



THE
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UNIVERSITY

RESEARCH SCHOOL OF PHYSICAL SCIENCES

SOLAR AMMONIA SYSTEM

NOTES ON COST

P O CARDEN

INSTITUTE OF ADVANCED STUDIES

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Notes on Cost

The costs of solar energy production particularly with regard to solar ammonia, have been dealt with at various times in publications of the Energy Conversion Group. Publications or extracts from publications are given here in chronological order. In addition two special notes have been prepared: on the relation between capital cost of a solar energy plant and the breakeven cost of primary fossil energy; and on the value of ammonia by-production.

Publications:

Extract from 'Artificial Intelligence in Solar Power Systems'
P O Carden 1974, pp 11-14 and tables.

'Corar Costs - Preliminary Estimates' P O Carden 1976.

Extracts from:

'Mass Utilisation of Solar Energy' P O Carden, S Kaneff

a. Section B Part II p 4. Cost constraints.

b. Appendix II 'The production of ammonia from solar energy'

7. ECONOMIC VIABILITY

Let us now turn our attention to the question of whether or not the solar power system using artificial intelligence can be competitive with alternative energy sources. In order to do this it is necessary to be more explicit in describing the design of a unit but in so doing, it is not intended to imply that a judgement is being made as to the best way of meeting the specification. It has been assumed that each flat mirror consists of a number of glass mirrors, approximately 50 cms square, attached to a common pressed steel support. The costs associated with these mirrors include a considerable fraction of the amount allocated in Table III for factory assembling and testing

A design with two rotary actuators per unit has been chosen. Each mirror support is mounted about a horizontal central axis from a triangular frame which in turn swings from a vertical pole like a gate. Two units may share a common pole in this arrangement (fig. 2). The pole may be held upright by means of horizontally extended feet or by fitting its end into a hole drilled in the ground. The mirrors may be so arranged that their faces can come together for mutual protection and when in this position they may act like a weather vane in high winds thus minimising wind forces.

The common focus is envisaged as being mounted on a guyed mast of a design that provides the required strength for minimum cost and in which rigidity is not necessarily a prime consideration. Three modified units track the common focus thus enabling its co-ordinates to be fed to the intelligence system. The cost of these units

and of two beacons are included in the cost of the common focus support.

The height of the mast would be approximately 200 m for the system of 10,000 units and one computer as described but there is no reason why a number of such systems should not share a common focus and power plant in which case the mast would have to be higher. The advantage of doing this lies in the fact that focus power is proportional to the square of the height and therefore there is the possibility of a considerable economy of scale with plant outputs approaching 200 MW_e .

Since we are endeavouring to equate solar energy to fuel oil with most probably thermodynamic conversion of heat to electricity in mind in either case, it is not appropriate to include a focus boiler in the costing nor any other part of the thermal and electric plant. It would, however, be appropriate to add that part of the cost of the common focus over and above the cost of an equivalent conventional boiler, less the cost of fuel handling, smoke emission control, etc.

It might be argued that the solar fuelled electric power station will be more remotely situated from the consumer than its oil fuelled counterpart and that, therefore, the unequal costs of electric power transmission should be accounted for. As contrary evidence we have the present trends to locate power stations away from consumers for environmental reasons (especially true in the case of the nuclear alternative) and to locate coal burning stations on coal fields.

Neither the non equivalence of the boiler or the inequality of power transmission costs has been taken into account in preparing the tables. Similarly the question of energy storage has been ignored.

Table I gives a notional set of figures covering the value of the energy produced in terms of the value of fuel oil saved and the various expenses involved in operation. The concluding calculation in Table I indicates that the sum available to

pay for interest and depreciation on the capital equipment referred to each square meter of collecting area is about \$8 per annum.

Table II shows that this sum allows a total capital expenditure of about \$42 per m^2 .

Table III shows how this allowable cost might be eventually apportioned assuming the mirror area of each reflective unit is $10 m^2$ and assuming that a system comprises 10,000 such units.

Several comments should be made about these tables. Firstly the value of the energy produced is, of course, critically dependent on the value assumed for the alternative fuel which, in this case, was chosen with some regard to present trends but mainly with the feasibility of the breakdown of costs in Table III in mind.

