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of
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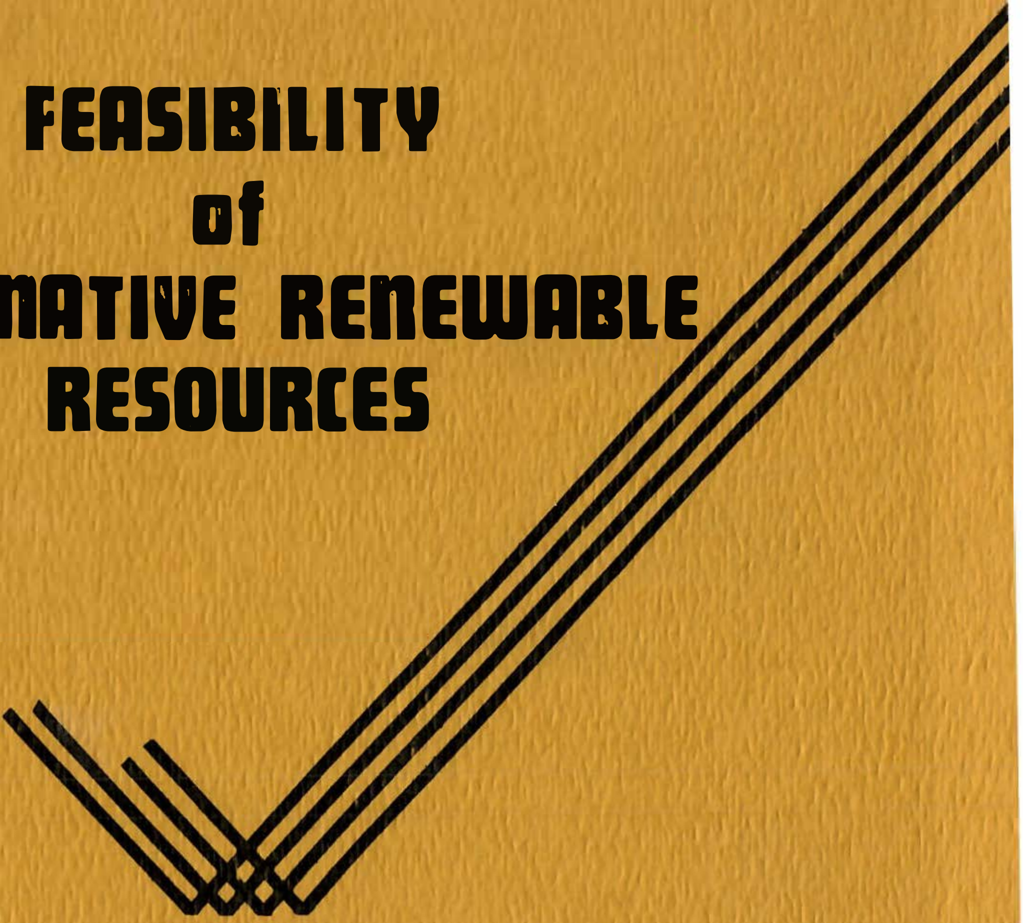

SYMPOSIUM ON

SOLAR ENERGY RESOURCES

COOMB'S LECTURE THEATRE
AUSTRALIAN NATIONAL UNIVERSITY

WEDNESDAY, 12th NOVEMBER, 1975

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1975

SYMPOSIUM

SOLAR ENERGY RESOURCES

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of
ALTERNATIVE RENEWABLE RESOURCES

Coombs' Lecture Theatre
Australian National University, Canberra, A.C.T.

Wednesday, 12th November, 1975

PROGRAMME AND PAPERS

Page

0930-1045 Session 1. Chairman: R.J. Millington

1. Fuel Requirements for Growing Plants.
   R.M. GIFFORD. CSIRO Division of Plant Industry 1

2. Photobiological energy conversion - a practical proposition?
   D.J. McCANN and H.D.W. SADDLER. Energy Research Centre
   University of Sydney 15

1045-1115 Coffee Break

1115-1230 Session 2. Chairman: W.E. Purnell

3. The energy cost of prospective fuels - with particular reference to fuels from "renewable" sources.
   G. GARTSIDE. CSIRO Division of Chemical Technology 41

4. Limitations of hydroelectricity in Australia.
   P.M. FLEMING. CSIRO Division of Land Use Research 53

1230-1345 Lunch

1345-1530 Session 3. Chairman: Anton Hayles

Panel Discussion on the Prospects of Renewable Resources.

