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RESEARCH SCHOOL OF PHYSICAL SCIENCES

MASS UTILISATION OF SOLAR ENERGY

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MASS UTILISATION OF SOLAR ENERGY

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* Section A can be read alone and presents viewpoints and accounts which are justified or elaborated in Section B.

OVERVIEW

SECTION A - AN OVERVIEW OF THE SUBMISSION

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INTRODUCTION

Some $3^1/2$ years ago, a study was commenced in the Department of Engineering Physics on the feasibility of mass utilization of solar energy. Among the complexity of reasons for this decision was the strongly-held view that if solar energy is to make significant impact on available energy resources, large scale systems are necessary to take advantage of economy of size and of sophisticated science and technology.* Because of the low power density of solar insolation, large systems require large collection areas which in turn pose problems of transporting energy to enable its gathering together (corradiation) into a central installation for utilization or conversion to other forms of energy (for example, into electricity) for further transport to the user.

The concept of a steerable array of paraboloidal mirrors, managed by a shared computer-controller, emerged from the outset as a potentially viable solution to the collection problem and effort was directed towards developing appropriate systems. The problem of gathering energy from each collector was resolved in principle some $2^1/2$ years ago when thermochemical energy transfer employing ammonia seemed to offer the most appropriate solution. Since then, theoretical studies extending over a year or so have supported the initial promise. Moreover, a major advantage of thermochemical energy transfer became clear: it allows solution of the all-important requirement of storage of solar energy through storing the reactants used in the process.

By this time it was apparent that the approach held great potential for mass utilization of solar energy and warranted greater support. Whereas during the first year only one staff member was involved, two others were added in the second year and eighteen months ago staff was increased to six (including three technical staff). Experiments were built

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* Large systems enable highly skilled staff to be employed, making possible the introduction of complex techniques which would not be feasible or practicable on a smaller scale.

up to provide information on the dissociation of ammonia at high temperatures and pressures, in addition to developing further the mirror array system. This work is now progressing from the stage where confidence in the proposed system has been established and the major unknown factors have been resolved: it seems that a prototype system can be made to work.

We view work on mass utilization of solar energy (involving relatively high temperatures in order to take advantage of high thermodynamic efficiencies) as being complementary to the great amount of research and development in low temperature utilization which has been the central, almost exclusive pre-occupation, so far. Three years ago there was little evidence of significant prospect for large physical* systems utilizing solar energy. The position now is very different: authoritative studies in the U.S.A. on the central tower concept have given grounds for expecting development of methods for the mass utilization of solar energy which, given appropriate resources and effort, may compete economically with other large scale energy sources.

Several multimillion dollar projects are now being funded to produce prototype systems on the central tower principle. The Solar-Ammonia project at The Australian National University (ANU) has not had the advantage of the considerable resources necessary to carry out comprehensive studies matching those in the U.S.A., but we can invoke their results as being relevant to our system as regards economic aspects and can point to technological features which are at least as favourable as those of the central tower concept.+

The Solar-Ammonia and central tower systems have several advantages in common, for example, in both systems feasibility can be demonstrated on relatively small prototype units, obviating the need to build full scale systems and do not require scientific or technological breakthroughs for their realization. However the ANU system has the considerable

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* That is, based on Physics and Chemistry, not Biology.

\+ Please refer to Appendix III in Part II of this submission.

additional advantage that it can provide practicable storage to cope with daily fluctuations, with variations due to weather, and even with seasonal fluctuations in insolation.

This submission outlines our philosophy on solar energy research and development in both general and specific aspects and discusses in particular the prospects for the mass utilization of solar energy especially in relation to the ANU Solar-Ammonia system. Recommendations, both general and particular, are made for research and development in solar energy in the Australian context. The submission is in two sections:

A An overview which can be read alone, presenting viewpoints, and

B A more-comprehensive account of both general and particular aspects, in two parts, presenting detailed argument in justification of expressed views.

UNCERTAINTIES ABOUT FUTURE ENERGY SUPPLIES

Until comparatively recent times, energy has been available from various traditional sources in relative abundance. The previous two decades have finally driven home the fact that fossil fuels have a relatively short life and that nuclear energy is not without its problems unless breeder reactors can be developed to acceptable standards. The future of breeder reactors appears still uncertain and nuclear fusion has yet to be demonstrated as feasible in the laboratory, let alone in commercial application.

Australia's oil and natural gas reserves appear to be relatively small: our coal reserves, while comparatively large in relation to our own needs, are not large in world terms and it will probably become impossible to retain them exclusively for internal use even if we so desired, for a number of reasons, including the attraction of increasing world prices.

In the long term the only alternatives to solar energy appear to be fast breeder nuclear reactors and fusion nuclear reactors, but there are still grave doubts about both of these alternatives. In any event, Australia does not have the resources to develop nuclear fission or fusion energy, both of which require complex expensive science and technology. However, we do have the resources to develop the less complex and more environmentally acceptable solar energy, the only renewable energy resource, particularly as potentially successful approaches to solving the major problems have now emerged.

EVIDENCE THAT SOLAR ENERGY MAY BE VIABLE ON A LARGE SCALE

Viability depends on technological practicability and economic competitiveness.

Technological Practicability. Although many difficult problems remain to be solved, both the ANU Solar-Ammonia System and the USA Central Tower Concept appear technologically practicable for realising the mass utilization of solar energy: granted adequate funds, both approaches could be developed to full scale application. Because the ANU System allows storage, we are attracted strongly to it, particularly as it has other advantages* and appears more appropriate to Australian conditions.

Economic Considerations. Our assessment based on relatively meager information at this stage suggests that mass utilization of solar energy might be achieved at a cost of 5 cents per kWh.+ USA estimates range down to about 3 cents/kWh, using presently available technologies, suitably applied. Although this figure is above current city prices by a factor of 2 or 3, there are even now remote towns in Australia where present power costs are greater than 5 cents/kWh: furthermore, with the normal development of specialized manufacturing industry, assisted by increasing demand and the economy of scale, costs should reduce, so reducing the price of this form of solar power.

Comparison with Alternatives. Apart from the likely reduction in solar energy costs through the progress of technological development and the economy of scale and increased demand, it is very likely that the price of oil and coal will rise steadily over the next decades with rises also in the running costs of nuclear stations. The latter will be due to a variety of reasons, including the necessity to introduce more complex operating methods in the interests of safety, the

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* Please refer Appendix III of Part II. By employing our Thermochemical approach using Ammonia, storage could be added also to the Central Tower method.

\+ Australian currency used throughout the submission.

installation of large solar power stations supplying power into the national grid when the sun shines (no storage), thereby saving their existing fuel. On the other hand, Australia initially needs smaller stations, stations capable of independent base load status for remote areas (using storage), stations whose capacity can be increased as necessary (obviating the need for large initial capital), and stations whose design minimizes the field labour force. At a later stage of evolution, Australia can contemplate supplying large towns and cities, as well as realising on our vast solar natural resources to export solar-based products: systems, fuels, fertilizers. If we left development of such resources to others, the opportunity would be lost to reduce power costs in remote areas and to develop our own technology and industry to a size of our present automobile industry and more. We would postpone the time when solar power is competitive and this in turn would delay the assistance to our balance of payments which would follow sale of superfluous coal and solar-produced fuels and fertilizers.

Even if nuclear power turns out to be more viable than it appears at present, we consider it would be unwise to rely on it completely. We conclude that with a relatively moderate increase in price of alternative energy sources likely to occur, there will come a time when solar power on a large scale will become the more viable proposition throughout the country, possibly in two decades or so. With the utilization of storage, solar power could then become a base load proposition. If this time scale is anywhere near the mark, a vigorous research and development programme is required now in order to ensure that working prototype systems are available in time.

AUSTRALIA'S POTENTIAL IN SOLAR ENERGY
SOLAR ENERGY AS A NATIONAL EXPORTABLE RESOURCE

Australia has large tracts of sunny land of small alternative use. If even a comparatively small proportion of the total insolation falling on these areas can be usefully harnessed, the impact on our own energy needs and on those of our overpopulated energy-hungry neighbours (South East Asia and Japan) could be substantial. This suggests the desirability to exploit solar energy on a large scale.

We believe this potential can and should be developed as a matter of urgency so that eventually solar energy will become a major energy source as far as Australia is concerned. We consider that following a period of evolutionary development, solar energy may eventually be exploited not only to supply electricity on a large scale, but also to give energy-rich products (such as nitrogenous fertilizers produced from air, water and energy), refined metals (by reduction of ore by solar-produced hydrogen or by electrolytic refining using solar-produced electricity), and transportable fuels (such as hydrogen, methanol* and ammonia+).

We consider the practicable way to realise this potential is to seek, from the outset, methods for achieving mass utilization. Our approach to mass utilization of solar energy is based on physical systems: while this stems initially from our particular expertise, it is relevant to point to certain advantages which physical systems enjoy. These advantages include high conversion efficiency, therefore requiring a minimum of land area; the ability to utilize land which appears to have little

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* Please refer to Appendix IV of Part II.

\+ Please refer to Appendix II of Part II.

other application; flexibility of nature of product* (electricity, transportable fuels, fertilizers and others) and possibilities for storage.* When located on non-arable land (which we have in abundance), physical solar stations would not compete with other approaches to solar energy utilization, such as biological (involving say fuel crops) which require arable land in great amount.

While biological methods for harvesting of solar energy remain relatively inefficient, we do not consider that Australia's potential lies primarily in this approach. This is not to say that research into biological methods should be discouraged, but simply that it does not seem practicable at this stage to rely on biological conversion of solar energy to contribute very significantly to our energy resources because of the competition for arable land either now or in the future (by needs which cannot be met in other ways), the low efficiency (hence large land requirements), the recycling problems with nutrients and the general public interest in conservation.

We stress our belief that once mass utilization of solar energy has been realised, benefits will accrue to us not only from applications within Australia. There is in addition considerable export potential for solar systems and products (particularly fuels and fertilizer) and this would lead to further economic advantages for us as well as enabling the eventual extension of our solar wealth to neighbouring regions, thereby bestowing mutual benefits.

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* These advantages are shared, to a degree, by biological methods.

SOLAR POWER GENERATION - CURRENT RELATED RESEARCH

Three areas of research related to our own(mentioned later in this section and in more detail in Section B, Part II) are considered:

High Temperature Thermal. Using directionally selective* steerable mirrors for the collection of solar energy at high temperature, coupled to conventional heat engines and electric generators, appears to be the cheapest method of converting solar energy to electricity and this will continue to be the case as long as mirror collectors are cheaper than solar cells, area for area.

The high temperature thermal method for mass utilization of solar energy favoured currently in U.S.A. is based on the tower concept, which employs a large number of near flat mirrors reflecting radiation to a receiver at the top of a tower about 1000 feet or more tall and therefore has the advantage that conversion of energy occurs in one place at the top of the tower. (Optimum size is about 100MW.)

Alternatively, a distributed configuration of a large number of dish-shaped steerable mirrors each having an individual focus may be used with the advantage that smaller sizes are viable and are more adaptable to natural terrain; further, steering is easier and the collectors are inherently rigid. Converted energy must be gathered (corradiated) from many individual mirrors.

Low Temperature Thermal Flat Plate Heaters. The pioneering work of CSIRO in this area is being further developed in attempts to produce increased temperatures which can generate boiling water or steam. Elsewhere, vacuum encapsulated flat plates are being developed to realise higher temperatures and lower heat losses. These devices employ special surface coatings which have the property of

* Please refer to Appendix I of Part II.

readily absorbing radiation but impeding its re-radiation and are said to be "emission selective".* Work in U.S.A. indicates that systems employing only this kind of selectivity cannot produce electric power economically, but that they represent the most practical way of providing low temperature heat, particularly in small installations.

"Directional selectivity" is an alternative to "emission selectivity" and is achieved by a collector which confines its re-radiation and absorption to a narrow beam such as in a searchlight. Because of the small area of the sun in relation to the sky, such a beam can be very narrow and still allow absorption of all the sun's incident energy. Re-radiation is also very small. Such systems can be realised by employing steerable mirrors to track the sun.

Photovoltaic (Solar) Cells. The main thrust in this work is into manufacturing methods to reduce costs, relying to significant extent on mass production. USA studies favour silicon and cadmium sulphide, the former being more abundant and having a higher conversion efficiency. Costs are still over two orders of magnitude greater than a figure of about $50 per square metre, which would be competitive. Viability might be established by employing concentrating mirrors. We point out to the Committee that our own projects involving steering and control of large numbers of paraboloidal mirrors, structure of pressed steel mirrors and the degradation mechanisms of mirror surfaces on metal substrates are relevant to such a mirror-cell combination.

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* Please refer to Appendix I of Part II.

WHY HAS SOLAR ENERGY UTILISATION NOT PROGRESSED FURTHER?

Until the Second World War, traditional energy resources appeared adequate and economic and little incentive existed for the development of alternative energy sources. The appearance of nuclear weapons in response to military requirements produced a large reservoir of skilled scientists and engineers whose efforts were later naturally turned towards peaceful use of atomic energy. With the aid of tremendous prestige, political sway, resources, applied effort and massive funding, controlled nuclear fission energy eventually emerged as a resource of great demonstrated potential.

No such factors have worked in favour of solar energy which does not appear to have been viewed as having military potential; neither has the ready availability of other forms of cheap energy given much impetus to solar energy research until comparatively recent times of impending oil shortage and increased concern for the environment

The lack of developed or obvious potentially-viable systems for collection, corradiation, storage, transmission and utilization of solar energy, coping with daily variations in insolation as well as variations due to weather and seasonal fluctuations, has contributed to a reticence to consider solar energy seriously, particularly as far as large scale use is concerned. (This has happened also in the case of other comparatively diffuse energy sources such as wind, tidal, wave and ocean temperature gradients.)

Lack of previous interest in mass utilization of solar energy, however, does not imply necessarily a lack of technological or economic viability, as events and developments are now revealing.

WHAT MUST BE DONE TO ESTABLISH SOLAR ENERGY AS A SIGNIFICANT NATIONAL RESOURCE?

Generally, research needs to be directed towards establishing means for using solar energy on a large scale. It is suggested that we need to concentrate on making the most of the special advantages we enjoy in relation to solar energy: high levels of insolation and vast tracts of land hardly suitable for other applications. We should make a special effort commensurate with the scale of our solar advantages that should be aimed at helping not only ourselves, but also our neighbours who are not so well placed in terms of energy resources. We should strive to produce solar power systems (particularly large scale systems), solar-produced energy rich products, refined metals, transportable fuels and other goods both for internal consumption and for export.

Achievement of the above objectives requires significant investment in research and development involving material and human resources: we should be prepared to set aside these resources in view of the potentially great advantages which exist.

THE KIND OF RESEARCH REQUIRED IN AUSTRALIA

Feasibility studies should be supported over a wide range of possible application areas consistent with objectives already outlined. It should be recognised that we lack information at all levels and in most directions. Some questions cannot be answered without direct involvement in specific projects: such projects should be funded.

As in the case of nuclear energy it is imperative that we keep abreast of all development; this is achieved best by becoming involved ourselves in such developments. However, we can do more than just keeping abreast because of our especially favourable position with solar resources and, moreover, we have special needs particularly in remote areas. Our strong position to capitalize on our resources demands that we be responsible and develop our resources quickly in the manner most suited to our own needs and objectives. This means that we must do our own research. Because of the large magnitude of our solar resources, we should be able and be prepared to commit research efforts commensurate with our potential in view of the likely returns from this investment. Research should be pursued on a broad front, including particularly the mass utilization of solar energy.

Research might be identified in two classes, both of which should be pursued:

Research specifically related to Australia: systems for remote townships; systems tied to specific topological, geographic, or climatological features; systems applicable to domestic, industrial and rural applications.

Research relevant to utilisation of solar energy elsewhere; specific aspects of exportable systems and products.

WHO SHOULD DO SOLAR ENERGY RESEARCH IN AUSTRALIA?