Secondly the value of energy produced is also critically dependent on the efficiency of accumulation, i. e. the efficiency of transmission of the energy from collectors to common focus. The 75% figure given in table I is felt to be justified on the grounds that re-radiation, convection, and conduction losses can in principle be reduced to a few percent with relatively small cost in an optical system which means that the major loss is associated with the reflectivity of the mirrors and the transmittance through the focal cover. An unfortunate aspect of the single focus system is that a mirror rarely faces the sun directly and so the average collection aperture is less than its surface area. This effect is also taken account of in Table I.

Thirdly, over the lifetime of a unit, charges for installation and maintenance are stated to be less than 8% of the value of the energy produced, pointing to the effectiveness of the application of rules 5, 6 and 7 for reducing costs. Lastly, the stated cost of the items directly related to artificial intelligence is not a large proportion of the total allowable cost - at the most 15%.

Discussion of whether or not the stated cost figures will or can be achieved is beyond the scope of this paper. The author feels, however, that all the figures given

are within reach and he bases his opinion on existing costs and trends, the results of development work being carried out at the ANU, and advice from manufacturing experts. For example : the present wholesale price of the motors for purchase in large quantities is about the figure stated in Table II; the expectation of low cost complex integrated circuits is corroborated by ref. 4 : the expected cost of the mirror support is based on information from ref. 5 : specific development projects at the ANU give promise of achieving the figures stated for both the reduction drives and sensors.

TABLE I **

Value of Energy Collected per Unit

Assumptions :

mirror area 10 m^2

effective collection aperture 6.7 m^2

total solar energy collected per year 14.7 MW hrs.
(refer to fig. 3).

efficiency of accumulation 75%

heat delivered to focus 11 MW hrs.

value of heat delivered on basis of oil saved } \$88
@ \$14 per barrel

Running Expenses per Unit :

transporting spare parts \$.50

overall maintenance (1 manhour/year per unit). 5.00

\$5.50

Amount available to service capital $\$88 - 5.5 = \$82.5$

* the interest rate assumes a high proportion of finance from Government sources at say 9% and a reasonable profit margin on the remaining equity.

** the prices given are in Australian dollars and pertain to late 1973.

**
TABLE II

Capital Items

Assumed depreciation	group 1	10%
	group 2	5%
Assumed interest rate *		10%
Total capital charges	group 1	20%
	group 2	15%

All costs including those of the shared central facilities, are presented on a unit basis. It is assumed that there are 10,000 units sharing these central facilities.

Group 1 - Capital Items - 10 year Life

mirror units (refer to table III)	\$357
cables	5
initial transport (500 miles @ 10 cents/tonne mile	15
off-loading and installation (2 men and truck .15 hr. per unit).	3
	<u>\$380</u>
charges on capital @ 20%	\$ 76

Group 2 - Capital Items - 20 Year Life

focus support and building	\$ 40
central computer, communication, etc.	2
unit site preparation (1 man with bulldozer .1 hr. per unit	1
	<u>\$ 43</u>
charges on capital @ 15%	\$ 6.5
total charges on capital	\$ 52.5

Table III **

Notional Division of Allowable Capital Cost of \$357
for a Unit having Mirror Area of 10 m².

(The figures given below do not include a profit margin) *

	\$
Glass	25
Mirror Support	65
Reflective Surface	8
Fixed Frame	48
Two printed motors 20W each	25
Two reduction drives	40
Two sets motor electrics	16
Integrated circuit logic	5
Sensor	5
Assembly and Test	120
	\$357

Corar* Costs - Preliminary Estimates

1. Method. A recent study by Colorado State University (ref. 1) has established a methodology for comparative cost studies. In a section of this study is listed in detail the cost components of a preferred "distributed" solar energy system which has several items in common with Corar. This CSU preferred system will therefore be used in this paper as the basis for cost estimates of Corar, the cost of each Corar item being derived from the cost of a related CSU item through appropriate modification.
2. Storage. The significant difference between the two systems is that, whereas the CSU system has virtually no energy storage facility (provision for only a "few hours" by a thermal method which is not economical for storage times longer than this), Corar has provision for several months. This means that in comparing systems of equal collector area, the components of Corar on the consumer side of the energy store may operate at a much higher load factor** than the components on the collector side, or any of the components of the CSU system - up to a factor of 4*** higher which in turn means that the cost of these components may be reduced by a similar figure.
3. CSU system. The CSU study indicated that distributed systems are more economical than tower systems for power levels below about 100 MW_e . The most economical distributed system studied comprises fresnel reflector collectors, focal absorbers which convert water to steam, thermally insulated water and steam pipes to and from each collector, conventional steam turbine and electric generator, all operating at a temperature of 250°C . Table I lists the items comprising this system and their (1972) cost per installed kW_e .
4. Differences between CSU and Corar. The Corar system comprises all the items listed for the CSU system plus an additional one, viz synthesiser, separator and steam generator, which has been estimated to cost $135 \text{ \$/kW}_e$. However, as explained, for each kW_e of capacity in the CSU system, as little as 0.25 kW_e is required after the storage element in Corar since storage allows virtually continuous use of these items at full capacity.