Panel Members:

W.R. WATSON, First Assistant Secretary,
Australian Department of the Environment

P.P. McGUINNESS, Energy Correspondent,
Financial Review

D. PRUE, Vice-President, International
Society for Photobiology

A.H. CORBETT. Past-President, Institution
of Engineers, Australia, and former
Professor of Engineering, Royal Military
College, Duntroon.

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FUEL REQUIREMENTS FOR GROWING PLANTS

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SUMMARY

An integral part of any study of the feasibility of fuel production from plant matter must be documentation of all direct and indirect support energy requirements to drive the process. Likely energy inputs to the agronomic phase of the system are considered in this paper.

The Australian arable/pastoral system exemplifies a relatively extensive one yielding about 60 GJ $ha^{-1}y^{-1}$ as plant biomass. Total fuel requirements to achieve this production would fall in the range 5-10% of the unprocessed output. As examples of intensive systems, essentially non-irrigated U.S. maize and Hawaiian sugarcane were considered. The maize yielded 166 GJ $ha^{-1}y^{-1}$ and the agronomic fossil fuel input was 15-20% of this value. The input to the sugarcane system represented 7-17% of the fuel value of the biomass (which was 370 GJ $ha^{-1}y^{-1}$) depending on the skill in handling mechanization. To operate such intensive systems on a significant scale in Australia would require irrigation. Data on the energetics of irrigation are scanty but what is available suggests requirements under typical circumstances may be of the same order as the energy needs of all other inputs.

It is concluded that support energy for the agronomic system alone would in a self-contained system utilize a sizeable part (20-40%) of the fluid fuel synthesized from its products.

1. INTRODUCTION

Plant photosynthesis converts solar energy in the wavelength band 400 to 700 nm into chemical energy. This chemical energy can be incorporated by existing techniques into alcohols, hydrocarbons or other combustible fluids thereby becoming a renewable fuel for mobile vehicles. The emphasis of this paper is to appraise likely energy requirements for raising fuel crops by examining existing plant production systems.

2. ENERGY INPUT ANALYSIS

To estimate the net yield of synthetic fuel from a fuel crop scheme and the scale on which proposals may be biophysically feasible, several assessments need to be made:

a) areas, not irrevocably committed for other purposes, which may be suitable for fuel-crop production;

b) present net primary biological productivity of each packet of such land and any non-solar energy ("support energy") input required to sustain that productivity;

c) the probable yield (Y) of harvestable biomass from each packet of land under various proposed combinations of cultural practice, chemical and water inputs and harvesting frequency;

d) the yield at the factory gate of synthetic fuel (O) from the total amount of plant biomass (Y) taken from the fields;

e) the support energy requirements (i.e. other than the plant biomass (Y) used as feedstock/fuel) for the agronomic system (A), for transport between field and factory (T), for the factory processing (P), and for packaging and distributing the synthetic fuel to final consumer (D).

The overall efficiency of recovery of energy as synthetic fuel from harvested biomass may be defined as

$$E = \frac{O-I}{Y} = \frac{O - (A + T + P + D)}{Y} \qquad \text{........(1)}$$

where I is the total support energy requirement other than the energy content of the feedstock/fuel, Y.

For the whole process to be a net energy yielder it is necessary that $O > (A + T + P + D)$ in equation 1. In preliminary analyses it is tempting to simply compare O with the direct input to the conversion process, but the other inputs may well be large. There is some flexibility in equation 1 in that where a support energy input is in the form of heat a part of the feedstock (Y) could be burned to reduce the need for external energy sources (hence the term "feedstock/fuel").

In assessing the term I it is necessary to go beyond simply the direct energy need for each of the four stages, A,T,P, and D. For example, the energy needed for capital expenditure in all stages must be accounted for and where electrical energy is used the thermal inputs to the electricity generating system must be reckoned, as must the energy requirements of mining the coal which feeds the power station etc. If a complete analysis is not made then any energy gain from synthetic fuel system may be illusory if the system creates too many hidden demands on the rest of the global energy supply.

