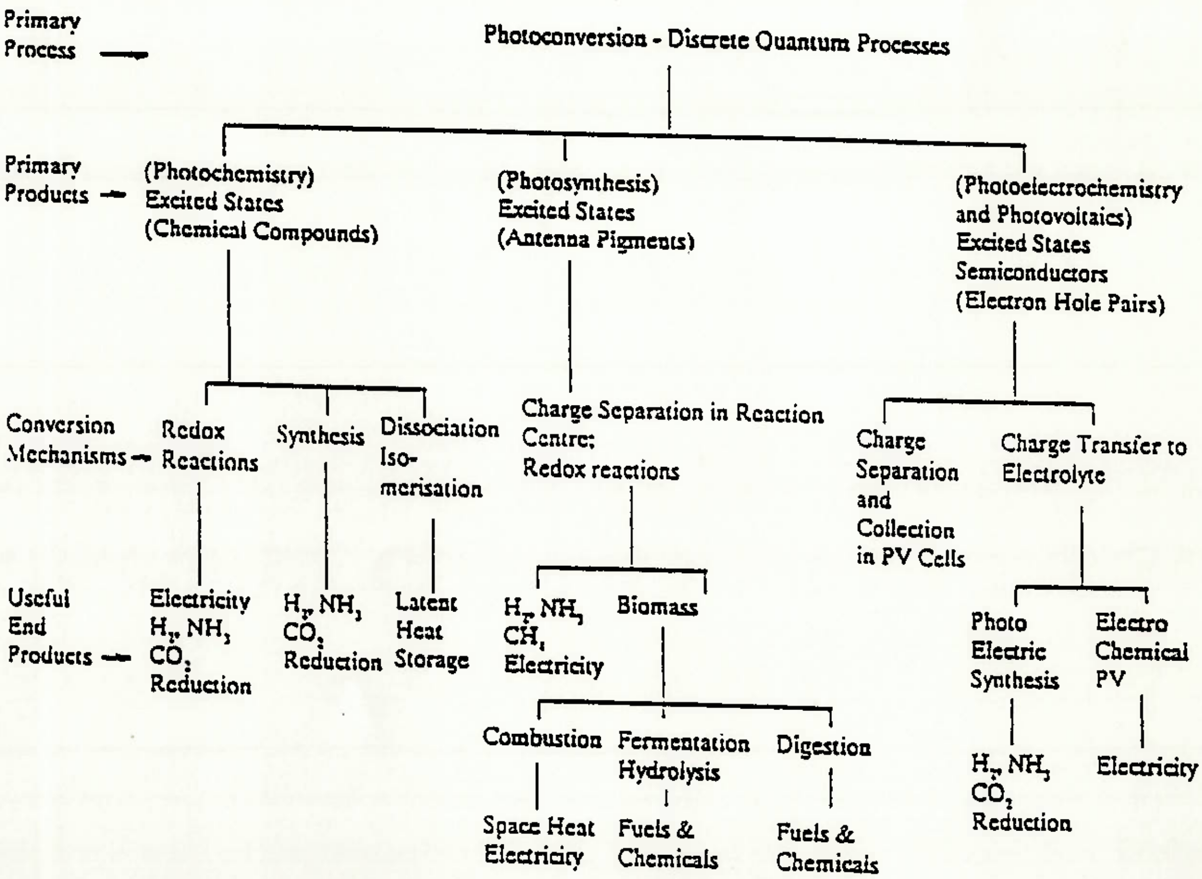


Figure 13(b) — Photoconversion Path.



The majority of products are fuels (hydrocarbon and nonhydrocarbon) and chemicals.

9. Conclusions

Solar thermal power has overcome the matter of credibility in being considered as a serious major energy source, as a result of both R&D achievements and installation of hundreds of megawatts of plant in California. Very large scale solar systems can be rapidly introduced, noting the example of salt companies which have some 300 square kilometres of collector area in Australia of solar evaporative ponds, and are increasing these at over 10% per annum, due to their competitive economics, and noting also the LUZ success in implementing 80 MWe parabolic trough systems in less than 8 months.

The first demonstration commercial Solar Thermal Power Station Project in Australia has commenced and is expected to be a forerunner of many larger systems in the years to come, especially as costs fall in response to improving technology and production, installation methods and rates. Systems up to 100–200 MWe in size seem practicable and cost effective when using steam energy transport. For much larger systems (1000 MWe), thermochemical transport and storage based on ammonia appears the most practicable and realizable within the present decade.

Many applications of solar thermal power systems are now practicable (on small or large scale) involving heat and/or electricity provision. A rich area for immediate development involves the application of relatively small systems for land reclamation and water desalination, both extremely pressing needs in many parts of Australia.

Various thermochemical systems are now becoming practicable in the laboratory and in pilot plants for many applications, including toxic waste conversion and water decontamination.