Hence the cost of this additional item together with the CSU costs of turbine and generator, condenser, and cooling have been divided by 4 to obtain the appropriate figures for Corar.

In addition, three other cost items on the CSU list have been modified to obtain the related Corar figures. The justification for this is as follows.

Collector materials: the CSU study assumes front silvered fresnel reflectors each on a separate support structure. Our feeling is that paraboloidal shell reflectors will prove ultimately to be less expensive simply because they are self-supporting. It is also probable that paraboloidal shells will have longer life because of their ammenability to geometries which provide self protection during inclement weather particularly when high winds occur. We are also mindful that fresnel reflectors are manufactured from petrochemically derived plastic material whose expense is likely to rise significantly at the time that solar energy will be economically competitive with fossil energy.

Foundation and supports: in Corar the mirrors are controlled from a computer-based centre, a feature which possesses capabilities aimed at eliminating the need for rigid foundations or precise setting up and adjustment of each mirror.

Transport piping, insulation and installation: Corar employs smaller diameter, uninsulated pipes.

5. Conclusion. Another factor of importance that has not been taken into account in compiling Table I is that in Corar steam may be generated at 450°C , significantly greater than CSU's 250°C . The resulting greater thermodynamic efficiency should further reduce costs.

According to the CSU study, the estimate of $411 \text{ \$/kW}_e$ relates to an energy cost of 3 cents per kW hr. The total of $286 \text{ \$/kW}_e$ obtained for Corar does not of course include the cost of storage. It is most likely that the predominant factor in the cost of storage will be the value of the reactants involved. These may be costed either as ammonia or as nitrogen and hydrogen depending how the reactants are introduced into the system. At present it appears that the cost of storage sufficient for at least two months smoothing may be added to Corar before its total cost equals that of the CSU system. At this point both would produce energy at a cost of 3 cents

per kW hr. However, in considering the value of this energy when fed into an existing conventional grid, the Corar energy is more valuable because, being continuously and predictably supplied, it enables a saving in (a) conventional energy-producing capital equipment, and (b) fuel. The CSU system on the other hand produces energy only when the sun happens to be shining and therefore it can be regarded only as saving fuel. Typical (1972) figures for these two values, for a large grid system, are approximately 1.5 cent and 0.5 cent per kW hr respectively (ref. 1). Thus Corar has more potential to be competitive, particularly for small isolated communities, than does the CSU system.

The CSU cost estimates are based on existing technology. Research, manufacturing and operational experience are likely to lower costs. Even so, as the CSU report concludes, "solar thermal electric power systems are found to have the potential to produce electricity at costs competitive with present conventional systems".

17 O. Corar
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Reference

1. "Solar thermal electric power systems"

Colorado State University, Solar Energy Applications Laboratory,
Engineering Research Centre, Report NSF/RANN/SE/GI-37815/FR/74/3.

Footnotes

- * Corar - the system under study at ANU - anagram for energy corradation using the reversible ammonia reaction.
- ** the ratio - $\frac{\text{average power}}{\text{maximum power}}$
- *** which might be the case if the system were situated at Griffith, N. S. W., where the average load factor of the incident radiation is about 0.25.

Table I

		CSU \$/kW _e	Corar
collector materials	*	75	60
fabrication labor and overheads		35	35
foundation and supports	*	70	30
tracking		15	15
transportation		7	7
installation		20	20
contingency		17	17
absorbers		25	25
transport piping	*	37	15
insulation and install			
turbine and generator		85	21
condenser		5	2
cooling		20	5
synthesiser, separator and steam generator			34
Total		411	286

(Both based effectively on Load Factor of ≈ 4 .)

Basis of comparison: equal collector area, equal annual energy output.

Alternative expressions for total costs in terms of installed kW_e capacity both excluding cost of storage:

CSU 411 \$/kW_e at 0.25 load factor.