There are two approaches to studying energy inputs to productive processes. One, the process approach, is to study the physical and chemical details of each sub-process and build up the budget for the whole process of interest. The other method is a macroscopic approach using national censuses of production and relying on the economist's 'Input-Output Matrix' technique. In this, all direct transactions of products and services between sectors of the national economy (367 sectors for the U.S.A. analysis) are recorded in dollar terms on a square matrix from which a second matrix can be computed showing the \$-value of the total input, direct and indirect from all sectors, required to produce one dollar's worth of output from each sector. Herendeen (Ref. 1) describes how he converts such a \$ I/O matrix to an energy matrix - a non-trivial exercise. This macroscopic economic approach goes a lot further than a simple one (used below) of converting \$-costs of a process to energy costs by means of a single coefficient - the ratio of national energy consumption to G.N.P. (Ref. 2).

Underlining the importance of accounting for indirect inputs Herendeen shows that, in the U.S.A., automobile manufacturers themselves use only about 6% of the total energy necessary to produce and market a car. Although this method has several drawbacks, for sectors of the economy which have homogeneous outputs such as cement or paper it can provide a useful crosscheck with process analysis.

One sector with an homogeneous output is the sugar industry. This is of interest since a possible source of liquid fuel is ethanol from fermentation of sugar (Ref. 3). I/O matrices give the total energy requirement for sugar production as 19 MJ kg^{-1} (for the U.K. in 1963), 16 MJ kg^{-1} (U.K. 1968) and 21 MJ kg^{-1} (U.S.A. 1963) (Refs. 4,5). The U.K. figures are for sugar from beet, and the U.S. ones for sugar from both beet (60%) and cane (40%). With the heat of combustion of sugar being about 16 MJ kg^{-1} it is evident that a sugar production system for ethanol would have to be very much less support-energy intensive than the system for culinary sugar in order to yield a net energy gain. Although less energy would be needed for refining sugar in an ethanol production system, any hydrolysis and fermentation steps in ethanol synthesis would require further inputs

In terms of calculating the energetics of proposed, as opposed to existing, productive systems the I/O matrix approach is not as useful as the process analysis method which relies on detailed knowledge of

'Energy Network Inputs' (Ref. 6). In Appendix 1 is listed various available estimates of a wide range of energy network inputs (E.N.I.) relevent, *inter alia*, to plant production systems. Where several estimates are available they have been listed. Now that energy analysis is in vogue new data is continually coming available. For most of the E.N.I.'s listed the *entire* energy requirement traced right back to logical origins is probably not included, but most authors go back in the network until further terms are small relative to the total and seem about the same magnitude as the confidence interval on the major inputs. To trace the entire network input to each product or process completely accurately would of course require prior knowledge of all other network inputs. Some of the items listed, however, have been derived from I/O tables.

Using such E.N.I.'s several agricultural systems have been analysed in the literature. I here discuss three of them to give some feeling for the magnitude of term A in equation 1.

3. AUSTRALIAN AGRICULTURAL PRODUCTION (1965-69) - AN EXTENSIVE SYSTEM

A study of the energetics of the Australian food system (Refs. 7, 8) may be adapted to the present purpose. The study was done before most of the data in Appendix 1 was available or unearthed but the overall conclusions hold although details may change.

The fuel value of all commercial products at the farm gate was estimated to be about 320×10^{15} J y^{-1} (58% grains; 24% sugarcane (i.e. 13% sugar, 12% bagasse), 3% fruit, vegetables and nuts; 2% meat; 6% dairy products; and 7% wool and cotton). The support energy for four major areas of input were, 56×10^{15} J y^{-1} for the energy network supplying fuel and electricity used directly on the farms, 19×10^{15} J y^{-1} leading to the fertilizer supply, 38×10^{15} J y^{-1} for steel based products (tractors, other machinery, construction steel etc.) and 4.4×10^{15} J y^{-1} for agricultural chemicals. In this analysis the energy requirements for capital depreciation and repair for the agricultural supply industries was not included and neither was the energy networks for construction and maintenance of farm buildings (except to the extent that steel was involved). Similarly, except to the extent that direct fuel use on the farm may have been involved, irrigation is not accounted for but may have been as high as 20×10^{15} J y^{-1} (Ref. 8). The sum of the four input terms listed above is 117×10^{15} J y^{-1}. This compares favourably with an input of about

130×10^{15} J y^{-1} estimated crudely using the ratio of national energy use to national GNP as a factor to convert $ value of farm output to energy value (Ref. 2).