In the longer term, employing solar energy to modify various hydrocarbon materials has an extremely important role to play (with many near term applications being practicable already), providing advantages which include:

- The resulting reformed fossil materials produce less greenhouse emissions.
- Solar energy adds to the total energy value: the process stores some 70% of the applied solar energy.
- A means is available, by storing the resulting product gases, for storing and transporting solar energy and providing baseload energy supply.
- These approaches allow fossil fuels to continue to be used — but more benignly — and an impetus is given for solar development at the same time.
- Solar gasification of fossil fuels but preferably of biomass, gives a starting point for the production of other fuels (such as methanol) and of various chemicals.
- Solar gasification:
  Allows recycling of CO_2.
  Allows removal of sulphur from coal.
  Eliminates NO_x in gasifiers while eliminating fly ash/slagging in combustion.
  Allows direct use in gas turbines, for process heat and as a town gas.

Syngas produced by solar gasification could take advantage of natural gas pipelines for reticulation as a possible prelude to subsequent use of solar hydrogen. A national pipeline grid is to be completed within the next few years (as indicated in Figure 14), facilitating the nationwide transport and storage of solar thermal and other energy, allowing solar energy to be collected in the vicinity of such pipelines near coal, oil or gas fields, and utilized around the country where needed.

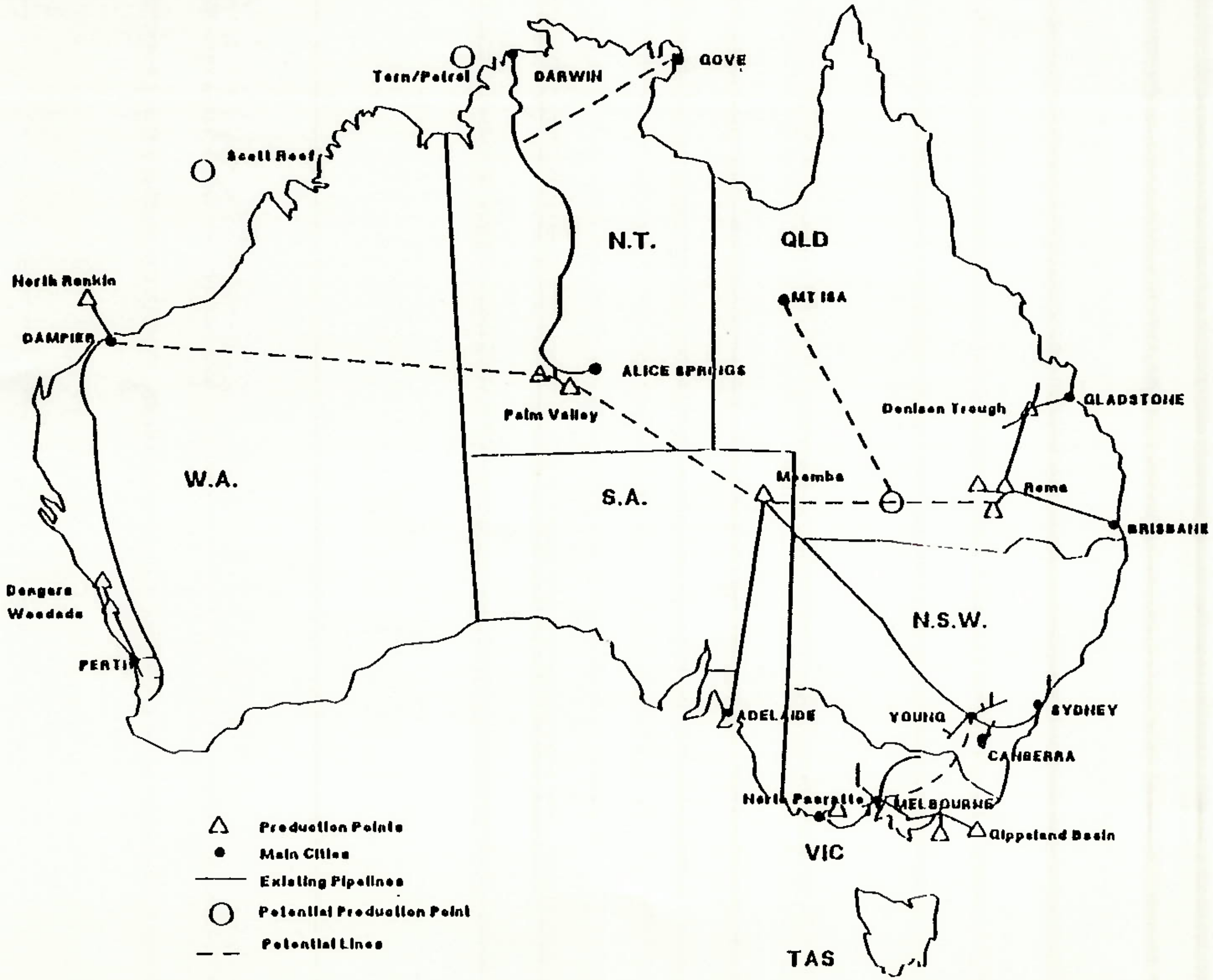


Figure 14 — Existing and Potential Australian National Natural Gas Pipeline Grid.

In the still longer term — 40 to 50 years — gradual transition to a largely solar-based energy system is expected to rely substantially on solar thermal energy in many forms — depending on society decisions and objectives.