Corar (286 x 4 =) 1144 \$/kW_e at 1.0 load factor

[Coal fired base-load plants 400 \$/kW_e at 0.8 load factor.]

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.

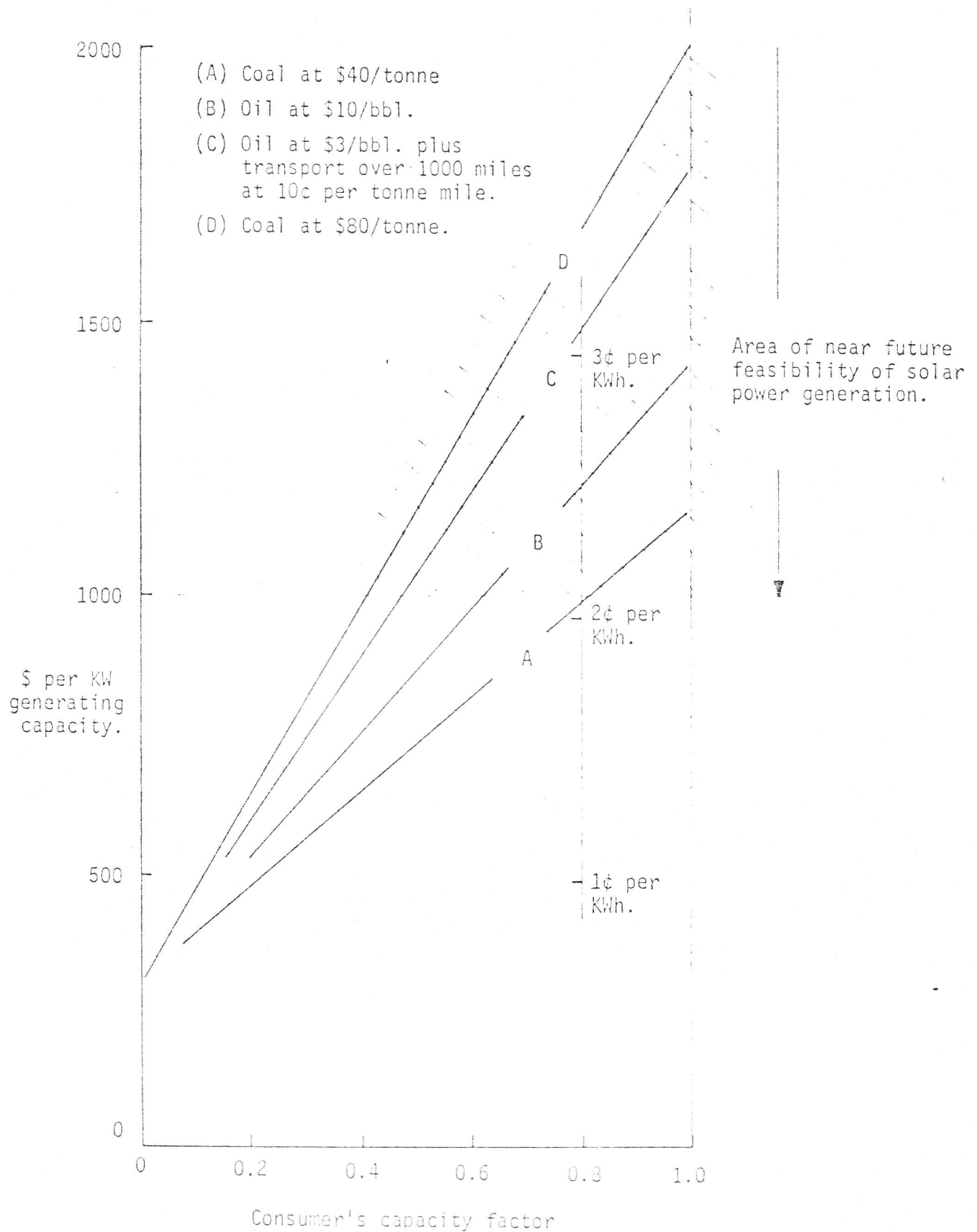
The method used previously to capitalise an energy rate of 1 bbl of oil per year may be adapted generally to capitalise all fuels in terms of \$ per KW of installed capital given the price of the fuel, a charge rate on capital, the conversion rate of fuel to electric power, and the capacity factor of 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 0.3 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.

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 2-3 times this amount.

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 m² which is within reach of existing technology.