There are few "experts" as yet in the field of solar energy research: everywhere researchers are seeking new ideas and discoveries. In this climate it seems premature to establish research institutes devoted solely to solar energy studies as it is our belief that new ideas and discoveries are most likely to come at this stage from small groups having access to other disciplines (e.g. physics, chemistry, engineering, geography, meteorology, economics and so on). Small groups displaying a high degree of individuality and diversity of ideas are found or can readily be formed in universities, but rarely elsewhere. U.S.A. experience has shown that groups in universities, sometimes in collaboration with outside organisations, have contributed most of the original ideas in solar energy research. We believe therefore that research will flourish best at present within the existing structure of universities and research establishments such as CSIRO, with appropriate collaboration with industry. Later when ideas are well formulated and the scale of the work has to be increased it would seem appropriate to form large institutes under single policy makers.* The U.S.A. has recognised the essentially premature situation regarding central institutes for solar energy research by considerably downgrading earlier proposals for a U.S.A. Solar Research Institute (Nature, Vol. 260, March 25, 1976, p. 277).

The field of solar energy research needs an influx of suitably educated and motivated young graduates and from this point of view the most effective way of attracting good graduates is for research to be carried on in universities.

We believe that all competent and enthusiastic researchers should be supported as long as each worker first

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* It may be noted that the Australian Atomic Energy Commission's establishment at Lucas Heights was formed well after the science and basic techniques of nuclear physics and engineering had been developed and was established at least partly in case nuclear power came to Australia.

demonstrates the relevance of his work to some feasible solution for the utilisation of solar energy. This is not to say that we undervalue pure research: on the contrary we recognise that applied research is based firmly on pure research findings. Funding of pure or "irrelevant" research presently being financed through well established channels should not, therefore, be cut off.

COORDINATION AND CONTROL OF RESEARCH : FUNDING

Coordination and control of research should be achieved primarily by fund allocation to workers who can demonstrate excellence and competence. Criteria for support of particular projects should be basically dependent on whether the work will contribute to or lead to reasonably viable methods of using solar energy.

We believe that at this stage to try to force the course of research in line with the opinion of a body of "experts" would be an undesirable development. Initiatives must come from the researchers themselves but clearly there must still be a mechanism for allocating funds equitably. Research should be encouraged and coordinated at two levels:

(1) A Parliamentary Committee whose function would be to determine the level of funding Australia can afford to expend on Energy Resources and on Solar Energy in particular and to determine the broad divisions of resource allocation within each energy resource, and

(2) An expert committee of scientists and engineers to recommend fund allocation to projects in accordance with the policy determined by (1). We believe the function of this body should be originally limited to ensuring that (a) workers who receive funds are competent; (b) the funds each worker receives are commensurate with the proposed research and (c) the proposed research and the degree of funding is relevant to stated, possible, practical methods of utilising solar energy.

Certain broad areas should be encouraged by making available generous funds, the aim being to establish a rational division of effort between fundamental studies and applied research (say 30%:70%) and, within applied research, a rational division between "custom built" (domestic heating, cooling, building and architecture, etc.) and "large scale bulk" (solar farms, power generation, etc.) ... (suggest 50%:50%

LEVEL OF FUNDING

Funding should be generous with the aim of making it eventually comparable with funding of nuclear and plasma research and reasonable on a per capita basis when compared with, say, the U.S.A. (approximate spending on solar energy research in 1976 in U.S.A.: $100m,* increasing to $130m+ in 1977 (Nature, Vol. 260, April 8, 1976, p. 477)).

It is not anticipated that a limit set by such comparisons will be reached for some time because of the present small number of solar energy research workers available and the consequent small amount of funds requested. However the growth in numbers of workers will depend largely on the ease with which existing workers attain funds. When the limit to available funds has been reached it may be necessary to avoid established areas growing at the expense of new areas by implementing appropriate controls. Notionally there should be adequate funds to support perhaps four or so large projects and many smaller ones.

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* That is, about 47 cents (Aust.) per capita.

\+ About 61 cents (Aust.) per capita.

THE A.N.U. SOLAR-AMMONIA PROJECT

Philosophy and objectives. We consider the possibility of solar energy providing a true stand-alone energy alternative which can compete with other energy sources. Desirable attributes include the capability of establishing initially on a small scale and expanding later as required; this would assist in supplying remote townships which now must pay very high energy costs. Such townships might be considered as first applications which would later evolve into large-scale systems for use elsewhere.

Because Australia has unused semi-arid lands in abundance, it would be advantageous to develop a system capable of converting solar energy in quantities in excess of our own needs thus enabling the export of solar energy via synthetic liquid fuels, for example.

Description of the system. The essential elements consist of collectors, an energy gathering corradiative network converging to a central station, energy store, means for recovering solar energy (e.g. as heat), means for converting the recovered energy into a usable form (e.g. steam generator coupled with a conventional turbo-alternator). Fig. 8.2 of Part II depicts such a system. We consider that paraboloidal mirrors pressed from sheet steel have the best chance of being viable collectors when tracking the sun. To transport energy from the collectors and to facilitate storage, solar heat energy is transformed into the chemical energy of a fluid flowing in pipes to a central station: this has good prospects for both energy transport and storage. The fluid (ammonia) undergoes chemical change in absorbing the collected solar energy and then passes to the central station where solar energy is recovered as heat by reversal of the chemical change. Energy storage may be achieved in the case of the ammonia system by storing the nitrogen/

hydrogen mixture resulting from dissociation of the ammonia by the solar energy: a feasible economic method for this storage is in natural underground reservoirs such as occur for water, oil and gas. It turns out that if high pressures are used throughout the system considerable economies result and storage is compatible.

Progress to date. A great deal of theoretical and design work has been carried out covering the areas of thermodynamics, reaction kinetics, system analysis, various specific engineering designs, and several cost studies. An experimental programme to fill knowledge gaps and demonstrate feasibility is currently in progress involving collector orientation control, measurement of the rate of dissociation of ammonia into hydrogen/nitrogen under a variety of conditions and with a variety of catalysts, studies of reflective films suitable for metal substrates covering the types of film, their manufacture and application to these substrates and the mechanisms of degradation of the films. Other work involves the study of underground storage and continuous measurement of the direct component of radiation.

Experimental results obtained so far indicate that compact economical designs are feasible.

Future programmes of research involve collector orientation control, reflective films, mirror collectors, energy transfer, storage and solar radiation measurements.

Potential and evolutionary development. The solar ammonia system is flexible as regards size of system. Collectors may be disposed to match terrain and other land uses. Minimum viable sizes should allow the system to be adapted to the needs of most remote townships. Evolutionary development should occur smoothly towards large base load stations made possible by relatively cheap underground storage. Following a period of such development, the system may eventually be exploited not only to supply electricity but also to produce nitrogenous fertilizers and fuels such as hydrogen, methanol and ammonia. (Please refer to Appendices II and IV of Part II.)

The prospect for utilization and export of solar energy in the form of ammonia is promising (refer to Appendix II). Ammonia is the basis of the nitrogenous fertilizer industry and the prospective demand for it will be great and perpetual. Ammonia may also turn out to be a useful liquid fuel.

The chemical simplicity of ammonia places it in the position of first candidate as a thermochemical energy transfer fluid. However, there are other candidates, notably methanol (wood alcohol) which is the basic starting chemical of many chemical industries. Methanol dissociates at high temperatures into a mixture of carbon monoxide and hydrogen.

The solar ammonia system might be made economically feasible even now by using ammonia production to effectively subsidize the electricity production costs. In the same way, by using an input of natural gas, naphtha or eventually coal for a solar methanol system (refer Appendix IV), methanol could be the basic product, again subsidizing electricity production.

Methanol has enormous potential as a fuel for process heat production and for transportation, as well as being the basis of a large chemical industry. A solar methanol system would effectively integrate solar energy utilization with fossil fuel usage.

Finally, it is relevant to indicate other economic benefits which would result from development of the solar ammonia system. Major industries which would be involved in implementation of the system, apart from those involved in power generation, are those concerned with manufacturing steel pipes, tubes and automobile bodies. The potential is immense; at least as great as the present motor body industry. Moreover, Australia's balance of payments would be improved to a marked degree by the sale at world market price of steaming coal saved.

Funding requirements and research programme. We have reached the stage where, on the basis of results so far achieved, a viable research programme has been mapped out. By increasing the present staff of six* to a total of sixteen, supported by appropriate funds for materials and equipment, we believe that a 5 year experimental programme would provide a sound basis of knowledge from which to commence a pilot scheme to achieve proof of concept. For this programme we consider a total of about $2 million (at May 1976 prices) is needed to achieve the results envisaged. On the assumption that University funding can continue at the current level, an amount of about $1,400,000 over 5 years would be needed to supplement present resources to reach the required level. These estimates do not include assistance which would be needed from interested industries in the form of materials and manufacturing services.

In offering this estimate we have in mind the importance of the project and its magnitude and potential. We believe the amounts sought are realistic in relation to the needs and scope of the project. It is relevant to mention that at least three groups in U.S.A. concerned with the central tower concept have received over $5,000,000 each to carry out feasibility studies.

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* Two others, not members of the Group, are providing machine shop support.

Successful completion of the abovementioned phase would lead to a Pilot Scheme with underground storage enabling proof of concept, a development which might take up to a further five years, depending on resources allocated.

Finally, a stand alone solar energy system would naturally follow proof of concept. Such a system would be suitable for a remote township and may cost of the order of $10 million for a 10 MW Solar System.

Further development would involve production of solar-based goods (e.g. fuels and fertilizer).

Stages beyond the first involving the acquisition of sound knowledge and data are of course very tentative at this time.

CONCLUSIONS AND RECOMMENDATIONS

* In the long term, the only alternatives to solar energy appear to be fast breeder nuclear reactors and fusion nuclear reactors, about both of which there still exist serious doubts. Even if nuclear power turns out to be more viable than appears at present, we consider that it would be unwise to rely on it completely. In any case with a relatively moderate increase in price of alternative energy sources, both fossil and nuclear likely to occur, there will come a time, we believe, when solar power on a large scale will become the more viable proposition, perhaps in about two decades or so. With the use of appropriate storage, solar power could then become a base load proposition.

* If our time scale for future developments is anywhere near the mark, a vigorous research and development programme is required <u>now</u> in order to ensure that working prototype systems are available in time. Doing something now will also enable us to save some of our oil, gas and coal for other purposes and for future generations.

* Australia does not have the resources to develop nuclear fission or fusion energy, both of which require complex and very expensive science and technology. We do have the capabilities and resources to develop the less complex solar energy, particularly as potentially successful approaches to solving the major problems involved have now emerged. As adequate information on which to base future decisions is lacking, feasibility studies should be supported over a wide range of possible application areas. Because some questions cannot be answered without direct involvement in specific projects, such projects should be funded.

* There is a good case for encouraging solar energy research in Australia (as opposed to adopting developments from overseas) since Australia has unique conditions and stands to gain in unique ways both nationally and internationally. Because of the large magnitude of our solar resources, we should be able and be prepared to commit research efforts commensurate with our potential in view of the likely returns from this investment. Australia should develop its own solar systems specifically suited to its own needs, including the desirable advantage of exporting solar systems and solar based fuels and fertilizers.

* At this stage research is best carried out in existing institutions by small groups displaying a high degree of individuality and diversity of ideas. Research should be coordinated and encouraged through the method of funding which should be set by: (1) a Parliamentary Committee to determine level of resources and their broad allocation, and (2) an Expert Committee to ensure that research workers receive appropriate funds for research which is relevant to practicable methods of utilizing solar energy.

* The initiative for research should come largely from research workers themselves and the activities of any controlling body should therefore be largely confined to ensuring the quality of research and its relevance to an ultimate working energy system. Government funding should be generous with the aim of making it eventually comparable with funding of nuclear and plasma research and comparable in magnitude on a per capita basis with the effort in other countries, particularly the U.S.A.

* Solar energy may be harnessed in a rich variety of ways: hitherto, applications of flat plate collectors and solar cells have been the most obvious. Many other prospects exist,

awaiting the application of man's ingenuity to the production of viable methods, including applications of photosynthesis and photochemical reactions, custom-built systems for building, even simply better building design; the list of schemes existing at different stages of conception and development is extensive. We are concerned to make a substantial contribution to our useful energy resources by taking advantage of our large tracts of sunny land of little alternative use. To realise this great potential and to make solar energy a major energy source for Australia requires research and development of mass utilization, in the form of power systems, from the outset.

* We submit that research into solar power systems is at least as justified as the present research in fast breeder and fusion reactors, particularly since solar power generation is practically free from criticism; is environmentally acceptable; is a true renewable resource; has few safety hazards; is technologically feasible; is at least as economically promising as the alternatives, given present knowledge; requires less complex technology and less resources to develop than the alternatives and is within the competence and resources of Australia. Finally, public interest, awareness and support is extensive.

* Studies in the U.S.A. and elsewhere including Australia, suggest that power generation systems for utilizing solar energy are economically viable or reasonably close to being so. With further work, there is a good chance that the viability will improve.

* The A.N.U. Solar-Ammonia Project, which has been developing with gathering momentum over the past $3^1/2$ years, appears at least as viable as other mass utilization of solar energy systems proposed in the U.S.A. and has the added advantage of providing short and long term storage capability.

Our theoretical and experimental studies so far indicate that if this project were to be funded to the extent of about $2,000,000* over a five year period (to finance salaries, materials and equipment) a sound body of knowledge and data would be produced from an experimental "closed loop" system to enable specification of a Pilot Scheme which could then be used to prove the concept. A further four or five years (or less, depending on resources) might be necessary to provide sufficient information to be able to build a stand alone solar ammonia system of about 10 MW capacity suitable for a remote township. Other developments may be directed to increase size and to exploit the solar ammonia process not only for electricity production, but also for the production of nitrogenous fertilizers and fuels such as hydrogen, methanol and ammonia. Such development would establish solar energy as a true alternative energy source, relieving the load on oil and coal, as well as acting as a source in its own right.

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* About $1,400,000 of this amount would need to come from a special grant if University funds continue to be available at the current level.

SECTION B - DETAILED ARGUMENTS

TWO-PART SUBMISSION

CONTENTS

PART I

GENERAL SUBMISSION

PART II

THE A.N.U. SOLAR-AMMONIA PROJECT

APPENDICES

PART I

GENERAL SUBMISSION

PART I

In this part of our submission we present material related generally to our principal area of interest which is large scale solar power generation using non-biological processes. This material includes a review of allied research areas and the reasons why we think government should lend financial support to our work. In addition we have included our opinion on a number of policy matters bearing on the degree of funding and the co-ordination of research throughout the country.

As we are perhaps the only research workers in Australia primarily interested in large scale solar power generation, we felt obliged to try to explain this situation and to adopt a somewhat defensive attitude. We feel that there has been a pervading view that solar power generation is either unnecessary or too complex and therefore too expensive. Thus we were led to include a presentation of some of the arguments we have heard against solar power generation together with our rebuttals of these arguments.

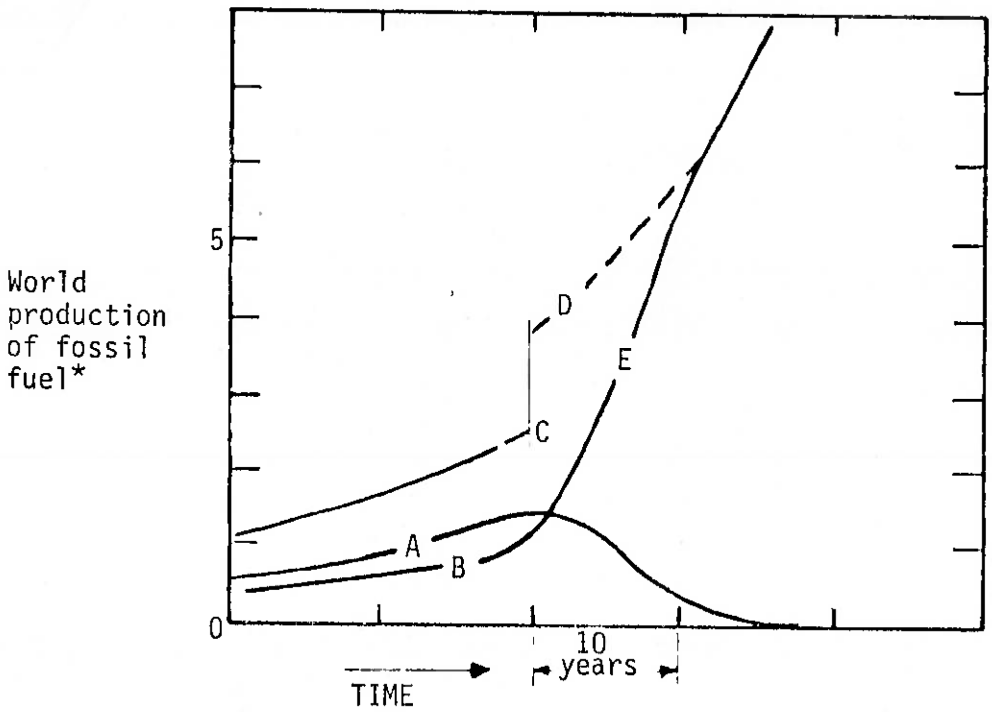
Finally, we have concluded with a summary and our recommendations.