The key to much of the developments discussed and the potential for further advances into new applications, has been the advent of large cost-effective paraboloidal dish collectors for producing high temperature solar heat and concentrated solar flux, combined with the use of already commercially available heat transport network technology and heat-to-work conversion machinery (turbo generators) and combined cycle plant. These techniques can be utilized now in small to very large systems and there already exists industry which can manufacture and install such systems.

In the near term, similar advantages apply for solar-driven chemical process involving gasification and other wellknown commercial reactions which need only the development of solar-driven reactors to produce an array of solar-modified fossil and biomass fuels, solar fuels, chemicals and means for energy storage and transport on a very large scale.

These developments can occur in the relatively short term without relying on major *breakthroughs*, given adequate support and encouragement to the benefit of all. In the longer term, even greater potential can emerge as a result of basic research and development of the many as yet untapped solar processes. But certain conditions must be satisfied in relation to the strategy and support for research and development of solar thermal energy: not only is a completely integrated approach necessary in considering overall systems, but a flexible and consistent technical policy which facilitates long-term research programmes is essential to allow the relevant technical knowledge and experience to be accumulated in this hitherto non-traditional area of human activity.

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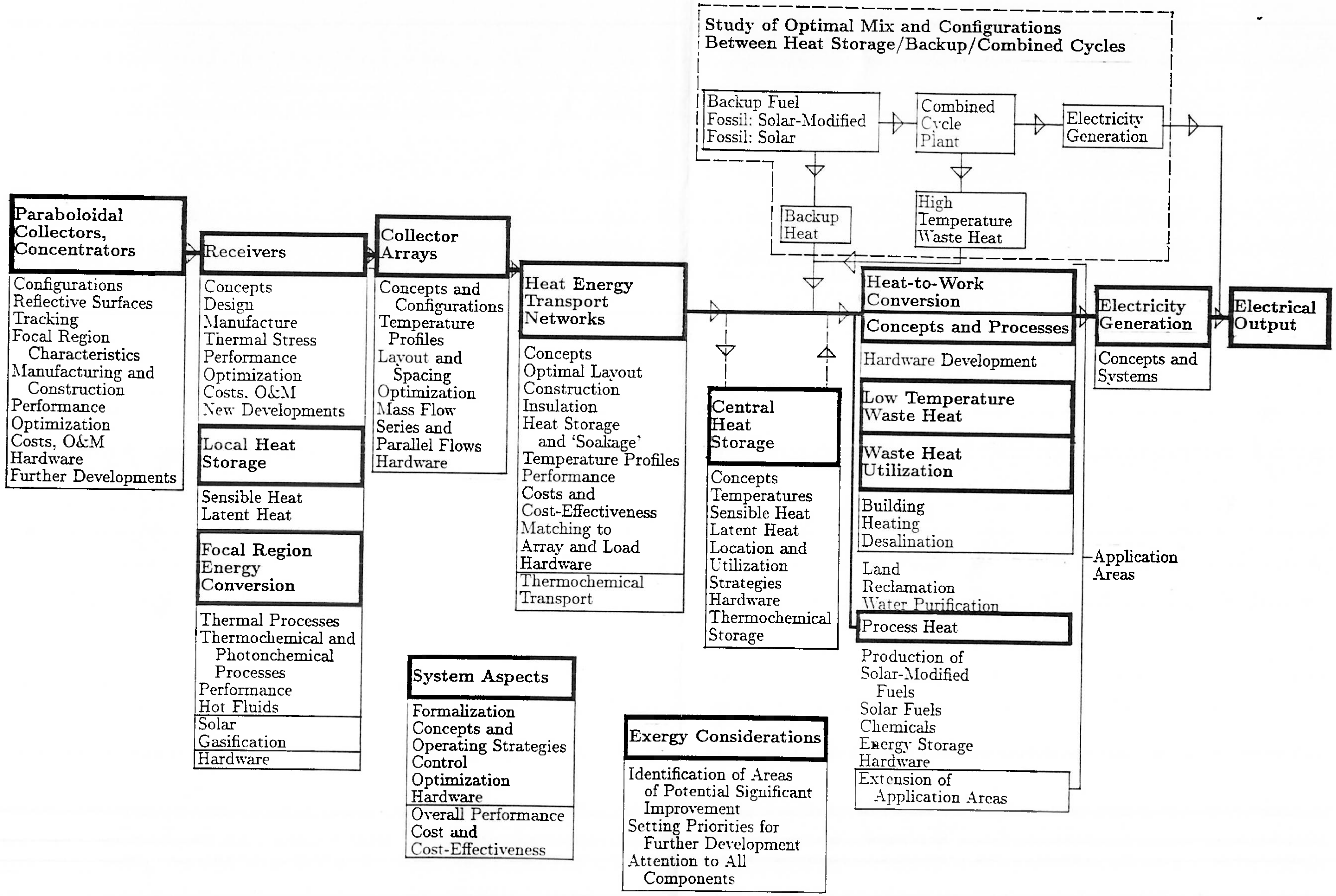

Figure 6 – Scope of ERC Solar Thermal/Thermochemical Systems R&D