OPTIMISATION OF STORAGE AND THE VALUE OF AMMONIA BY-PRODUCTION

A feature of the solar ammonia system is its facility for long-term storage. However, the cost of storage must be taken into account. When storing nitrogen and hydrogen underground the relevant cost of the facility is related to power not the stored energy and is estimated to be 200 \$/kW_e. Ammonia on the other hand is stored above ground in refrigerated vessels and these work out to be about \$40 per kW_e per day of storage, a day of storage being that required to run a 1 kW_e generator completely from storage for 24 hours. (Storage time is similarly defined.) The reactants are also included as a capital item, and at 155 \$/tonne, and assuming a work recovery efficiency of 0.3, this amounts to \$12 per day of storage per kW_e. In Figure 1 curve B shows the total capital cost of storage vs storage time, based on these figures.

Storage times shorter than 6 months may be used provided extra collectors are provided to help overcome the deficit during winter. Curve A shows the cost of collectors as a function of storage time taking into account this fact and based on direct insolation figures for Griffith NSW for 1972 and 1973. Collectors have been costed at 50 \$/m² and an overall efficiency of 0.2 has been assumed.

Curve C is the total of components A and B and shows a minimum at about 10 days of storage.

Evidently an ammonia storage facility is expensive and it would be an advantage to dispense with it if this were possible. Since ammonia is a saleable product, it may be bought and sold as required instead of storing it on site. An additional advantage of doing this is that capital for reactants is required for less time since, for example, one would tend to store in autumn for winter and therefore during spring and summer the quantity of reactants stored could be considerably reduced.

Curve B' has been calculated on the basis of buying and selling the bulk of ammonia required, the stock being held for only half the time as for Curve B but allowing a 50% loss in the transactions. A fixed charge for gas storage and for 10 days refrigerated storage has been included.

Curve C' is the sum of A and B' showing a longer optimum storage time, approximately 40 days, and a lower total capital cost.

Spare collector capacity during summer may be employed to produce ammonia as a by-product. Assuming a production rate of $0.128 \text{ kg/kW}_e\text{h}$ and valuing the ammonia at 155 \$/tonne, the return on sales barely compensates for the interest, operation and depreciation associated with the additional equipment necessary for production of the by-product. Based on $550 \text{ $/kW}_e$ for this additional equipment (electrolysis plant, synthesis converter and generator), the ammonia sale would return 16% pa, barely enough to cover expenses. However, should the value of ammonia increase, as it will in sympathy with the price of fossil fuel, the picture is different. For example if we assume ammonia valued at 310 \$/tonne, and allowing 20% pa of the additional plant capital cost to cover all expenses, the balance may be employed to service the solar plant and storage facility effectively cancelling a certain amount of the capital cost of that equipment. This has been the basis of Curve D which has been calculated again assuming 20% pa of the cost of solar plant and storage facility for associated expenses. Curve B'' is the same as B' but modified for the increase in value of the reactants. The resultant total effective capital cost ($A + B'' - D$) is given by C'' which now indicates that about 10 days' storage is all that is needed. The component of the cost of the generated power available for sale attributable to the capital items considered here (comparable to the fuel component in an oil fired plant) is about 3 ¢/kWh. This figure will be sensitive to further increases in the price of ammonia, becoming negative at about 400 \$/tonne.