1. SOLAR POWER GENERATION - SUPPORTING ECONOMIC ARGUMENTS

In this section we argue that the price of steaming coal will rise substantially over the next few decades and that it is likely that nuclear power will also rise in price. In the meantime solar power, which is probably already competitive for remote townships, will benefit from the "learning" process and from the economic benefits of increased production as more small solar power stations are built. Eventually these two effects will make solar power cheaper than alternatives even for city communities.

1.1 The price of coal. As oil stocks deplete and the cost of finding new deposits continues to increase we can expect the price of oil to increase with time. This trend will continue to encourage power generation authorities to gradually switch to nuclear power or coal fired stations. For a number of reasons it is likely that developing nations and many others will prefer coal to nuclear power (perhaps after purchasing one nuclear station for prestigous and strategic purposes). Thus as oil becomes scarce one would expect an increase in demand for steaming coal for electric power generation.

A second and more important result of a growing shortage of oil will be the consequent increase in price of gasoline which will in turn eventually make the oil-from-coal conversion economical. When this occurs a second demand pressure will be placed on coal and it is inconceivable that the price will not respond. This second demand pressure will be enhanced by the fact that the energy value of the coal used in the oil-from-coal process greatly exceeds the energy value of the resultant oil. Thus typically 0.7 tons of coal will be needed to replace one barrel of gasoline whereas only 0.2 tons of coal will be needed to replace each barrel of fuel oil for power generation.



A Oil production

B Coal production

C Oil plus coal

D Coal only - yielding same useable energy as C on following basis:
Oil for external combustion replaced by coal 1:1.
Oil for internal combustion(automobiles, diesel locos,aircraft) replaced by coal in ratio of 3.5:1 via oil-from-coal process.

E Growth rate in coal production to meet demand is 20% p.a. over ten year period.

* in arbitrary calorific units.

FUTURE DEMANDS ON COAL.

Figure, 1.1

We see in addition a third demand pressure on coal also due to transportation difficulties upon the demise of oil. We expect public transportation to respond by increasing the degree of electrification, e.g., by increasing the number of electric trains, and by the reintroduction of electric trolley buses. It is likely that automobiles will be partly replaced by short range battery driven electric cars. These developments towards electrification will therefore place a third demand on electric power generation and therefore upon steaming coal.

It is most unlikely that the accelerated demand from these three factors will be met by the normal growth in supply which is only around 5% p.a. To even partly meet the accelerated demand, investment will have to be unusually high and this will only occur if prices are high enough to return the required profits.

In this scenario it is our belief that the price of coal will escalate several fold.

1.2 <u>Nuclear energy</u>. An increase in the price of coal should make nuclear power even more competitive than it supposedly is already. However, there is evidence that the running costs of nuclear stations are likely to escalate faster than the running costs of coal fired stations. In the Australian scene two factors are of great significance (a) nuclear stations are becoming larger in order to maintain economic supremacy yet for sparsely populated countries with limited distribution capacity, several smaller stations would be preferable to one large one. (b) nuclear stations take a decade of building time before becoming productive and therefore correspond to a poor deployment of capital.

With regard to the safety of nuclear power stations and the satisfactory disposal of waste, we believe that present public discontent on these issues will inevitably lead to more complex operating methods and monitoring equipment designed to satisfy the critics. This increase in complexity may completely answer the criticisms but it must, in our view, also increase the down time required for executing safety routines and for checking back-up systems and circuits. Already alarmingly low capacity factors (ratio of actual power to maximum power capability) have been reported, 35-40%, due to shut downs resulting from a variety of causes. If this trend continues the cost of nuclear power will be effectively trippled.

Our overall view of nuclear power is that there are sufficient doubts to warrant the view that it would be unwise to rely upon it completely.

1.3 Present and future price of solar power. During the short history of research since 1973, several comprehensive system studies have been undertaken, particularly in the USA, which indicate that solar power using present technology, would cost less than 5 cents (Australian) per kw hr.* Our own studies support this view. Although this figure is above current city prices (by a factor of 2 or 3) two important points must be considered (a) in Australia there are localities where present power costs are considerably above 5 cents per kw hr, thus a market may already exist; (b) once this market begins to be satisfied it is common experience that the development of specialised manufacturing techniques and the increase in scale of production should reduce costs, which in turn should reduce the price of solar power.

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* "Solar thermal electric power systems" (3 volumes) National Science Foundation report NSF/RANN/SE/G1-37815/FR/74/3 prepared by Colorado State University and Westinghouse Electric Corp. November 1974.

"Status report on a high temperature solar energy system" Sandia Laboratories report SAND74-8017, A.C. Skinrood et al. September 1974

"Solar thermal power systems based on optical transmission" National Science Foundation report NSF/RANN/SE/G1-39456/FR/75/3 prepared by University of Houston and McDonnel Douglas Astronautics Co. October 1975.

1.4 Conclusion. Thus we conclude that a moderate excursion upwards in coal price, of the size we have intimated, is likely to occur and will lead to a point where solar power will then become the more viable proposition throughout the country. This occurrence will roughly coincide with maximum world oil production estimated to take place within 2 or 3 decades. On this time scale a vigorous research and development effort is required in order to finally produce a working prototype in the time available.

2. SOLAR POWER GENERATION - OTHER SUPPORTING ARGUMENTS

2.1 Australia's potential. Australia possesses large tracts of sunny land which at present are of little commercial use. If eventually even a small proportion of the solar energy falling on these areas could be captured, this country would possess an energy source sufficient not only for its own meager needs but for the needs of the South-East Asia (and Japan) region.

In order for this vision to materialize the solar energy collected would have to be "fixed" into a transportable form. This could be achieved by either producing in Australia energy rich commodities, e.g. nitrogenous fertiliser (from air, water and energy, refer to Appendix II) or refined metals (either by reduction of ore by solar produced hydrogen or by electrolytic refining using solar produced electricity). Alternatively solar energy could be "fixed" in the form of a transportable fuel. Many research workers regard hydrogen as the fuel of the future which is of course transportable as a gas or liquid. Whether or not this view will prove correct it does appear that hydrogen will play an important role, if not as the final fuel itself, then at least as an intermediary for the hydrogeneration of other substances to form fuels such as methanol.

The spectre of Australia continuing to be the "energy bowl" of the region after the coal (and nuclear?) era has passed is one which captures the imagination and one which, if it came to pass, would bring immense prestige and benefit to this country.

It is pertinent to include here a note on biological methods for harvesting solar energy. Although it is not our purpose to discourage research in this area, i.e. the harvesting and subsequent processing of fuel crops, e.g., trees, sugar cane, we are of the opinion that the realisation of Australia's full potential does not lie in this direction. The difficulties are fundamental: (a) low efficiency of conversion of solar energy; (b) nutrient recycling problems; (c) competition with food production for the arable land available; (d) adding to the already increasing demands on forests.

The best estimates of the energy potential of Australia from biological conversion methods is many orders of magnitude less than for non-biological methods.

2.2 The alternatives to solar power. In the long term the only alternatives are (a) fast breeder nuclear reactors; (b) fusion nuclear reactors.

It is to be particularly noted that the present generation of nuclear power stations do not provide a long term solution to the energy problem.

We wish only to point out that there are grave doubts about both of these alternatives. Experience with present experimental fast breeders indicates that there are several technical and economic problems still to be overcome. There are of course increasing difficulties on the environmental and safety issues. In comparison fusion reactors are further away from reality since the physical concepts are not yet proven. We feel it is worth emphasising that it is only the second generation of fusion reactors employing deuterium alone that could provide a long term solution since the first generation presently being worked on and based on deuterium and tritium requires lithium as a fuel. In order to provide a portable fuel for vehicles both of these alternatives would have to be coupled to a synthetic fuel industry using heat or electricity as the primary energy source. Almost certainly hydrogen would be produced in large quantities either to be used as a fuel or as a first step to produce some other form of fuel.

Thus, in the long term, there is no simple formula among the alternatives to solar energy for a substitute portable fuel, and in this regard solar energy fares no worse than the alternatives. Should a process for photo dissociation of water eventuate, it might fare much better.

Again, we do not wish to discourage research in any of the above directions but only to reiterate the wisdom of having "extra strings to one's bow". On this basis research into solar power is at least as justified as the present research related to fast breeders and fusion, particularly since solar power generation is practically free from criticism on all counts: environmentally it is acceptable; it is a true renewable source; there are few safety hazards; it is technically possible; it is at least as economically promising as the alternatives, given present knowledge. Perhaps of greatest significance is the public's increasing awareness of the issues and their growing recognition of solar power as the ultimate long term solution.

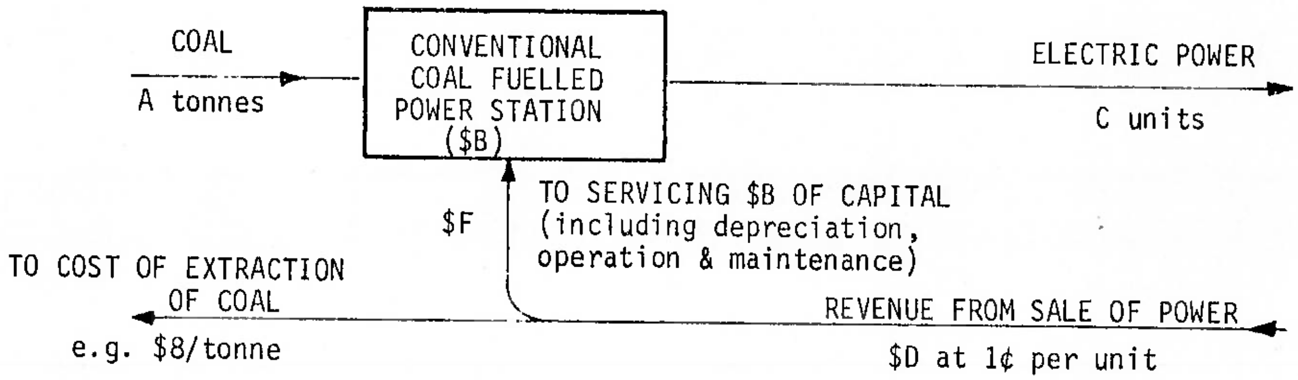
3. SOLAR POWER GENERATION - REBUTTAL OF ARGUMENTS AGAINST

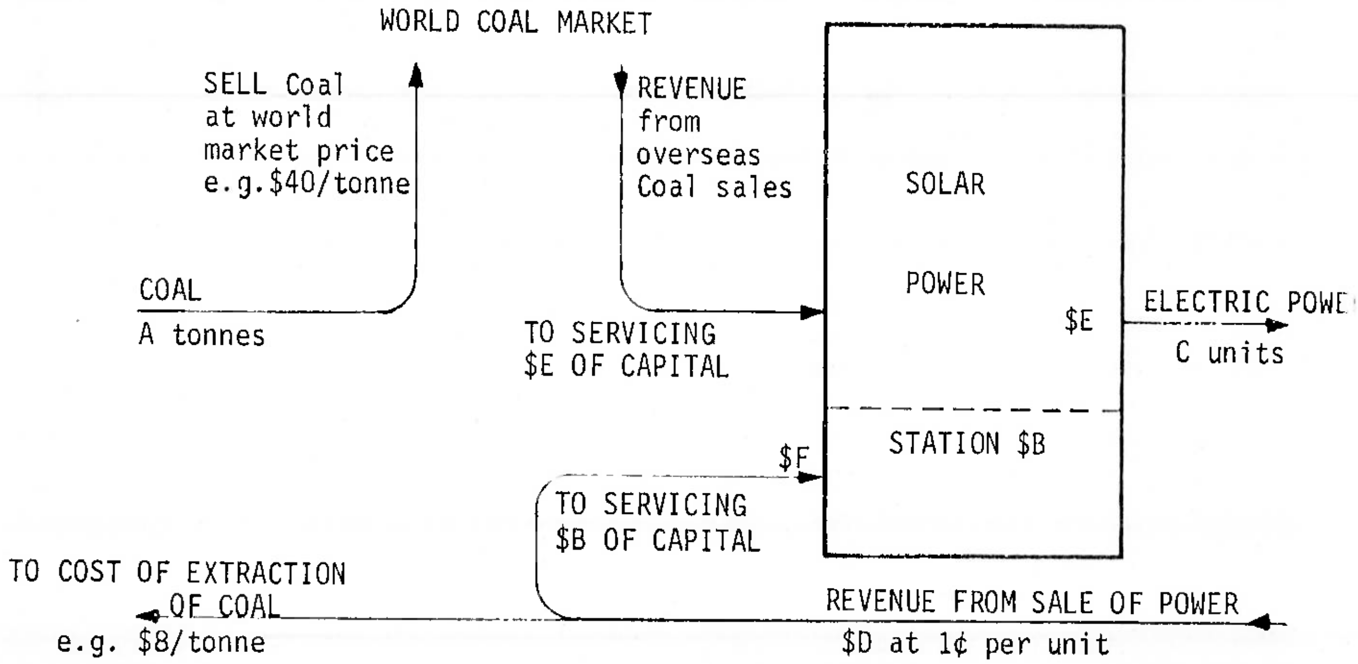
3.1 Australia has superfluous coal for power generation therefore it doesn't need solar energy. This statement is based upon a view of the future several decades hence where Australia has not substantially increased her coal exports above present levels, and where the cost of coal for the indigenous power generation market is calculated as basically the cost of extraction. We believe this view to be erroneous on three counts. First, as we have pointed out, the demand pressures on coal are likely to result in enticingly high world market prices for coal. Our reserves are small by world standards (less than 2%, though large on a per capita basis) and have therefore a high propensity to being swallowed up in a relatively short time by a greatly enlarged export trade.

Secondly, although it may be policy to value coal only in terms of extraction cost, these costs will escalate due simply to the pressure of unionist miners in the export trade demanding a share of the profits, demands which will undoubtedly be successful and which will then flow-on to miners supplying the home market (already happening). This mechanism will tend to make the effective price of coal to Australian power stations follow world market price.

Thirdly, it is questionable whether it is in the public interest to continue to produce power by burning coal if an alternative solar power system is capable of delivering power at an identical price while at the same time allowing the release of coal to the profitable export market.

It is our view that the only rational method of valuing coal for Australian power stations is by parity with world market. Once this is done, the real cost of coal-derived power may be determined and compared with alternatives. We believe solar power will be shown to be competitive at an early date when viewed in this way.





ILLUSTRATING HOW SOLAR POWER STATIONS SHOULD BE FINANCED FROM OVERSEAS COAL SALES.

TOP: Conventional coal station operating from "captured" mine.

BOTTOM: Solar station generating same power at same price. Coal mined at same rate. Solar power station at $1000/KW would be viable, (see fig.8.1)

Figure 3.1

3.2 Solar energy is not a substitute for oil. Only a small percentage of Australia's energy needs are in the form of electricity - the real problem is the imminent shortage of oil. It is true that a present breakdown of the energy allocation shows only about 10% in the form of electricity. However, we believe this proportion is bound to increase as oil becomes scarcer simply because the only two alternatives to oil are coal (including oil-from-coal) and electricity (from whatever source).