So taking, for the purpose of this discussion, 130×10^{15} J y^{-1} as the energy input to the 1965-69 Australian agricultural system the energy input was equivalent to 40% of the heat of combustion of the commercial products. However, for renewable fuel synthesis the above-ground crop residue would also be of interest. This was about 460×10^{15} J y^{-1} (Ref. 9) which together with commercial products amounted to 780×10^{15} J y^{-1} of farm product expressed as heat of combustion. Support energy inputs listed are 17% of this but do not include requirements for harvesting the residues. Taking the analysis a step further, one can consider the primary plant energy needed to feed the farm animals. Since most of the stock food is foraged by the animals, there is no accurate figure available but about 2300×10^{15} J y^{-1} was estimated (Ref. 7). Based on the proportion of stock on arid rangelands (Refs. 10, 11) we can assume 80% of the forage (or about 1800×10^{15} J y^{-1}) came from the 21 Mha of sown pasture in the 1965-69 period. To harvest this by taking, say, four passes of the forage harvester per year would use directly as fuel from 15×10^{15} J y^{-1} to 100×10^{15} J y^{-1} according to whether item 1.30, 1.31 or item 1.29 plus 1.33 is used from Appendix 1 as the conversion factor. So if, hypothetically, we eliminate animals from the Australian agricultural system and think in terms of all the crops, crop residues and forage from sown pasture being used as a feedstock for synthetic fuel then a total output at the farm gate of about 2600×10^{15} J y^{-1} (or 60 GJ $ha^{-1}y^{-1}$) would be produced for a support energy input in the range 140-230 $\times 10^{15}$ J y^{-1} (or 3.4 to 5.6 GJ $ha^{-1}y^{-1}$) - which is less than 10% of the yield. This example is presented simply to gain initial perspective of what sort of level of energy inputs might be expected for the term A in Equation 1 for an extensive fuel-crop production system. No suggestion is intended that displacement of food and pastoral production by fuel crops should be regarded seriously as an option.

4. MAIZE AND SUGARCANE PRODUCTION - INTENSIVE SYSTEMS

Two high yielding crops suitable for intensive production, for which data on support energy inputs are available, are maize and sugarcane. Using national data Pimental *et al.* (Ref. 12) studied the energy inputs to the United States maize crop.

In 1970 the average corn yield (81 bushels/acre) had a heat of combustion of 83 GJ $ha^{-1}y^{-1}$ and required as fossil fuel input (excluding grain drying) 28 GJ $ha^{-1}y^{-1}$ (44% as the energy network for direct fuel use; 39% for fertilizer; 15% for machinery; 0.8% for agricultural chemicals; 1.2% for irrigation). These inputs exclude capital depreciation of farm and agricultural supply industry buildings.

The weight of crop residue would be about equal to the weight of grain (Ref. 13) hence the total crop fuel value would be about 166 GJ $ha^{-1}y^{-1}$. The inputs listed above, to get the grain crop to the farm gate, represent 17% of this. Extra energy to take the stalks to the farm gate would not raise the total inputs much.

For sugarcane production Hudson (Ref 14) presents notional data for the Hawaiian crop. Sugarcane being a perennial has an advantage over maize, an annual, in that it is necessary to plough, cultivate and plant only once every five years. Hudson considered a non-irrigated skilfully and efficiently mechanised system yielding 70 t $ha^{-1}y^{-1}$ of green cane for crushing - a yield comparable with the current mean Australian (partially irrigated) yield. Calculated input (excluding cane transportation to the factory which used 3.7 GJ ha^{-1}) was 26 GJ ha^{-1} (29% for the energy network supplying fuel for direct use; 35% for fertilizers; 35% for machinery; and 0.6% for herbicides). The above-ground dry weight yield for such a crop would be about 25 t ha^{-1} (7 t sugar, 6 t bagasse, 12 t leaves) having a fuel value of about 370 GJ ha^{-1}. Thus for this example fossil fuel inputs represent 7% of yield. However, two points need to be observed: the E.N.I.'s assumed by Hudson for ploughing and furrowing seem low in comparison with other estimates of similar operations (Appendix 1, compare item 1.15 with items 1.11 to 1.14, and item 1.25 with other heavy cultivation operations) and secondly in a separate table Hudson (Ref. 14) cites (without detail) fossil fuel inputs to sugarcane production of 40 GJ ha^{-1} for 'efficiently mechanized' systems and 63 GJ ha^{-1} for 'inefficiently mechanized' systems. So support energy input for non-irrigated sugarcane seems to range between 7 and 17% of energy yield.