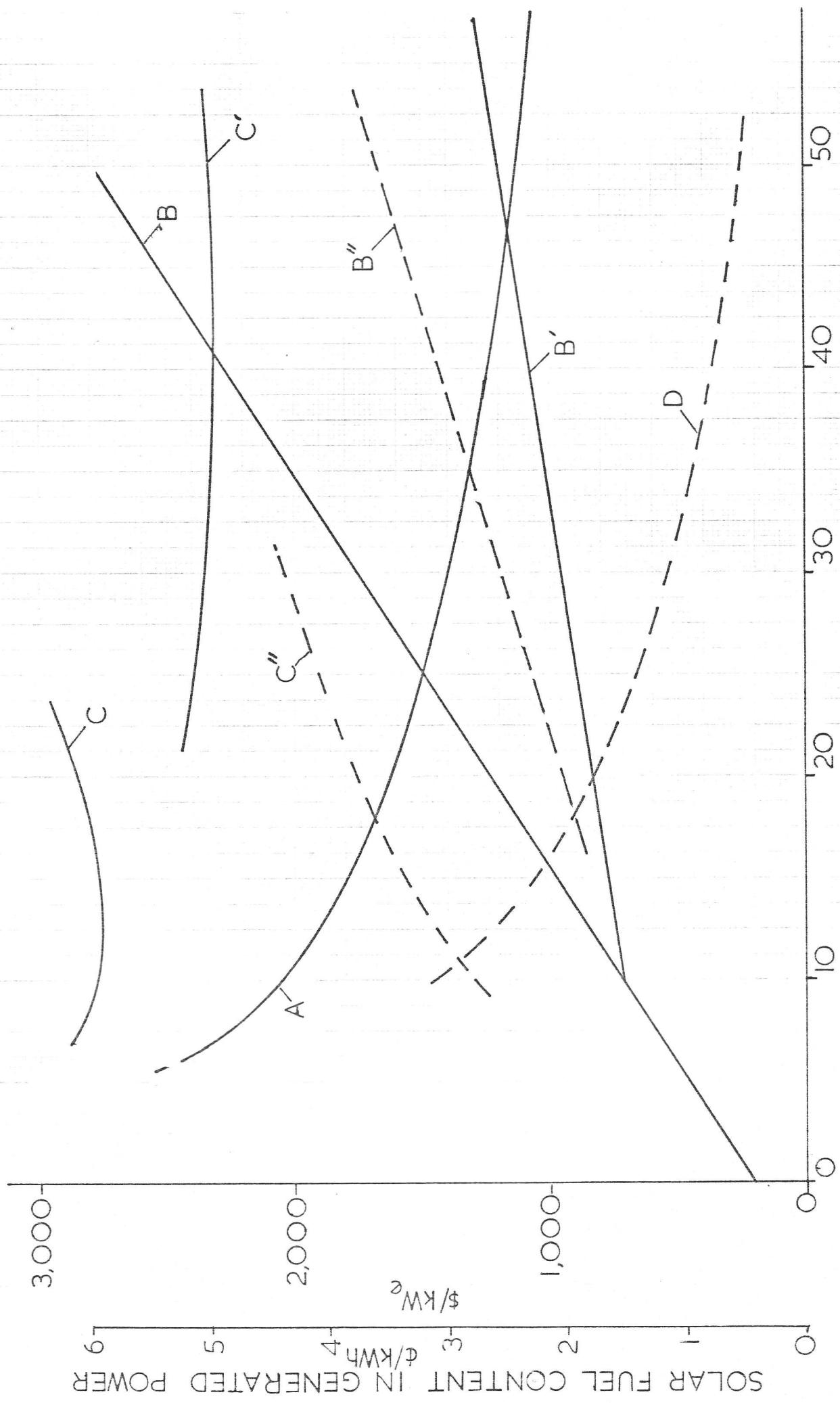


fig.1

EXPLANATION OF FIGURE 1

- A Collectors at 50 $\$/\text{m}^2$
Overall efficiency 0.2
- B Storage:
Fixed cost \$200 underground storage nitrogen/hydrogen
Reactants valued at 155 $\$/\text{tonne}$ (12 $\$/\text{day}$)
 NH_3 refrigerated storage facility 40 $\$/\text{day}$ storage
Work recovery efficiency 0.3
- B' Alternative storage:
Provide 10 days refrigerated storage for NH_3 . Buy and sell
 NH_3 as required for 50% less, (but capital required for only
half the time). NH_3 at 155 $\$/\text{tonne}$ (buying).
- C Sum of A + B
- C' Sum of A + B'
- D If NH_3 valued at 310 $\$/\text{tonne}$ (sensitive to fossil fuel price)
Net capitalised value of NH_3 by-product allowing for: 20% to
cover interest operation, maintenance of additional plants;
 NH_3 production 0.128 $\text{kg}/\text{kW}_\text{e}\text{h}$; 550 $\$/\text{kW}_\text{e}$ additional plant costs.
(All spare solar energy used.)
- B'' Cost of alternative storage with NH_3 at 310 $\$/\text{tonne}$.
- C'' Sum A + B'' - D.