However, we base our argument not on the demand pressure on electricity but on coal. As already pointed out the pressures on coal come from many sides - an alternative to oil for power generation, for the petrochemical industry, for gasoline. The role of solar power would be to reduce the pressure on coal. It should happen automatically if the two sources are allowed to compete.

3.3 Employ overseas technology which we will be able to purchase in due course from U.S.A. The needs of the USA are different from ours. The USA has a higher population density than Australia and is criss-crossed by electric power grids and pipe lines. There is no such thing as a remote township in the USA.

The power consumption is much higher in the USA than it is in Australia and therefore power stations are generally larger. Power stations of the size aimed at in the USA might cause distribution problems in Australia.

The problem in the USA is basically shortage of fuel. In Australia it tends to be shortage of capital and the high energy price in areas away from the cities.

Thus in the above context it makes sense for the USA to develop solar power stations which are large and which can connect to the national grid (refer to section 4.1).

Even if they produce energy only when the sun shines (no storage) they will be attacking the basic problem by saving fuel.

Australia, on the other hand, needs (a) smaller stations; (b) stations capable of being independent base load stations for remote areas (i.e. with energy storage facilities); (c) stations whose capacity can be enlarged without interfering with power production, thus obviating the need to tie up capital for long periods of time during construction; (d) stations whose design minimises the field labour force (the cost of which is higher in Australia than in USA) and is adaptable to a variety of terrains and weather conditions; (e) stations of a type capable of being enlarged - eventually to a size appropriate for supplying large towns and cities.

We could, indeed, disregard our remote townships, some of which are no doubt already viable propositions, and wait until the USA eventually developed large solar stations competitive with coal stations such as Liddell. In the meantime we would have lost the opportunity to almost immediately reduce power costs in remote areas and to develop our own technology and industry which promises to grow to at least the size of the present automobile industry in Australia. We would also be postponing the day when solar power is competitive since our own developments would be tailored more accurately to our own needs and this in turn would delay the improvement in Australia's balance of payments that would follow the sale of superfluous coal.

4. SOLAR POWER GENERATION - RELATED RESEARCH AREAS

The research in progress at the A.N.U. is described in Part II of this submission. In this section we touch on three significant related areas of research in order to provide a back drop to our own work.

4.1 High temperature thermal. The collection of solar energy at high temperature is usually achieved by employing steerable mirrors in a directional selective device or system as discussed in Appendix I. The high temperature is used to heat the working fluid of a heat engine, e.g. steam, the advantage being that by so doing the conversion efficiency of heat energy to mechanical energy is improved. Modern steam plant for example operate at sufficiently high temperatures to achieve at least 35% efficiency and similar efficiencies are possible using high temperature solar collectors. Conversion efficiencies of other methods, e.g. solar cells, are considerably less.

Moreover high temperature solar collectors coupled to conventional heat engines and electric generators appear to be the cheapest method of converting solar energy to electricity. It is probable that this will always be the case since it is likely that mirror collectors will always be cheaper than solar cells, area for area. (However, see section 4.3 for mirror-cell combination.)

The high temperature thermal method presently favoured in the U.S.A. is the tower concept which employs large numbers of near flat mirrors reflecting radiation to a receiver at the top of a tower 1000 ft or so tall. The optimum system size is about 100 MW. Tower systems have the advantage that conversion of solar energy occurs at one place at the top of the tower.

An alternative is the "distributed" configuration employing a large number of dish shaped steerable mirrors each having an individual focus. Distributed systems have smaller optimum sizes and are more adaptable to the natural terrain. They are also easier to steer and the dish shaped collectors are inherently rigid. However they possess the disadvantage that converted energy must be gathered (corradiated) from numerous individual mirrors. This objection would vanish if the network required for controlling and powering mirrors (necessary in either system) could be combined with the corradiation network required for the converted energy in the distributed system. Our work on the solar-ammonia concept, which is a distributed system, suggests this is possible.

4.2 Low temperature thermal - flat plate heaters. The pioneering work of CSIRO is well known in this area and it is common knowledge that attempts are presently being made to increase temperatures in order to generate boiling water or steam. Elsewhere vacuum encapsulated flat plates are being developed which promise higher temperatures and lower heat losses.

These devices rely on the use of special surface coatings known as selective coatings whose function is to provide an unimpeded path for absorption of radiation but an impediment to the re-radiation of energy from the hot surface.

An important alternative to this "emission selectivity" is "directional selectivity". In essence, directional selectivity is the property of a collector which confines its re-radiation and absorption to a narrow beam much the same as a directional radio antenna. Since the sun occupies a very small area in the sky (1/100,000 of the sky) the beam may be very narrow and still allow absorption of all the sun's incident energy provided the beam is pointed that way. Conversely, because the beam is so narrow, re-radiation of energy is reduced to a very small value.

A more lengthy discussion of the pros and cons of emission and directional selectivity is given in Appendix I. Suffice it to say here that the most practical known methods of achieving directional selectivity employ steerable mirrors whose orientation is controlled so as to keep the collection beam in constant intersection with the sun.

Work in U.S.A. strongly suggests that systems employing only emission selectivity cannot produce electric power economically. On the other hand, such systems or devices are undoubtedly at present the most practical way of providing lower temperature heat, especially for small custom-made installations, as they do not require the almost constant managerial attention that the alternative does.

4.3 Photo voltaic (solar) cells. In this area of investigation, workers in the U.S.A. have given priority to silicon and cadmium sulphide. Of the two, silicon appears to be favoured because of its abundance and higher conversion efficiency expected eventually to reach a maximum of about 20%. The major problem, as with all forms of solar energy collector, is to reduce the cost per square meter to a competitive figure of the order of $50 or less. The present cost of silicon cells is 500 or so times too great.

The main thrust of investigation is therefore into manufacturing methods for reducing costs. These methods will rely largely on mass production and therefore, to be viable, must in one step reduce costs sufficiently to attract a mass market. Because of the specialised nature of this work it is unlikely that Australians will be attracted to it.

It is likely that one of the first economic applications of photo voltaic cells will be in conjunction with a concentrating mirror of parabolic or paraboloidal form. The object here would be to extract more electricity from the expensive solar cell by increasing the intensity of radiation upon it. This mode of use is cheaper because basically one square meter of mirror collector is very much cheaper than one square meter of photo voltaic cells. Unfortunately silicon cells are not very suitable for operation at greatly increased intensities (i.e. 1000 fold) and other materials such as gallium arsenide might have to be used.

We wish particularly to draw the attention of the Committee to this mirror-cell combination because it virtually reduces the cost of cells by the required 1000 or so to render them commercially viable. Several of our projects viz the steering and general control of a large number of paraboloidal mirrors, the structure of pressed steel mirrors and the degradation mechanisms of mirror surfaces on metal substrates are relevant to this mirror-cell combination.

5. POLICY

5.1 Who should do research in Australia? At this stage the way ahead is unclear. Workers all over the world are still searching for ideas and discoveries and therefore what is required is a climate which will encourage this type of activity. Particularly to be avoided is the creation of a body of controlling "experts" charged to make pronouncements on the relative merits of research projects or to coerce workers into "promising fields".* It is therefore our belief that, with appropriate safe guards, all competent and enthusiastic researchers should be supported in whatever institution they happen to be. We would require however that each worker first demonstrate the relevance of his work to some feasible solution to the utilisation of solar energy. If there is any judgement to be made at all as to the merit of a particular project (presuming the researchers are sufficiently competent and enthusiastic) then it should be on this matter of relevance.

* We are not against a body of "controlling experts" at a later stage of development.

This is not to say that we undervalue pure research. On the contrary, we recognise that applied research is based firmly on the findings of pure research and would therefore oppose any move to reduce the funding of pure or "irrelevant" research presently being financed through well established channels.

On the matter of competence of research workers, it is worth remarking that previous experience in solar energy will be a rare quality among new workers and therefore cannot necessarily be used as a measure of competence. But in order to assess relevance a worker needs to call upon a mixture of science, engineering and economics seldom found in a single individual.

We are also opposed to the establishment of solar research institutes at this stage. It is our belief that new ideas and discoveries are most likely to come from a number of small groups having good access to other disciplines, e.g. physics, chemistry, engineering, geography, meteorology, economics, etc. Thus at present research will flourish best within the existing structure of universities and research establishments such as the CSIRO. Later, when ideas are well formulated and the scale of the work has to be increased, it will be appropriate to form large institutes under single policy makers.

In this regard an analogy may be drawn to the Atomic Energy Commission's establishment at Lucas Heights which was formed well after the science and basic techniques of nuclear physics and engineering were known.

It is also interesting to recall that the justification for establishing Lucas Heights was *in case* nuclear power came to Australia. Presumably, then, even when a solar research institute is warranted in Australia, it will not require justification beyond the precautionary statement that it is *in case* solar power comes to Australia.

5.2 Degree of total funding. The requests for funds will of course depend on the number of research workers attracted to this type of research. The growth in the number of research workers will largely depend on the ease the existing ones have in obtaining funds.

The limit of total spending would be best set by comparison with spending in other countries and by comparison with spending on nuclear energy research in Australia. It is not anticipated that a limit set by these comparisons will be reached for some years because of the present small number of solar energy research workers. Hence, with no present overriding financial restrictions to take cognisance of there is every reason to be generous in order to encourage growth in numbers of research workers.

It is unavoidable that a limit will eventually be set to total spending on solar energy research. Because of this, limits should soon be set to the various subdivisions, e.g. "custom built" (domestic and industrial) heating and cooling, building and architecture, etc.) and "large scale" (solar farms, power generation, synthetic fuels, etc.). This would prevent the established research areas growing at the expense of the newer ones and thus would avoid an unjustifiably large share of the total funds going to the former after the limit on total spending has been reached. The method of subdividing and the setting of limits to funds should be on non-scientific grounds. We feel that these decisions should arise from an expression of the community as to what it feels it needs. Thus there is a case for two guiding bodies - one comprising lay members of the community who deal with the broad issues of fund allocation to all forms of new energy sources;* and a more professional body whose duties are discussed in the next section.

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* This might most appropriately be a Special Committee of Parliament.

5.3 Co-ordination and control. As previously suggested, we believe that to try to force the course of research in line with the opinion of a body of "experts" would be a retrogressive step. The initiatives must come from the researchers themselves but clearly there must still be a mechanism for allocating research funds equitably.

Thus we believe that the function of a co-ordinating and control body should in the first place be limited to ensuring that (a) workers who receive funds are competent; (b) the funds each worker receives are comensurate with the proposed research; and (c) the proposed research is relevant to a stated possible practical method of utilising solar energy.

The importance of the last requirement cannot be overstressed. In our view there must be in the mind of the researcher (and the controlling body) a clear picture of the consequences of his work. If his object is to invent then he must be able to state what else, besides success in his particular venture, would be required, before a practical working system could be achieved. Hopefully the researcher will have chosen to forge the most critical of the missing links but if he has chosen the least critical and by-passed the most critical, his work cannot be judged to be as relevant as it might otherwise have been. An estimate of the probability of ever forging *all* the missing links in a particular chain would be a useful figure of merit equally applicable to each missing link in the chain. If then it should be necessary to fund some projects at the expense of others this figure of merit could be applied in order to establish priorities. But we stress that in our opinion no project passing (a) and (b) above should be left without funds at all as a result of its low priority.

On the other hand, projects rated with a high figure of merit, that is ones related to an overall system having a high probability of being technically and economically viable, should be funded by those industries who stand to make profit once the system is marketed.

Thus the function of government funding should be to encourage the risky ventures, even the extremely risky ones, but with most emphasis on the moderately risky.

6. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Studies in the USA and elsewhere, including Australia, suggest that several systems for utilizing solar energy are economically viable or reasonably close to being so. This includes systems for power generation. With further work and in due course there is a good chance that their viability will improve.

There is a good case for encouraging solar energy research in this country (as opposed to adopting developments from overseas) since Australia has unique conditions and stands to gain in unique ways.

At this stage, research is best carried out in existing institutions by small groups displaying a high degree of individuality and diversity of ideas.

Government funding should be generous with the aim of making it eventually comparable with the funding of nuclear and plasma research and comparable in magnitude, on a per capita basis, to the effort in other countries, particularly USA.

The initiative for research should come largely from the research workers themselves and the activities of a controlling body should therefore be largely confined to ensuring the quality of research and its relevance to an ultimate working energy system.

PART II

THE A.N.U. SOLAR-AMMONIA PROJECT

Part II

7. PHILOSOPHY

This part of our submission deals with the research projects of the energy conversion group, Department of Engineering Physics, A.N.U., the reasons for selecting the projects, and the goals of the researchers.

7.1 Goals. Our work has been prompted by a process of self questioning which runs along the following lines. Solar energy is often thought of as a supplement to fossil and nuclear energy, not as a true alternative which could, if necessary, stand alone. We wish to know if it is possible for solar energy to provide a true alternative, i.e. to provide a power source that is both large enough and reliable enough.

In considering the form that such a solar energy system might take we have been mindful of two important considerations. (a) A proposal is likely to be more acceptable if a monetary return at an early stage in its development is indicated. It will be even more acceptable if at this early stage the power units are relatively small. One should therefore try to conceive a power system which conforms to an evolutionary process of development that proceeds from small units to larger more economical ones yet being suitable at each stage to a special economically viable application. (b) Clearly there are townships where remoteness now causes relatively high energy prices and where the incidence of solar radiation in the vicinity is high. If the evolutionary process of development is possible then obviously one would look to these townships as being first applications. Therefore our search for a true alternative solar energy source has been qualified to the extent that it should be immediately applicable to small remote sunny townships but capable of evolving eventually into a large scale source.

Consideration of the extent of Australia's potential solar energy resources has further qualified our search. The extent of these resources, conservatively estimated on the basis of 10 MW of electric power, or its equivalent, per square kilometre of sunny land area, are such that the potential of the now unused semi-arid parts of Australia vastly exceeds the country's projected needs. Indeed, it more nearly matches those of the region around Australia including South East Asia and Japan. It would be advantageous then if we could discover a system at least compatible with the notion of development to this major extent and compatible with a likely projected method for manufacturing a synthetic liquid fuel which would enable solar energy to be exported.

7.2 Specific problems. A system which satisfies the requirements of the previous section must comprise certain basic elements. Certainly it must have an energy storage component in order to provide power during the night and on dull days. Certainly it must have a means of collecting the solar energy and these collectors must cover an easily calculable area in the cheapest possible manner commensurate with good efficiency and compatibility with the rest of the system. Because the areas covered by the collectors tend to be large as the collected power approaches tens and hundreds of MW there is also a problem of conducting the collected energy to a terminal or processing centre and subsequent transmission in bulk from that centre.

If the system is to be suitable for remote townships it must be one where ground preparation and field work during the construction and assembly stage is kept to a bare minimum because the maintenance of a labour force in a remote area is expensive. This requires in turn that the system be compatible with all likely terrains - flat or steeply undulating, and with a likely range of natural ground covers. The system must also be able to cope with a variety of weather conditions - hot and dry, rain, high humidity, cyclones, dust and sand storms.

8. RATIONAL SOLUTION

An examination of sunshine records at Griffith in central NSW has revealed that a square metre of surface situated near that town or at any similar sunny location, and continually turned to face the sun, will collect during a year the energy equivalent of about one barrel of oil or almost one fifth tonne of coal*. For all intents and purposes therefore the one square metre is equivalent to one barrel per year of oil or one fifth tonne of coal per year provided the surface is allied to a method of efficiently collecting and storing the solar energy and a means of presenting the energy to a consumer (e.g. a power station) as high temperature heat. The equivalence may be expressed in dollars by supposing that we require the collector surface, with its allied equipment, to repay itself in seven years (i.e. 15% to cover interest, depreciation, operation and maintenance). For oil and coal priced at $10 per bbl and $40 per tonne respectively, the equivalent cost of the collector etc. must then be $65 per m^2 when compared with oil, or $49 per m^2 when compared with coal. The oil and coal prices above are about the world market prices.