Both these maize and sugarcane systems were non-irrigated (the proportion of the U.S. maize crop irrigated was trivial). The American corn-belt is superb for high crop yields, and rainfall in Hawaiian plantations is great. To obtain comparable yields in most non-utilized potential crop areas in Australia would require irrigation. Without irrigation it has been demonstrated (Ref. 9) that a significant quantity of fuel crop, relative to projected fossil fuel demand, could not be grown.

Unfortunately studies on the energetics of irrigation are sparse. Watering may be from pumped ground water or by gravity feed from dams; the capital and running energy costs would be markedly different for each. For the systems surveyed in the Appendix (items 2.28 to 2.33) values for water supply range from 3 to 12 MJ per m^3 water supplied. It is not clear to what extent capital depreciation is included in these figures. Judging by the US$ cost of establishing various irrigation schemes in the world (Ref. 15) and using the 1967 energy equivalence of the G.N.P. dollar for the U.S.A. (80 MJ/dollar, Ref. 16), to convert a typical cost (US$400/acre) to joules gives 80 GJ ha^{-1}. Assuming that irrigation schemes are amortized over 100 years this capital investment is equivalent to 0.8 GJ $ha^{-1}y^{-1}$. With regard to running costs, if each irrigated hectare requires 8000 m^3 y^{-1} irrigation supply (the average for Australian irrigation calculated from Gifford *et al.* (Ref. 17)), then the range in the Appendix (3 to 12 MJ/m^3) gives a further support energy input of 24 to 96 GJ $ha^{-1}y^{-1}$ - high figures compared with the sum of all other inputs to the above maize and sugarcane systems ranging from 26 to 63 GJ $ha^{-1}y^{-1}$.

5. CONCLUSIONS

For a system as extensive as Australian arable and sown pasture production, support energy inputs to the agronomic system would amount to only 5-10% of the energy content of recovered plant material, but costs of transportation to factories would be greater than for intensive systems, and total potential synthetic fuel production would fall short of national demands by a wide margin (Ref. 9). For intensive systems in moist climates, yields are high but support energy needs are also high - up to almost 20% of the energy content of production; for a well-controlled mechanized system, however, support energy costs might be kept below 10%. For broadscale intensive production, irrigation would probably be needed in Australia the energy requirements for which are a major unknown but may be very substantial.

When expressed as a percentage of the gross output of synthetic fuel from the plant material, the agronomic inputs would be about twice as high as the above-mentioned figures, assuming about 50% recovery of the heat of combustion of biomass as fuel. Thus it seems likely that agronomic support energy requirements alone would consume an appreciable part of the synthesized fuel in a totally renewable system. It could be argued that systems designed specifically as fuel crops might achieve a better biomass yield per unit input than food crop systems designed to maximize yield of particular plant organs or constituents at particular states of maturity. However, any potential gain there, may be partly offset by extra energy inputs needed to recycle minerals from the crop to the soil in a fuel crop system intended to approach a totally renewable energy source. Certainly these results suggest that the fuel cost of plant production would have to be explored closely for any specific proposed 'fuel from photosynthesis' scheme.

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APPENDIX 1

ENERGY NETWORK INPUTS (E.N.I.)