THE RELATION BETWEEN CAPITAL COST OF A SOLAR ENERGY PLANT AND BREAKEVEN COST OF PRIMARY FOSSIL ENERGY

We aim here to present an argument, the results of which are free from the effects of inflation. It is often argued that as the price of energy increases, the price of a solar energy plant will increase because of the energy content in its capital equipment. Solar energy will not therefore become viable. The energy content in capital equipment is now usually estimated on the basis of so many MJ per \$ calculated on the ratio of national primary energy usage/gross domestic product. In 1974 in the USA this ratio was 55 MJ/\$ and on the basis of the primary energy being predominantly coal at 10 \$/tonne we can estimate the ratio of energy cost/capital cost as only 0.017. For the sake of simplicity we assume this ratio applies to all capital equipment whenever the cost of primary energy relative to other costs eg. wages is as it was in 1974. We call this relative cost = 1 in Figures 1 and 2. A sloping line can now be drawn, such as A, the ordinate of which represents the capital cost of plant at any other relative cost of primary energy, while the ordinate at energy cost = 0 represents the part of capital cost that is not energy dependent. Thus as the relative cost of primary energy grows, a larger proportion of the cost of a capital item becomes attributable to the cost of energy. The appropriate slope of line A is such that the ordinate increases by 0.017 as the abscissa goes from 0 to 1.

Other lines such as those marked C_s represent the relative costs of renewable energy sources, the subscript in brackets representing how many times more expensive each is than the coal fired plant represented by A. The line B represents the relative value of fuel used in the coal fired plant capitalised at an interest rate of 10% pa. It has been drawn in correct proportion to A on figures for 1974 viz coal 10 \$/tonne, capital value of coal plant 400 \$/kW_e. A lead factor of 0.8 was assumed. As explained, 1974 was taken as representative of a relative fuel price of one.

Line F is the sum B + A. Breakeven conditions (renewable source produces energy at the same price as non-renewable source) are represented by the intersection of C_s and F and these interactions are plotted separately in Figure 2.

The advantage of this methodology is that the results should be insensitive to the effects of inflation per se although inflation may be a prerequisite to recessional conditions in which the relative cost of primary energy has increased.

It is worth remarking that an increase in relative price of primary energy must go with a real change in life style and attitudes. Consumers and producers will actually have to go without some material thing or service assuming they continue to use energy at the previous rate. Because of this, people in western democracies will resist increases in the relative price of primary energy by demanding commensurate increases in wages. It follows that mere dollar increases in coal or oil will not ensure the viability of a renewable energy source. It also follows that the viability of renewable sources will always look best in times of severe recession (dislocated life style) and worst in booms (restoration of status quo life style).

The most insidious effect of this almost automatic mechanism for maintaining the status quo life style is that a pending shortage, which may be of crisis proportions and duration, is completely disguised. Many argue that the operations of the free market will dictate when it is time to turn to new, more expensive energy sources but the mechanism described here works against the operation of the free market for it shields any attempt of a producer to signal the coming of a shortage by raising the price.

The mechanism therefore converts what could be a gradual slope downwards to a new level of economy based on renewable energy sources into a level run terminated by a cliff. However, because of the cliff, and despite the level run, the obvious need to build up new energy sources becomes even more pressing than it would otherwise be if all the signals of the free market were flashing conspicuously.