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* The figures are .9 bbl oil or .17 tonnes coal after allowing for a collection efficiency of 70%.

They do not necessarily apply in Australia due to the effective subsidisation of both oil and coal produced for home consumption. But they are probably near the mark for remote townships because of high transportation costs.

8.1 Cost constraints. The equivalent costs of a square metre of solar collector, are in effect cost constraints which one must work to when searching for a viable system. An alternative expression for this cost constraint is in terms of dollars per kilowatt of power generating capacity, viable values of which are much higher than is customary for coal or nuclear stations because the fuel and associated annual charges of these stations are being replaced by extra capital equipment.

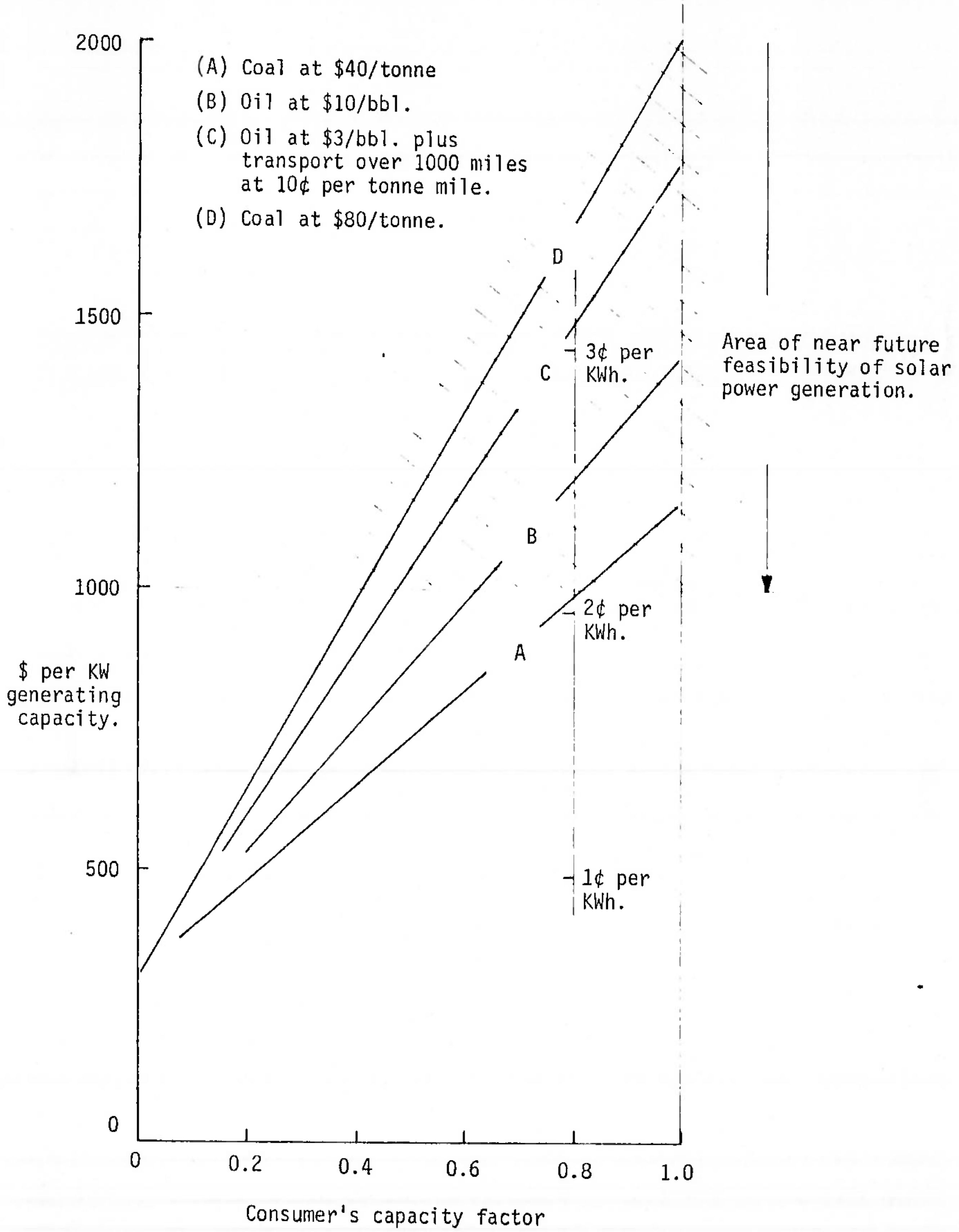
The method used previously to capitalise an energy rate of 1 bbl of oil per year may be adapted generally to capitalise all fuels in terms of $ per KW of installed capital given the price of the fuel, a charge rate on capital, the conversion rate of fuel to electric power, and the capacity factor of the generator. This latter factor, which depends on the pattern of consumption, is the fraction:

$$\frac{\text{energy produced per year}}{\text{maximum energy that could be produced}}$$

Fuel usage is proportional to capacity factor and therefore the total capital equivalent of a conventional power station varies with the capacity factor.

These features are brought out in the graph (fig. 8.1) where the total capital value per kW of generating capacity is shown as the sum of the usually quoted figure for the generating plant of 300 $ per kW plus a figure for the capitalisation of the fossil fuel estimated as described above.

The area of interest to us is shown shaded, i.e. the area where the total capital value of conventional plant



$$\text{Capacity Factor} = \frac{\text{Average power}}{\text{Maximum power capacity}}$$

TOTAL CAPITAL EQUIVALENT OF FOSSIL FUELLED POWER STATIONS AND MINIMUM COST OF POWER AT 0.8 CAPACITY FACTOR.

Figure 8.1

is high (say above \$1,000/kW) because the higher this value the easier it will be to make an equivalent solar energy system of equal or less capital value. The graph shows that a solar energy system is more likely to be competitive when it has a high capacity factor and when conventional fuels are expensive. The requirement of high capacity factor means that we should aim at what is commonly called a base load station.

When viewed in the light of the evolutionary process of development previously discussed, this goal of a base load station is significant. For remote townships the capacity factor is set by the consumer and is likely to be around 0.5 but if there is already a conventional plant it might be relegated with advantage to the role of a peaking station thus increasing the capacity factor of the solar station. But as development proceeds, and solar stations become competitive for supplying the larger communities, they would be vying directly with coal stations which are themselves now used as base load stations (with hydro electric peaking plants). It follows that coal stations would best be employed then as peaking stations where they would still be competitive (provided they were competitive with hydro electricity at this task).

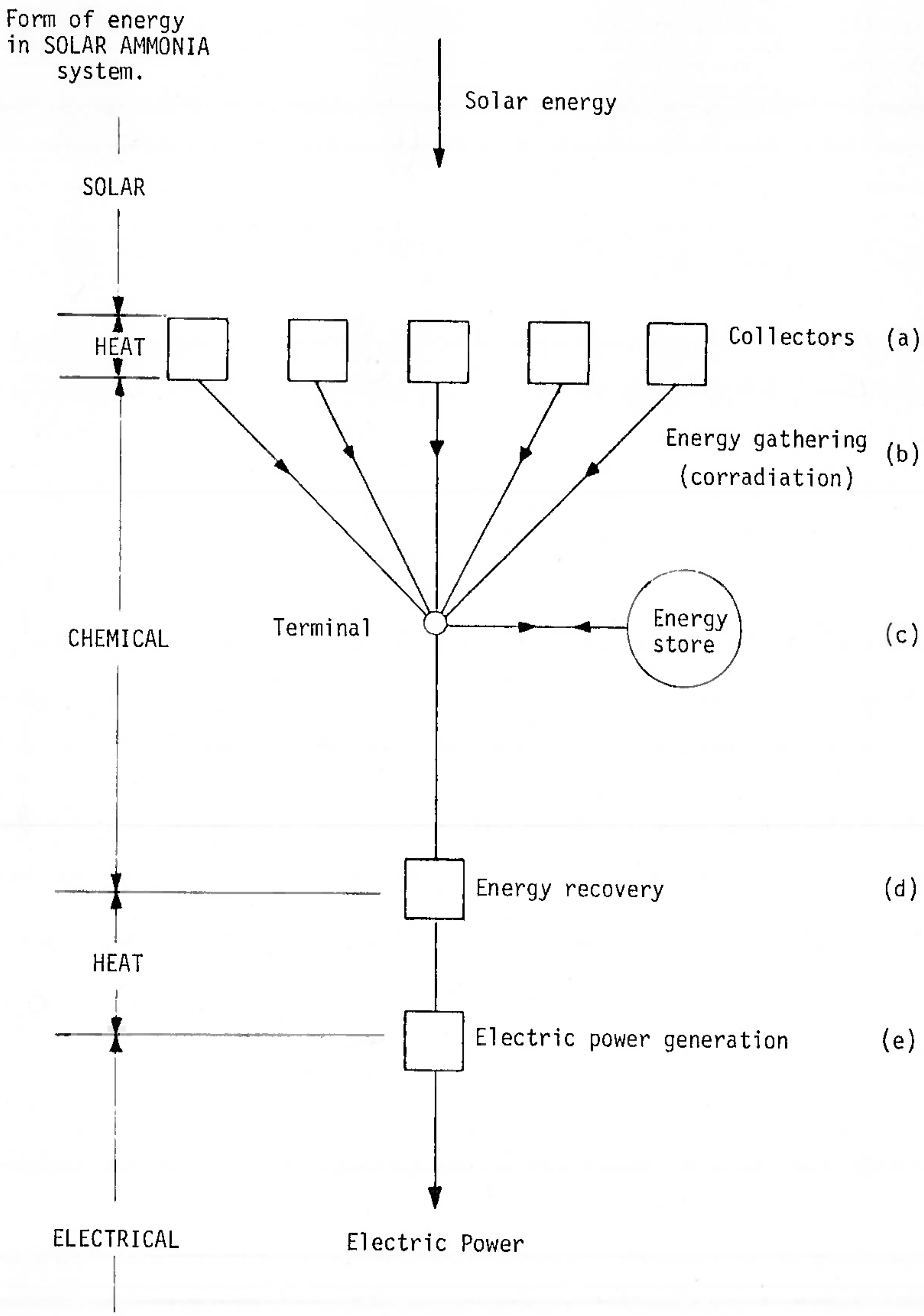
The conclusion which may be drawn is that there are effects which hasten the competitiveness of solar power on a large scale once it is shown to be competitive for remote townships. For it might be possible for the high capacity factor - moderate fossil fuel price situation of large scale generation - to be simultaneously and equally as attractive for solar energy as the low capacity factor-high fossil fuel price situation of remote townships.

8.2 Evolution. We have previously touched on the concept of evolutionary development. It is envisaged that a first viable application might be a station of about 10 MW_e for a mining community situated in Western Australia, Northern Territory, Queensland or South Australia. If this were to prove successful the market for similar stations would increase enabling further development, operating experience and economies of scale in manufacturing. We would expect the viability of solar stations to increase because of these effects and also because of the continuing increase in fossil fuel prices. Thus eventually they should be acceptable as large scale base load stations. We hesitate to put a time scale to this evolutionary process. One might expect an expansionary phase around 2000.

8.3 Essential elements of a base load solar power station. The essential elements are depicted in the diagram fig. 8.2. They are (a) the collectors; (b) energy gathering corradiative network converging to a central terminal; (c) energy store, (d) means for recovering the solar energy, e.g. as heat, (e) means for converting the recovered energy into a usable form, e.g. a steam generator coupled to a conventional turbo-alternator.

These essential elements could take many forms, e.g. the collectors (a) could be photo voltaic cells in which case the recovered energy in (d) would be raw direct current. But in this case it would be difficult to find a form of storage for element (c) and in fact this element might have to be placed after element (e) (e.g. by use of hydro electricity and water storage). For the reasons in the next paragraph there are great advantages to be gained by inserting the storage element as close to the collectors as possible. The system which we are studying has this feature and in addition enables the energy to be recovered as high temperature heat (although it is not stored as heat).

Our data on the incidence of solar radiation indicates that the capacity factor of elements (a) and (b) viz the collectors and gathering network will not exceed 0.25.



ESSENTIAL ELEMENTS OF A BASE LOAD SOLAR POWER STATION

Figure, 8.2

That is to say that in effect the sun shines brightly for only one quarter of each 24 hour day and for the rest of the time the collecting and gathering equipment must lie idle. Since one must pay for the maximum capacity of this equipment it follows that one must pay at least 4 times as much as would be necessary if the sun shone evenly, but correspondingly less brightly, day and night.

This factor, large as it is, must be increased still further because of a second consideration. All the elements (a) to (e) will have an efficiency of less than one, i.e. they will perform their task with some loss of energy. Hence, the average energy flow through element (a) is necessarily larger than the average energy flow through (e). It is unlikely that an overall efficiency of 20% will be exceeded which implies that the average energy throughput of the collectors and gathering elements will be 5 times the average power finally supplied to the consumer. Combining this factor with the previously derived factor of 4 implies that the power capacity of the pre-storage elements (a) and (b) must be 20 times the average consumption.

Of course this factor does not contain the full story. The form that the power takes at various stages is also important. For example, power in the form of heat may be more expensive to transmit than electrical power; power in the form of chemical energy of a fluid may be cheaper to transmit.

However we must conclude that an effective way of reducing the cost of a solar power system should be to provide an energy store as close to the collectors as possible and to employ a particularly inexpensive method of transmitting power from the collectors.

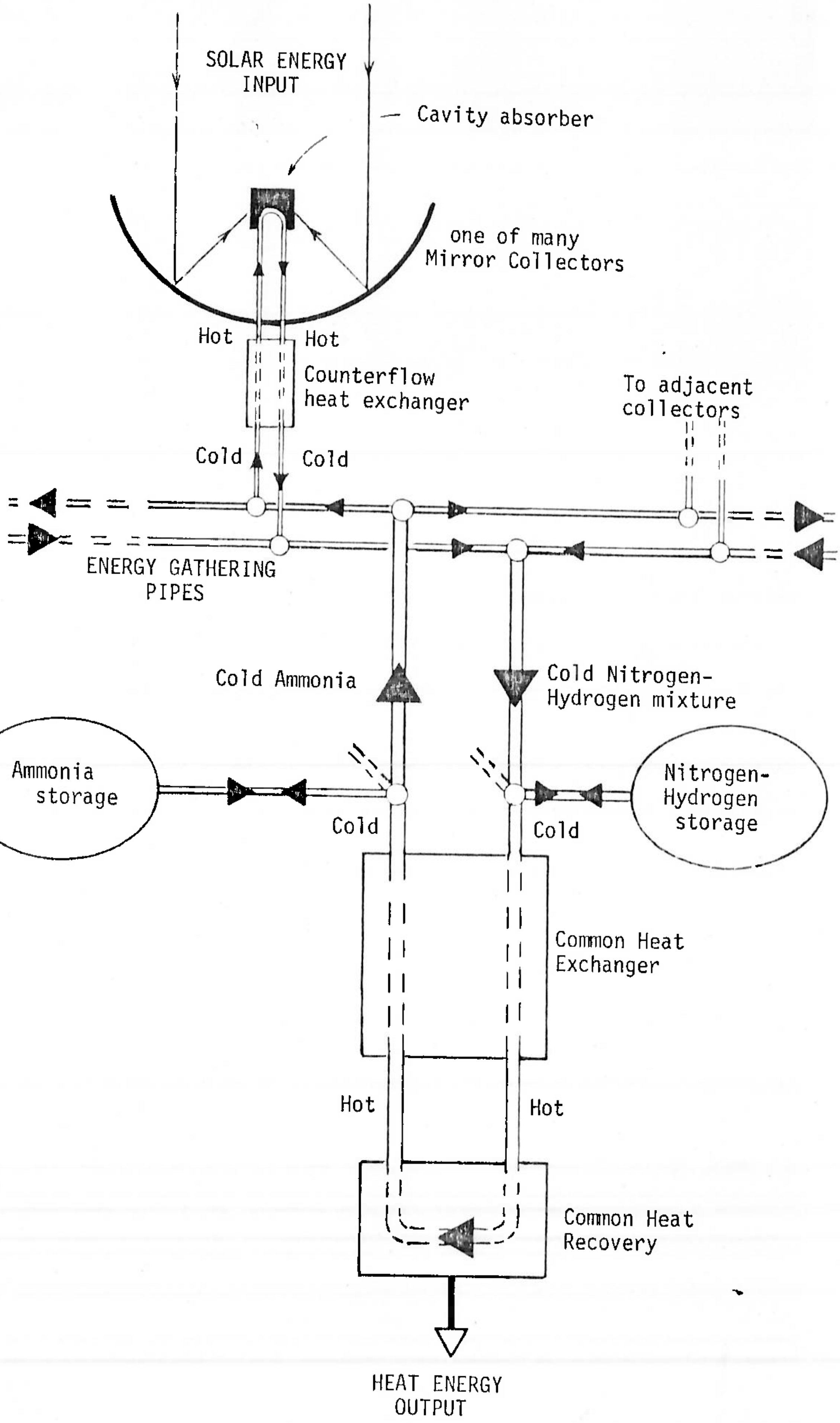
8.4 Storage - optimum capacity. From our observations of the annual variation in solar radiation we conclude that in order to use all the energy collected as effectively as possible, about 2 months of "black out" storage should be provided (i.e. if the sun were blacked out, the storage should allow the station to continue generating at an unaltered rate for 2 months). However the same result could be achieved by increasing the collector surface and reducing the storage, for an increase in collector area will reduce the number of winter days during which a net call on storage will have to be made.

Since both collectors and storage require investment funds, it is possible to discover an optimum combination having lowest overall cost. For the ANU solar ammonia system we believe the optimum figures are about 2 weeks of black out storage and up to 40% excess collector area, but these figures are very tentative.

The excess collector area would of course gather a superfluity of energy during summer and therefore it would be advantageous if a use for this energy could be found. One possible use applicable to the solar-ammonia system and discussed in Appendix II, is to manufacture ammonia. Sale of this would defray expenses and thus enable the price of electric power to be reduced. An intriguing outcome of this proposal is that the price of electricity should decrease as the price of fossil fuel increases, a possibility which springs from the fact that the production cost of ammonia is largely the cost of the energy locked chemically within it.

9. SOLAR-AMMONIA SYSTEM

It is evident from the previous discussion that in order to be viable a large scale solar energy system would have to cost no more than about $50 per square meter of collector. This figure applies to the collector element



SOLAR AMMONIA SYSTEM.

Figure, 9.1

itself and allied components up to the conventional steam generator. Higher figures, perhaps ten times higher, are applicable to smaller remote stations.

This cost constraint is difficult to meet and severely restricts the technologies from which one may choose. Nevertheless we believe we have selected a combination of technologies which has the best prospects of meeting the constraint. There follows a description of the elements of the solar-ammonia system which we have conceived and are presently studying.

9.1 Energy collection. We consider that paraboloidal mirrors pressed from sheet steel (similar to car bodies) have the best chance of being viable collectors. These are directional selective collectors, the two disadvantages of which are discussed in Appendix I, viz. (a) loss of the diffuse component of radiation; (b) requirement for tracking the sun. We consider that these disadvantages are more than compensated for by the advantages listed as follows:

(a) the basic form is inexpensive - one thin sheet press-formed in a simple operation. The dish shaped paraboloidal form is inherently rigid, so extra stiffening members do not have to be manufactured and attached.

Discussions we have had with experts in press forming indicate that collectors of this form will be sufficiently accurate and inexpensive although for the larger sizes, e.g. up to 5 meters diameter, wider steel sheets would have to be manufactured and also larger presses. However the volume of production would be great enough to justify many innovations in manufacturing equipment. For example, in employing collectors of 10 m^2 aperture area, some 2,000 collectors would be required per continuous MWe of generating capacity.

(b) Although tracking is a problem, it has the advantage of making the collector 1.4 times more effective in collecting solar energy when compared with the most favourably oriented fixed collector because the radiation always falls perpendicularly on the tracked surface.

(c) As previously discussed energy losses are comparatively small because the bulk of the collector is at ambient temperature. The mirror concentrates radiation onto an absorbing element losses from which are also small by virtue of its small size. Thus this type of collector is suitable for high temperature collection ($\sim$500°C).

A great deal of interaction occurs between the various features of a tracking mirror collector. For example, the necessity to be moveable in order to track offsets susceptibility to wind and sand damage because the collectors may now be evasively oriented. As an illustration of this consider two collectors sharing the same fixed vertical support by being hinged either side of it rather like two clam shells. This configuration would enable the collectors to close together and so provide mutual protection for their mirror surfaces at the same time forming an admirable aerodynamic structure which, when allowed to 'wind vane',would be capable of riding out strong storms.

We are hopeful that the same clam action might be used to control humidity and thus extend the life of the metallised mirror film. This might be achieved by closing the clam at night fall and at the onset of cloudy and rainy weather.

Similarly, because the collectors are moveable their supports need not be mounted on the ground in any specific or permanent manner. This obviates the requirement for foundations and on-the-spot adjustments of any kind which in turn ensures that field assembly costs will be as small as possible.

Thus the need to track provides advantages that will probably outweigh the disadvantages. Whether this proves to be the case or not, we foresee the solution to tracking being greatly helped by the rapid developments in electronics, computers and small motors. In order to extract the full advantages from the tracking facility we are experimenting with methods of controlling the movement of the collectors which are specifically suitable for handling the large numbers involved. The methods involve the use of a simple sun pointing error detector on each collector together with a shared computer.

The small absorbing element at the focus of each mirror collector will most probably be a hollow structure with a narrow mouth (a cavity) into which the reflected radiation will be directed. We have tentative designs of this device which appear to be practicable and inexpensive. The operation of this "cavity absorber" will be explained in greater detail in the next section.

9.2 Energy gathering (corradiation). In order to transport the energy from the collectors and to facilitate energy storage, we have chosen a method whereby solar heat energy is transformed into the chemical energy of a fluid flowing in pipes to the central terminal. We believe this method has the best foreseeable prospects for both energy transport and storage.

Thus in principle a fluid is made to flow through the cavity absorber of each collector where the fluid undergoes a chemical change in absorbing the collected solar energy. The fluid then passes to the central terminal where the solar energy is recovered as heat by reversal of the chemical change. The fluid, now in its original chemical form flows back to the individual collectors.

The particular reversible chemical change we have chosen to investigate first is the one involving ammonia. This substance changes to a gas mixture of nitrogen and hydrogen (hereinafter called an N-H mixture) upon absorbing solar heat, and reverts back to ammonia upon releasing the captured energy. Both of these processes occur at high temperature. However it is particularly important to note that although energy is absorbed and released as heat, its containment within the fluid does not cause the fluid to be hot. The energy enriched fluid may in fact travel from collector to terminal at the same temperature as the natural surroundings and the same applies also to the returning fluid. This is made possible by providing heat exchangers at both collector and recovery plant that enable the exchange of heat at each of these components from the outgoing to the incoming fluid.

9.3 Energy storage. Once the solar energy has been captured in the N-H mixture it remains only to store the N-H mixture in sufficient quantities in order to store a desired amount of energy. When the energy is eventually recovered it is also necessary to provide a storage space for the ammonia that will be produced. However, since ammonia is easily stored as a refrigerated liquid, the main problem is to find a sufficiently inexpensive storage vessel for the N-H gas mixture. The volumes of N-H gas involved are usually impractically large if the mixture is uncompressed but may be reduced to almost manageable size if it is compressed to several hundred times atmospheric pressure. However, it is then found that suitable high pressure storage vessels would be too expensive in comparison with our previously stated cost constraints.

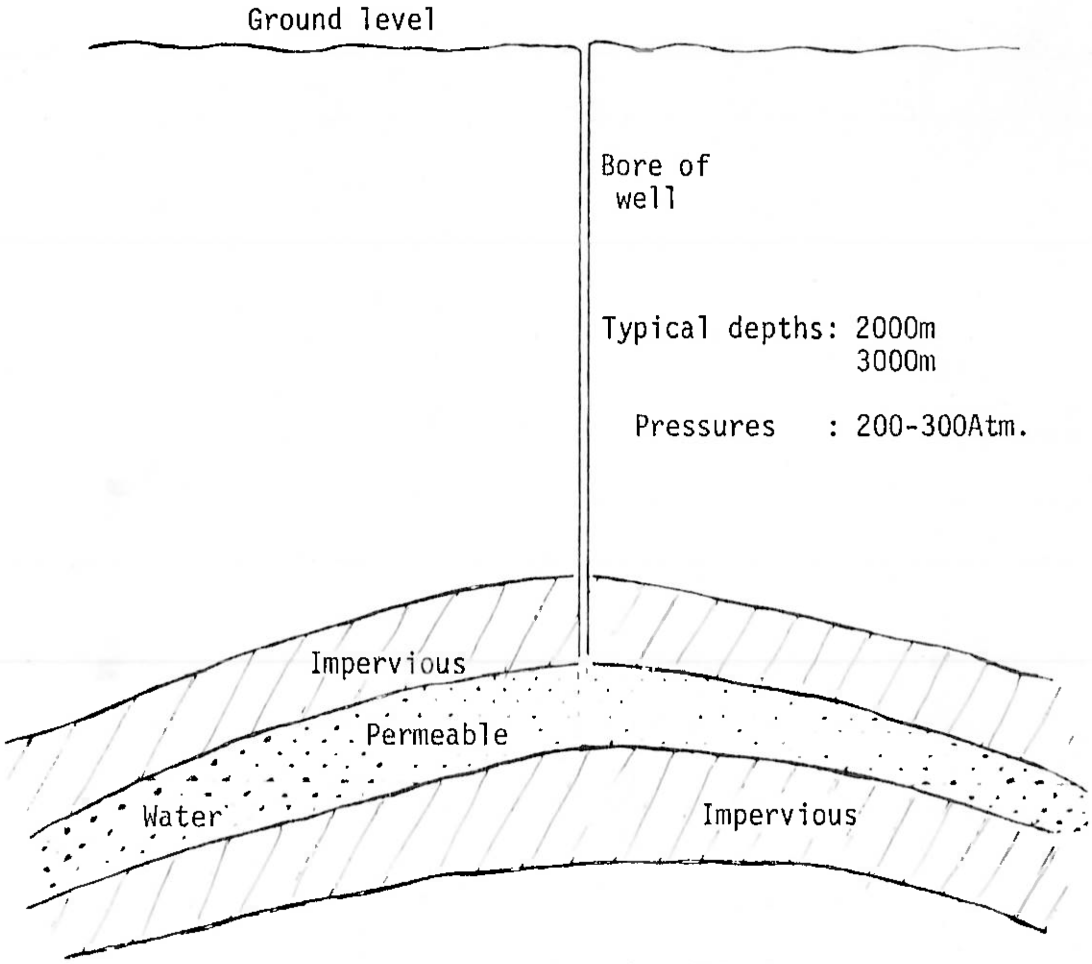
The only feasible economic method of storing the N-H gas is in natural underground reservoirs such as occur for water, oil and gas. There is a great variety of such reservoirs associated with sedimentary basins underlying three quarters of the continent. If disused oil or gas wells are used or an existing water bore, access to the reservoirs is already available. The general form of an underground reservoir is shown by the illustration of an aquifer in fig. 9.2. The top and bottom of the reservoirs are impervious cap rock and the sides are generally formed by trapped ground water. Between the top and bottom is a porous sedimentary rock or sand formation and the myriad small spaces between the rock particles constitute the reservoir.

An important feature of such reservoirs is that each has an operating pressure dictated by its depth. The pressure comes about through the weight of ground water contained in the earth above. In order to store gas in these reservoirs a pressure at least as high as this operating pressure must be exerted on the gas before it is able to push back the ground water that will otherwise be occupying the reservoir.

Another feature of underground reservoirs is that the maximum rate of entry and exit of the gas to the reservoir is dictated by the density of the gas, higher densities being the more favourable. Thus, because high density arises from high pressures, it is advantageous to employ deep reservoirs and this appears to be true also in economic terms despite the greatly increased expense of drilling deep wells or bores. It appears that a favourable depth would be 2,000 to 3,000 meters which would entail gas pressures of 200 to 300 times atmospheric pressure.

The economics of underground gas storage appear favourable but if they are to be employed it is necessary to ensure that the above-ground parts of the solar power system can be made compatible with the high pressures involved.

9.4 Compatibility of ammonia/N-H with high pressure gas storage. We have concluded that the best way to match the above-ground components with the requirement of high pressure gas storage is to operate the whole energy transfer system at roughly about the same high pressure. This mode of operation has several advantages:



Section of an AQUIFER, also
DISUSED OIL AND GAS WELLS,
SALT DOMES.

STORAGE OF GAS UNDERGROUND.

Figure, 9.2

(a) the avoidance of costly gas compressors which would need to consume a large fraction of the station's power production. Even if some of this compressor power were recovered during the withdrawal of the N-H from storage by employing an expansion engine, the nett power loss would still be significant.

(b) high pressure is favourable to most of the energy transfer components. The cavity absorbers and heat exchangers are considerably smaller and cheaper when designed for high pressure. This is because the volume flow rates are correspondingly smaller and the heat transfer mechanism more effective.

(c) the use of high pressure allows the pipes carrying the fluids to be considerably smaller in diameter and some to be also smaller in weight. In particular, the pipes connecting each mirror may be reduced to about 1/4 inch diameter which enables them to be laid as long continuous lengths of tubing reeled directly off a spool instead of the costly alternative of aligning and joining numerous shorter more rigid lengths. Since the assembly costs of the pipes are likely to be greater than the manufacturing costs, these benefits are significant.

Moreover, the smaller tubes are more flexible and are therefore able to conform more easily to natural terrain contours. They also enable a simple flexible connection to be made to the moveable collectors.

The ammonia/N-H reversible chemical reaction is compatible with high pressure. Ideally one would like a reaction which proceeded in either direction to an equilibrium composition of about half ammonia and half N-H at the selected operating pressure and temperature although a small deviation from this ideal is in order for solar power systems. This follows from consideration of the great number of cavity absorbers per energy recovery unit, their total cost, and the need for them to operate reliably without supervision. Thus it is beneficial to choose conditions and reactions that favour the energy absorbing reaction, if need be at the expense of the energy recovery reaction. The ammonia reaction equilibrates at about 35% ammonia for 300 atmospheres pressure and 500°C which is very satisfactory for our purposes.

Other properties of ammonia, nitrogen and hydrogen, lead us to conclude that the ammonia reaction is a reasonable choice. Although the N-H mixture is inflammable in air the wealth of experience in the ammonia synthesis industry indicates that the danger of fire is minimal. Generally there are no materials problems with N-H except hydrogen embrittlement which requires some care in selection of ferrous alloys. Ammonia is of relatively low toxicity and the gas is lighter than air. It is easily stored as a refrigerated liquid at atmospheric pressure and the liquid may be raised in pressure with negligible energy loss because it is almost incompressible. All common ferrous metals and most non-ferrous metals are compatible. Of the plastics, teflon and some synthetic and natural rubbers are suitable for use with ammonia.

The universal and perpetual availability of nitrogen and hydrogen and the kinship of ammonia to life processes also lends a certain aesthetic appeal.

10. IMPLICATIONS

Having now reviewed the components of the solar-ammonia system we are in a position to examine its implications especially in the light of the goals of section 7.

Certainly the system appears to be flexible because the collector modules are relatively small and it should only be a matter of choosing the right number to match any load from a few kW to hundreds of MW. However there are certain minimum viable limits. The central control of the tracking of the collectors requires probably a minimum of 10,000 collectors or about 5MW_e (base load). Again underground storage will probably be available in modules of about 10 MW_e (base load) per well. But apart from these limits the system is flexible in that the collectors may be disposed in any pattern in accord with the local terrain and other land uses and in a manner requiring a minimum of field labour. Moreover the system is capable of dealing with a variety of weather conditions by virtue of its tracking control sub-system which, incidentally, provides excellent around-the-clock performance monitoring of each collector and will therefore greatly reduce the cost of maintenance.