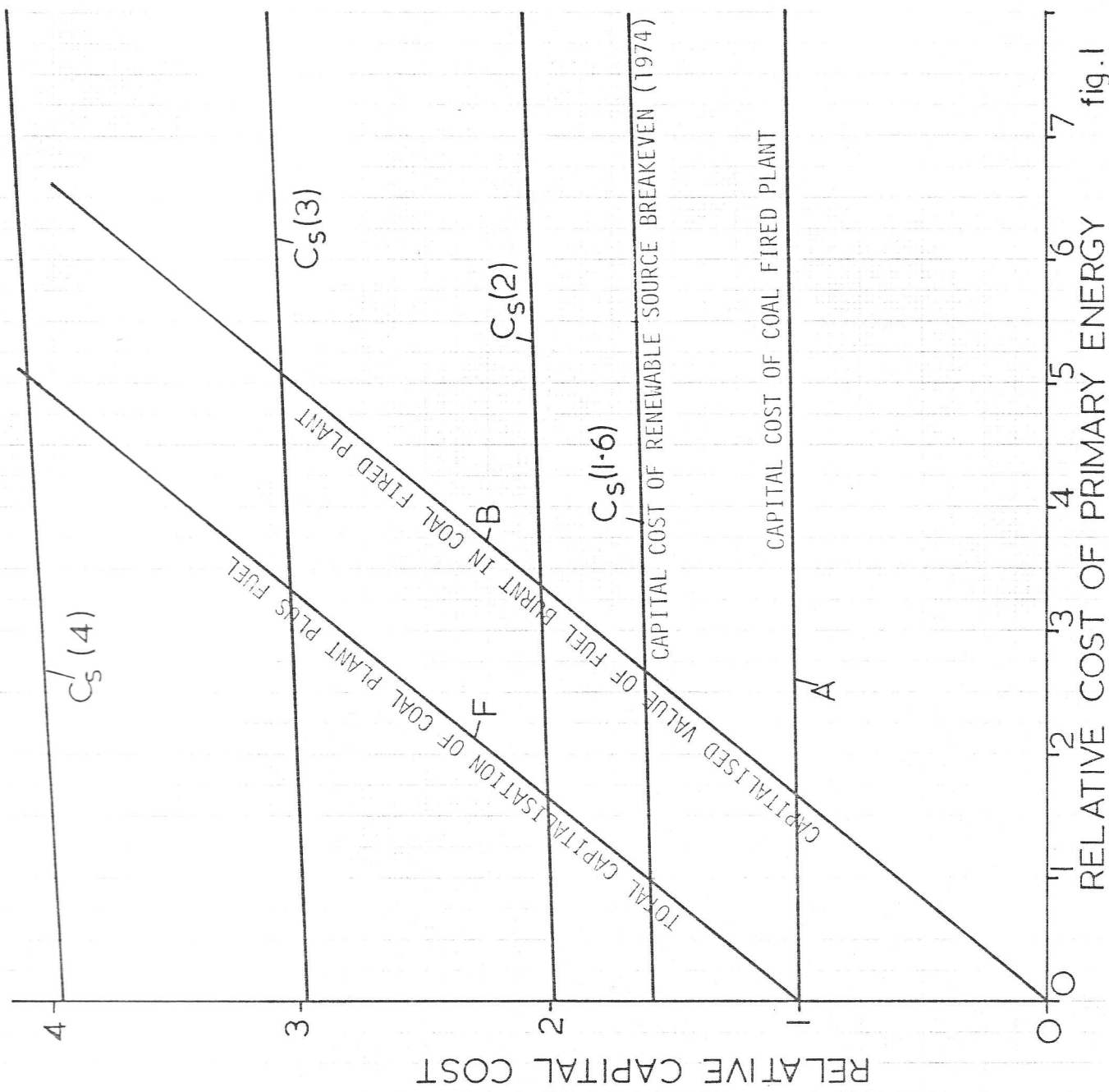


fig.1

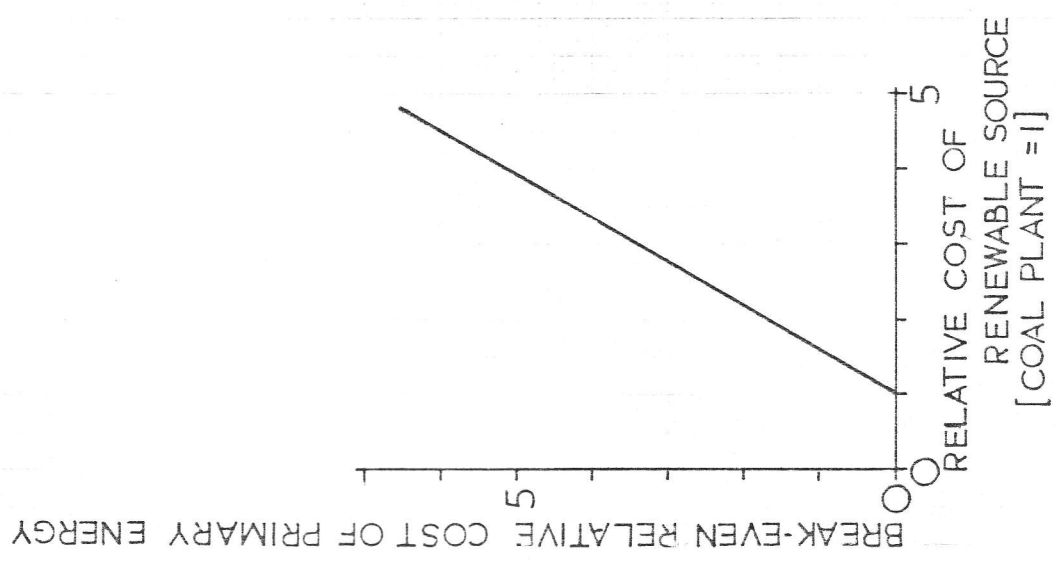


fig.2