The minimum viable sizes quoted above still allow the system to be adapted to the needs of most remote townships.* Thus the system is compatible with an evolutionary process of development because many of these towns are in sunny localities and now experience high energy costs. In many cases the present energy costs are high enough to raise the cost constraint on the solar system to well over \$100 per m^2 of collector and this is almost certainly achievable with present technology.

Evolutionary development should occur smoothly towards large base load stations made possible by cheap underground storage.

The prospect for export of solar energy in the form of ammonia is promising (refer to Appendix II). Ammonia is the basis of the nitrogenous fertiliser industry and therefore the prospective demand for it will be immense and perpetual. Ammonia may also turn out to be a useful liquid fuel.

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* Power for small settlements such as cattle stations might better be supplied by individual solar powered generators with battery storage following the ideas being developed at the Electrical Engineering Department of Queensland University.

There are several other economic benefits which should be mentioned. The major industries that would be involved in the implementation of the solar ammonia method of power generation are those concerned with manufacturing steel pipes, tubes and automobile bodies. The potential is immense. For example, in order to feed a growth over 50 years to 10,000 MW_e of solar power generation, approximately 1.5 million pressed steel collectors would be required per year valued at perhaps 500 million dollars.* This is comparable to the present Australian motor vehicle body industry. The pipe and tube manufacturers would be similarly stimulated as would, of course, the steel industry. Moreover, Australia's balance of payments position would be improved over the period by an average of $650 million per year through the sale, at the world market prices, of the steaming coal thus saved.

11. RESEARCH

11.1 Progress to date. The energy conversion group has grown from a single member in 1973 to a total of six persons at present whose previous backgrounds range from a variety of skilled technologies, to engineering, physics, chemistry and metallurgy.

A great deal of theoretical and design work has been carried out covering the areas of thermodynamics, reaction kinetics, system analysis, various specific engineering designs, and several cost studies.

An experimental programme designed to fill in the knowledge gaps and demonstrate feasibility is underway comprising:

(a) collector orientation control - a rotatable platform fitted with a simple sun detector is connected to a small computer with the object of deriving versatile

* Assuming: area of each collector 10 m^2; cost 30 $ per m^2; life 15 years.

programs that require only 1/10,000 of the total time available to perform control computations. Such programs would then be capable of controlling 10,000 collectors in the manner described previously.

(b) the measurement of the rate of dissociation of ammonia into nitrogen and hydrogen under a variety of conditions and with a variety of catalysts. The object of this work is to gather data that will enable us to design the cavity absorber and heat exchanger and to examine a number of questions related to life of components, selection of materials and system behaviour. Experimental results obtained so far indicate that compact economical designs are feasible.

Projects recently commenced are:

(c) detailed theoretical study of underground storage;

(d) experimental study of reflective films suitable for metal substrates covering the types of film, their manufacture and application to the substrate, and the mechanisms of degradation of the films.

(e) continuous measurement of the direct component of radiation in a few representative sunny locations. We have tried processing related data accumulated by others but have discovered that there is virtually no reliable source of the specific information we require. We are therefore building our own field monitoring and recording station. In the course of this work we have consulted the Bureau of Meteorology and although they expressed an interest in beginning their own series of measurements, they are at present restricted by finance.

11.2 Future programme. Our future programme of research comprises the following projects:

(a) Collector orientation control. It is planned to continue experiments with a new two-axis tracking mount and to further develop the computer programmes. A mirror collector will probably be attached to the mount in preparation for experiments with a cavity absorber.

(b) Reflective films. Apparatus is now being built for simulating a variety of weather conditions and for measuring several optical properties. The primary object of research with this equipment will be to determine the fundamental mechanisms of deterioration of several types of reflective metal films. The effects of humidity, water droplets and hygroscopic dust particles will be particularly examined. We plan to isolate the major causes of deterioration and devise practical means of controlling them, e.g. by employing the "clam" configuration. It is planned to extend this work to cover film manufacturing and application techniques.

(c) Mirror collectors. This project is concerned with the design of paraboloidal mirrors, and their mounts, manufacturing methods, and testing, e.g. in wind tunnels. It will involve some co-operation with industrial research laboratories contacts with which have already been made.

(d) Energy transfer. The experiments now proceeding on the dissociation of ammonia will be extended into an examination of a complete energy absorbing, transferring and recovery system.

(e) Storage. A literature search and allied theoretical and system studies will continue. We hope to be able to do some laboratory experiments related to the solution of hydrogen in water in permeable rocks at high pressure and also measurements of the viscosity of high pressure N-H gas mixtures. We would like eventually to carry out a field test with an existing well or bore.

(f) Solar radiation measurement. The field monitoring and recording station will be completed and employed to gather relevant data.

11.3 Financial requirements. We can envisage a three stage development of the Solar Ammonia process, only the first stage of which is relatively clear at present.

Experimental plan. A five year period seems to be required to complete our initial programme which is intended to provide a sound body of knowledge from which a Pilot Scheme or 'Proof of Concept' can be commenced. For this programme, we believe a total of about $2,000,000 is needed to achieve the results envisaged. This amount, at May 1976 prices, would fund our present staff of six (plus two others providing workshop assistance) and allow us to expand the group by 10 persons, as outlined in Table I. Allowing for existing staff expenditure which has built up now to the rate of $100,000 per year and an expenditure at present of about $20,000 per year for materials and equipment, and on the assumption that this funding can continue from University sources, an amount of about $1,400,000 over five years would be needed as a special grant. (If University sources could no longer provide the present staff and materials and equipment, then the full $2,000,000 grant would be required.) Considerable assistance from industry in providing materials and manufacturing services would be needed in addition. (We expect such assistance would be forthcoming.)

We consider it might be possible in this plan to carry out experimental studies on a "closed loop" system which takes solar energy from computer-controlled paraboloidal mirrors tracking the sun, transfers the energy through the ammonia process and gives an output of heat or electricity and/or ammonia. Notional output power would be of the order of several kilowatts. Underground storage would not be involved at this stage unless a great deal of assistance can be provided (for example from the oil or gas industry). However, a considerable amount of theoretical and practical work on storage would be carried out.

Pilot scheme. Data and techniques resulting from the first phase would allow Engineering Design and Optimization of a pilot scheme intended to ensure proof of concept. Depending on the nature of the results achieved the proof of concept phase might take a further several years, perhaps less than five, depending on allocation of resources at that stage.

Solar power system for remote township. Successful completion of the Proof of Concept experiment would enable the specification and building of a (say) 10 MW solar ammonia stand alone system at a remote township at a cost which may be of the order of $10 million.

We stress the very tentative nature of the above figures. Our theoretical and experimental investigations so far lead us to believe that a successful prototype system can be built in the manner indicated but until this is realised in actual practice, there is no absolute assurance of success.

12. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Important features of the solar-ammonia system for power generation are:

Collectors are steerable dish mirrors press formed from steel sheet. The reflective film will probably be anodised aluminium.

Collectors are to be steered by an advanced method which promises to negate the presently recognised disadvantages of moving collectors.

Long term, loss-less energy storage is possible.

The energy store is adjacent to the collectors. Thus only the collectors and the lines to the store operate at low capacity factor. Among the few proposals that provide for long term storage, none possess this advantage which has important economic implications.

Energy is stored as chemical energy of a gas mixture. The most economical reservoirs for this gas are natural ones occurring underground at moderate depths. Consequently, system pressure is determined by the natural pressures in these structures which are a few hundred atmospheres.

Compactness of system components results from adoption of these pressures.

The minimum viable plant size is about 10 MW.

An early application will be to a remote township.

The system can produce ammonia as well as electricity. Production of both by the same plant is economically favourable.

The implementation of solar power generation will have far reaching economic effects on indigenous industries.

We recommend support of our work by means of a special grant to the A.N.U. of at least $1.4 million to cover the next five years.

TABLE I

	Research Workers (existing position in brackets)	Technical Workers (existing position in brackets)	Research Equipment
(a) Collector orientation			
research equipment			$50,000
1 dedicated computer			$30,000
1 research worker	1		
1 technical worker		(1)	
(b) Reflective films			
apparatus & instruments			$40,000
1 research worker	(1)		
1 technical worker		1	
(c) Mirror collectors			
1 research worker	1		
1 technical worker		1	
(d) Energy transfer			
control equipment, pumps and instruments			$60,000
1 research worker	(1)		
2 technical workers		2	
(e) Storage (excluding field tests)			
research equipment			$40,000
1 research worker	1		
(f) Radiation measurements			
research equipment			$40,000
1 research worker	1		
1 technical worker		1	
(g) General instrumentation			$40,000
Shared workers			
1 research worker	(1)		
3 technical workers		(2) 1	
	(3) 4	(3) 6	$300,000

In addition to the above we estimate a requirement for expendable research materials of about $40,000 per annum.

Summary.	Total salaries (16)	$1,500,000
	Equipment	300,000
	Expendable materials	200,000
		$2,000,000*

* At May 1976 prices.

APPENDIX I

TWO FORMS OF SELECTIVITY WHICH REDUCE RE-RADIATION LOSSES FROM COLLECTORS

Emission selectivity. This is the property of special surface coatings, usually referred to as "selective coatings", which allow easy absorption and re-emission of high temperature energy, as for example that coming from the sun, but poor absorption and re-emission of low temperature heat, as for example that coming from the surface itself if not too hot. Thus the sun's energy enters the surface easily and at the same time the surface's own heat is prevented from easily escaping.

Directional selectivity. This is the property of a collector which confines both its absorption and re-emission of energy to a narrow intrinsic beam in a similar fashion to a directional radio antenna. Thus the beam acts as a two way path between the collector and anything which the beam intersects. Since the sun occupies a very small area of the sky (1/100,000) the beam may be very narrow and still carry all the energy that could possibly travel directly from the sun to the collector. Conversely, the narrowness of the beam greatly reduces the re-emission of energy from the collector thus rendering it highly efficient.

Contrasts and comparisons. Whereas absorptivity/emmissivity ratios of as much as 100:1 may be achieved (with difficulty) with emission selectivity, equivalent ratios of 1000:1 are easily obtained using directional selectivity. Directional selectivity is therefore able to achieve higher temperatures for a given loss, and unlike emission selectivity there is no inherent limitation to the ratio as the operating temperature approaches the sun's temperature.

Both methods suffer from degradation of critical surface properties: for emission selectivity the entire surface area of the collector must maintain the selective property at the working temperature; for directional selectivity the collector surface is a mirror surface at ambient temperature whose reflectivity usually worsens with time. In the latter case the absorber element itself is relatively small in size (e.g. 1/1000) whose surface need not possess any exotic property.

Emission selectivity effectively reduces the re-radiation loss from the collector-absorber surface but there is still the problem of the convection and conduction heat losses. Hence with each square meter of collector employing emission selectivity there must be associated an equivalent area of an impediment to each of these additional losses. These impediments are generally a glass sheet in front and a mineral wool sheet behind the collector surface or alternatively a glass envelope back and front containing a vacuum.

In contrast, directional selectivity requires only that the bulk of the collector surface be an ambient temperature mirror. There are no convection or conduction losses from this collector surface so no secondary impedimentary surfaces are required. The very small absorber element does suffer however from convection and conduction losses since it is at the operating temperature but because of its very small relative size these problems and their solutions are reduced proportionally.

The one difficulty of employing directional selectivity not shared by the alternative is that the directional beam must be continually moved so as to intersect the sun. This is generally accomplished by steering the whole collector.

One criticism often raised against the use of directional selectivity is that sky or diffuse radiation is excluded from the collecting beam. This diffuse radiation often amounts to 10% of the maximum direct radiation from the sun. Thus it tends to be a more significant fraction of the total energy in generally overcast localities but in sunny inland areas is less significant. In any case the loss due to the exclusion of the diffuse radiation from directionally selective collectors is generally more than offset by the reduction in re-radiation, convection and conduction losses (assuming similar operating temperatures). The unimportance of the diffuse radiation even to emission selective collectors is aptly demonstrated by the usual practice adopted in orientating these collectors so as to maximise the direct radiation input at the expense of collecting the full amount of available diffuse radiation.

APPENDIX II

THE PRODUCTION OF AMMONIA FROM SOLAR ENERGY

In the solar ammonia system energy is transferred by continuously dissociating and resynthesising ammonia. The essential components for the production of ammonia therefore already exist.

The method envisaged for producing an excess of ammonia for external consumption is to use the output of electricity to electrolyse water into oxygen and hydrogen, and to extract nitrogen from air by fractional distillation of liquid air. The former process requires most of the electrical energy. Both processes produce oxygen as a saleable by-product.

The nitrogen and hydrogen gases so produced are converted to ammonia by the synthesiser, then extracted from the system and sold.

The solar ammonia system may be used to simultaneously produce electricity and ammonia for external consumption. The advantage of dual production is that the proceeds from the sale of ammonia may be used to reduce the electric power costs, an arrangement that will be economically viable before the advent of commercial solar systems devoted entirely to ammonia production. This is because optimised solar power generation systems will have excessive collector capacity during summer and therefore, provided ammonia production is confined to this season, the marginal cost of production will not contain a servicing charge for extra collectors. It appears that, even with present technology, a marginal cost of production of about 100 $ per tonne could be achieved which is to be compared with a market price of about 300 $ per tonne.

The marginal cost of production is independent of collector costs. However in order to profitably operate a system devoted entirely to ammonia production, the collectors must be cheaper than a certain maximum which will depend on the prevailing market price of ammonia. At present the break-even maximum cost of collectors appears to be about 90 \$ per m^2 which is just within reach of existing technology.

Fig. II(a) illustrates what may be achieved in the near future. The plant costs shown are either existing values or projections into the near future and the choice of capacities of the several components is based on hourly measurements of solar radiation at Griffith, N.S.W. for the years 1972 and 1973.

This illustration shows that it will be possible to defray costs almost entirely through the sale of ammonia leaving a residual of a few cents per kWh to be recovered through the sale of electric power. Obviously the position will further improve as the market price for ammonia increases as it is bound to do in proportion to increases in oil and natural gas prices. Fig. II(b) shows the expected dependence of the price of electric power on the price of ammonia based on collectors at 30 \$ per m^2 and Fig. II(c) shows the dependence on the cost of collectors.

One may conclude that a most promising method of solar power generation is in combination with ammonia production which has the most valuable property that the price of electric power reduces as the price of fossil fuel increases.

CASH FLOW

per square metre

INCOME		OUTGOING	
		To collection charges	\$4.50
		To storage charges	\$1.44
		To storage access etc.	\$3.80
From sale of ammonia	\$8.50	To N-H generation	.56
	\$8.50		\$10.30
		Net outgoing	\$1.80

Hence charge to consumer \$1.80 for 164KW hours

= 1.1 cents/KWh.

Alternatively: per square metre

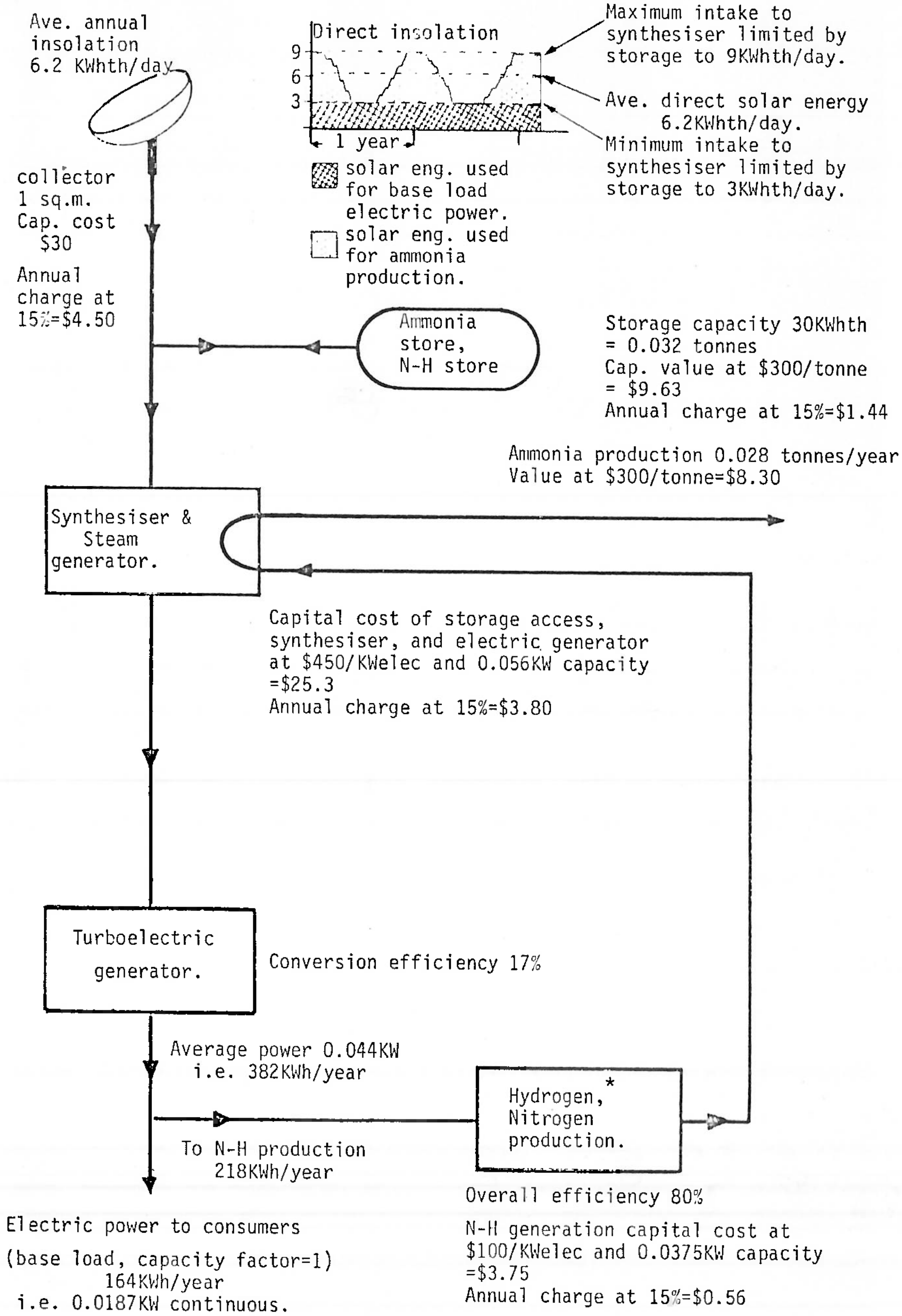
Total capital	\$68.7
Capital attributable to ammonia production as 15% investment	\$56.7
Balance of capital attributable to consumer power generation	\$12.0

Equivalent \$/KW = 12/0.0187

= \$642/KW.

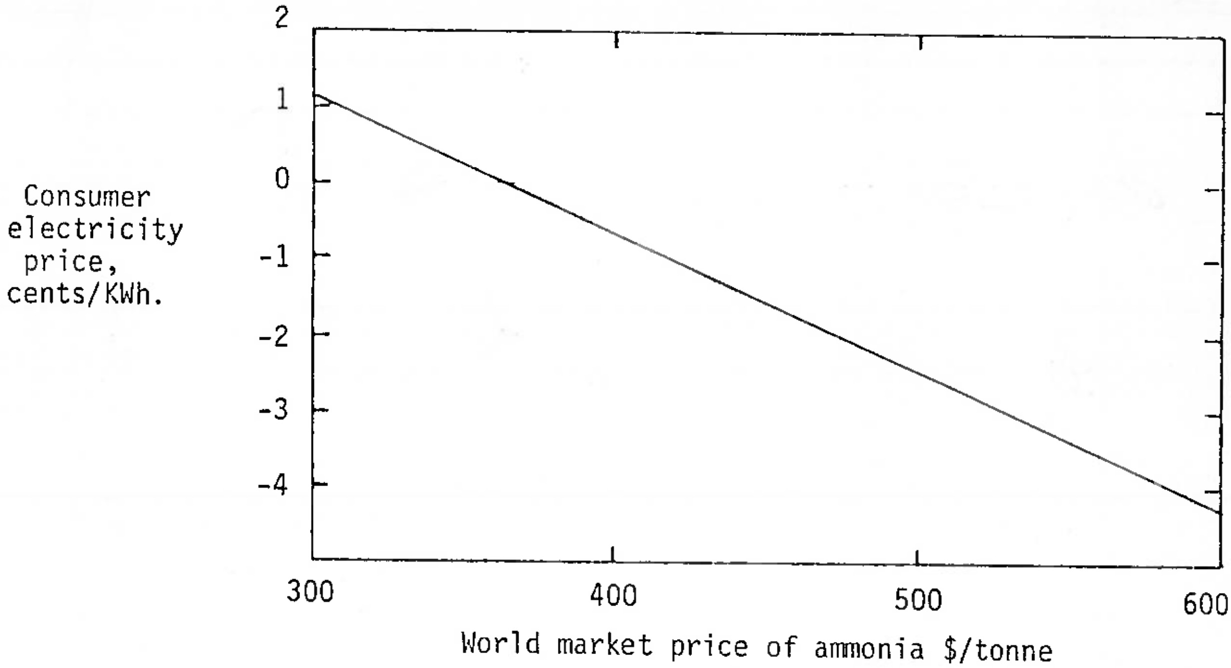
SOLAR POWER GENERATION COMBINED WITH AMMONIA PRODUCTION: AN ECONOMIC ASSESSMENT

Figure II(a) (and opposite)



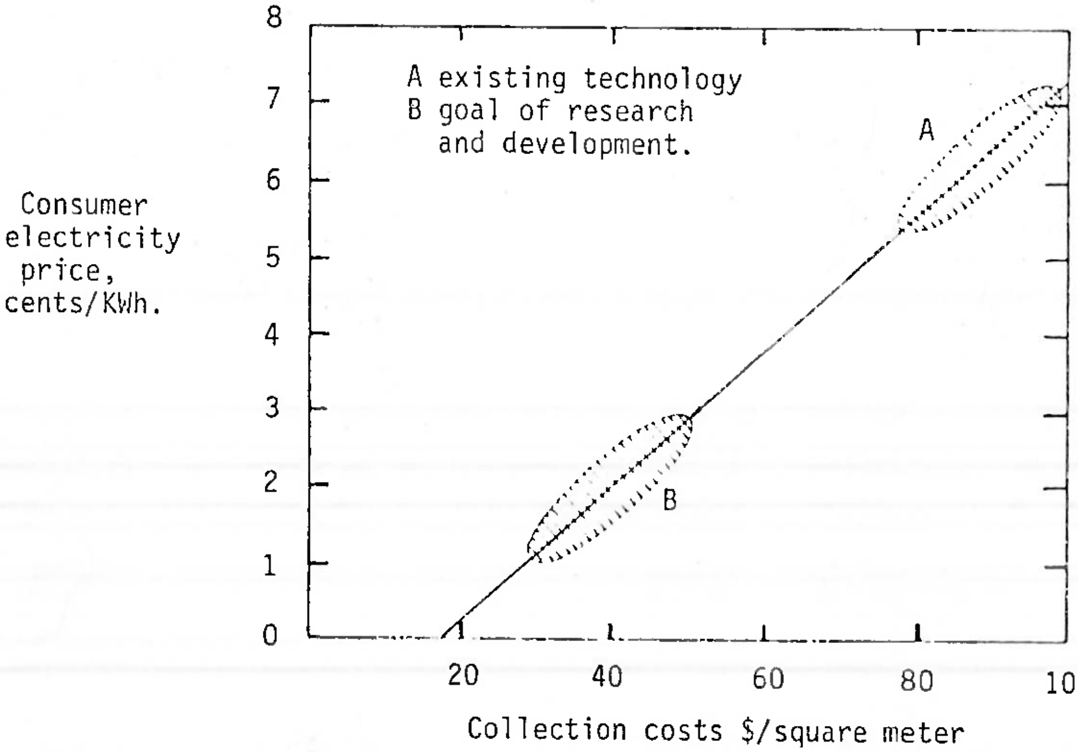
*Hydrogen from high pressure electrolysis of water; oxygen a byproduct.
Nitrogen from fractional distillation of air, oxygen and rare gases byproducts.

Figure II(a)



SENSITIVITY OF ELECTRICITY PRICE TO WORLD MARKET PRICE OF AMMONIA

Figure II(b)



SENSITIVITY OF ELECTRICITY PRICE TO SOLAR ENERGY COLLECTION COSTS

Figure II(c)

APPENDIX III

SOLAR AMMONIA SYSTEM: COMPARISON WITH CENTRAL TOWER SYSTEM

The solar-ammonia system is classed as a distributed system, i.e. it is based on a large number of individually focussing mirror collectors. Distributed systems may be contrasted with the tower concept described below:

1. Central tower. A large number of heliostats surround a tower upon which is a single receiver. Each heliostat is flat or almost so and is continually angled so as to reflect sunlight onto the receiver. There might be 10,000 or 100,000 heliostats for each tower which might be up to 500 m high.

Certain sites for the tower are more favourable than others, e.g. a hillside facing the equator would be favourable provided it was roughly circular and of sufficient size (approx. 4 tower heights in diameter). The site has to be carefully surveyed because of the need for each heliostat to be as close as possible to the tower without unduly blocking the reflected energy from its neighbours or being shaded by its neighbours. Arising also from the need to conserve space and for careful layout it is likely that a certain amount of ground preparation is required in the form of levelling out local irregularities in topography.

Several proposals call for rather large heliostats, e.g. 6 m x 6 m which are to be assembled in situ and which require firm concrete foundations. Several proposals call for accurate alignment in situ of a sensor placed in front of each heliostat as the error sensing device of the heliostat steering servo-mechanism. One proposal calls for the adjustment, in the field, of about 20 individual facets of each heliostat.

The tower turns out not to be a comparatively expensive item. It has however to be built in situ, adjacent to or within the array of heliostats and obviously requires special expertise to erect.

The heliostats must be continually steered so as to face a point in the sky angularly half way between the sun and the receiver. This is generally achieved by fixing on the ground in front of each heliostat a sensing device through which some of the reflected radiation passes. Deviations in the direction of this radiation from the true direction of the receiver on top of the tower are detected by this device and used to correct the facing direction of the relevant heliostat. Thus each sensing device must be rigidly mounted and individually adjusted.

The required accuracy of steering is influenced by the fact that the reflected radiation travelling to the receiver from each heliostat will waver in direction by twice the steering error.

In general the heliostats will rarely face the sun squarely. It follows that the area of the heliostats required to intercept a given quantity of radiation is greater than the aperture area of a distributed system wherein all the collectors face the sun squarely all the time.

2. Comparison. Mirrors in the solar-ammonia system are paraboloidal in shape with a flange around the rim, a basically more rigid configuration than a flat surface required by the heliostats of the central tower system and a potentially cheaper form to manufacture.

Nevertheless, American cost studies comparing tower systems and distributed systems and based on existing technology, show, area-for-area, heliostats to be slightly cheaper than paraboloidal mirrors. However further development of both tower and distributed systems is likely to reverse this situation.

The solar-ammonia system, for example, stands to gain considerably from the fact that it is based on pressed steel mirrors using equipment and techniques already developed for the motor industry. However this advantage cannot yet be realised because: (i) large enough presses are not available, (ii) suitable methods for applying mirror surfaces to steel are yet to be selected. Despite these problems there is considerable promise that mirrors made in this way will, in the long term, turn out to be cheaper than those considered in the American studies and also cheaper than flat heliostats even after allowing for their evolution through cheaper manufacturing methods.

Both heliostats and mirrors have to be moved in accordance with the relative motion of the sun. The provision for power and control wires to the heliostats in central tower studies appears to have been partially overlooked until recently. Hildebrandt et al. at Houston University have stated verbally that recent estimates they have made for their central tower study are $2 to $3 per foot for these lines which is presently causing considerable concern. In contrast, recent estimates for the connecting tubing for the transport of the reactants in the ANU Solar-Ammonia System run at 22 cents per metre (i.e. 11 cents for each of a pair) for the materials alone. The high cost in the first case for the U.S.A. system is attributed to the need for protection either by burying or by routing overhead and presumably a coaxial cable is included for control signals. On the other hand it is our hope that the steel tubes can serve the tripple purpose of reactant transport, control power and control signals. It is probable that the tubes will be sufficiently robust to lay directly on the ground.

In summary, there is hope that ultimately the mirrors and tubes of the Solar-Ammonia System will be cheaper than the heliostats and cables of the central tower concept. If this is so, and remembering that the transport of energy along the tubes will also be thrown in for free as it were, our distributed system will have a decided advantage over the central tower system. However it may still be offset by the aggregate cost of focal devices and the central synthesis components (which must be set against the cost of the tower and receiver on top of it, energy transport down the tower and possibly a steam generator, if sodium is used as the heat transport medium).

Lifetime, operation and maintenance and the effect of weather are not specifically considered in any of the U.S.A. cost studies. The central control concept of the A.N.U. scheme should be particularly effective in lowering costs associated with these aspects. Wind and sand damage is taken especially seriously in the Solar-Ammonia concept and as a consequence, there has been evolved the basic "clam" configuration in which two paraboloidal mirrors can be made to form an aerodynamically low drag profile which provides mutual protection for the two mirror surfaces. The method of steering the mirrors involves an adaptive or learning process which eliminates practically all in situ field adjustments or alignments. Consequently the mirrors need not be anchored to the ground, although the present proposal calls for them to be bolted in pairs to posts set and backfilled in augured holes.

3. Summary. The Solar-Ammonia System promises to have the following advantages over the central tower:

(a) paraboloidal mirrors are inherently rigid whereas flat mirrors of the central tower require additional structure to attain rigidity and therefore must be more expensive;

(b) mirror control is easier because sensors are mounted on the mirror instead of fixed on the ground and adjusted, and because less steering accuracy is required;

(c) there are fewer constraints on site selection and on the placing of mirrors relative to each other;

(d) provision of a tower and the vertical energy transfer in it is avoided;

(e) there is inherent capacity for energy storage;

(f) the essential mirror umbillicals may be made to serve two functions: energy transfer from mirror and mirror control. The latter function must be provided in the central tower as well as in the A.N.U. system.

(g) the effective aperture is always equal to the actual aperture (in the tower system the effective aperture is generally less than the actual because the heliostats do not face the sun squarely).

APPENDIX IV

THE SOLAR METHANOL SYSTEM

Ammonia is not the only fluid suitable for thermochemical energy transfer, although because of its inherent chemical simplicity we believe that it is the first choice for development of a viable energy transfer system. Of the several alternative working fluids that have been suggested, we have recently begun to take an active interest in methanol, or as it is more commonly known, wood alcohol. Methanol is a chemical of vast commercial importance, the 1970 figures indicating an annual production rate for the Western World of over 8 million tonnes, increasing by more than 1 million tonnes per year. It is the basic raw material of many chemical industries including the manufacture of plastics, adhesives and synthetic resins. Methanol is synthesized at high temperature and high pressure from a mixture of hydrogen and carbon monoxide derived currently from natural gas or Naphtha feedstock, with coal expected to be used extensively in the future.

The similarities of a solar methanol system to the solar ammonia system discussed in detail in this submission are clear. In the solar methanol system, methanol rather than ammonia is dissociated at high temperature and high pressure at solar collectors, and the hydrogen and carbon monoxide gases produced are resynthesized at the central plant, again with the release of considerable amounts of high grade heat suitable for electricity production. Both methanol and ammonia are of considerable commercial importance and are therefore both suited for the duel system of electricity and commodity production from solar energy, as discussed above in Appendix II. Indeed, methanol is valuable not only as the primary source of a wide range of chemicals and plastics, but is also one of the logical replacements for liquid petroleum fuels. In this latter context, a solar methanol system has vast commercial potential and indeed could be the vehicle for eventually integrating solar energy utilization with the coal industry.

PHOTOGRAPHIC SUPPLEMENT