ITEM No	PROCESS OR COMMODITY	E.N.I.	COMMENTS	SOURCE REF
1.	Transport and machinery operations		E.N.I.'s in section 1 are all direct fuel consumption only. No allowance for lubricants, capital, energy cost of energy etc.	
1.1	Trucking (U.S.A. figures)	2.4 MJ/t.km	250 HP, 40t trucks; no empty trips	18
1.2	Trucking (Aust.; prof. haulier)	2.4 MJ/t.km	av. of all agric. supply and products hauliers	19
1.3	Trucking (Aust.; business trucks)	9.2 MJ/t.km	av. of all trucks operated by agric. supply and commodity businesses and forestry operations. Would include empty return trips.	19
1.4	Rail (fast 40-car freight)	1.3 MJ/t.km	U.S.A. data	18
1.5	Rail (100-car freight train)	0.5 MJ/t.km	U.S.A. data	18
1.6	Rail (200-car freight train)	0.3 MJ/t.km	U.S.A. data	18
1.7	Rail (Aust.; over-all freight)	0.6 MJ/t.km	calc. from published statistics; judgements made about passenger/freight allocations.	7
1.8	Shipping (fast 15,000 t. container ship)	0.5 MJ/t.km		18
1.9	Shipping (26,000 vessels)	0.1 MJ/t.km	Based on data supplied for the Christmas Is./Adelaide phosphate run.	7
1.10	Shipping (100,000 super tanker)	0.1 MJ/t.km		18
1.11	Moldboard ploughing	1 GJ/ha	U.K. data; medium size tractor and medium soil	20
1.12	Moldboard ploughing	0.68 GJ/ha	U.K. data	21
1.13	Moldboard ploughing	0.8 GJ/ha	U.K. data	22
1.14	Moldboard ploughing	0.5 GJ/ha	Californian estimate. Crawler tractor 6 furrows	23
1.15	Ploughing (sugarcane field)	0.31 GJ/ha	Hawaii, assumes 0.2 litre fuel/ (H.P. hour)	14
1.16	Chisel ploughing	0.34 GJ/ha	U.K. data	21
1.17	Heavy cultivating	1 GJ/ha	U.K. data, medium size tractor and medium soil	20
1.18	Disc harrowing	0.27 GJ/ha	U.K. data	21
1.19	Rotary cultivation	0.57 GJ/ha	U.K. data	21
1.20	Cultivator (4-row)	0.3 GJ/ha	Californian estimate. 1 pass over the ground	23
1.21	Light harrowing	0.25 GJ/ha		20
1.22	Spring-tine harrow	0.23 GJ/ha	U.K. data	21
1.23	Sub-soiling	0.38 GJ/ha	U.K. data	21
1.24	Rolling	0.08 GJ/ha	U.K. data	21
1.25	Heavy rolling	0.23 GJ/ha	U.K. data	22
1.26	Furrowing (sugarcane field)	0.15 GJ/ha	Hawaii, assumes 0.2 litre fuel/ (H.P. hour)	14
1.27	Drilling	0.11 GJ/ha	U.K. data	21
1.28	Drilling	0.13 GJ/ha	U.K. data	22
1.29	Mowing	0.31 GJ/ha	U.K. data	21
1.30	Forage harvesting/chopping	0.18 GJ/ha	Grass, U.K.	21
1.31	Forage harvesting/ensiling	1.2 GJ/ha	Maize silage crop, U.K.	22
1.32	Sugarcane harvester/loader	5.5 GJ/ha	Hawaii, assumes 0.2 litre fuel/ (H.P. hour)	3
1.33	Baling (straw or hay)	0.11 GJ/ha	U.K. data	21
1.34	Fertilizer spreading by tractor	0.11 GJ/ha	U.K. data	21
1.35	Spraying by tractor	0.11 GJ/ha	U.K. data	21
1.36	Aerial spreading, spraying, seeding	0.07 GJ/ha	Australia 1972-74	24
1.37	Aerial spreading, spraying, seeding	4.0 GJ/h	Australia 1972-74	24
1.38	Aerial spreading, spraying, seeding	3.3 GJ/h	California 1972	23
2.	Fertilizers, chemicals and water		Section 2 includes the energy requirements of energy in each E.N.I.	
2.1	Superphosphate in Aust. (9.6% P)	21 GJ/t (P)	Incl. mining, transport and manuf. (excl. capital costs)	7
2.2	Phosphoric acid (H_3PO_4)	25 GJ/t (P)	U.K. data incl. mining etc. and fixed + capital costs	25
2.3	Phosphoric acid	15 GJ/t (P)	U.K. data excludes fixed and capital costs	6
2.4	Sulphur in U.K.	1.5 GJ/t (S)	From France 35% for recovery; 65% transport	25
2.5	Sulphuric acid (H_2SO_4)	-1.4 GJ/t	U.K.)Net energy gain dependent on degree of use of process	
2.6	Sulphuric acid (H_2SO_4)	-0.2 GJ/t	U.K.)heat evolved	
2.7	Ammonia	80 GJ/t (N)		26
2.8	Ammonia (NH_3 gas)	61 GJ/t (N)	U.K. Incl. capital costs. Natural gas feedstock	25
2.9	Ammonia (NH_3 gas)	62 GJ/t (N)	Overall world figure	6
2.10	Urea (NH_2 CO.NH_2)	77 GJ/t (N)	Av. for 5 processes examined	6
2.11	Urea (in bags)	81 GJ/t (N)	Incl. capital costs and packaging	25
2.12	Ammonium nitrate	62 GJ/t (N)		6
2.13	Ammonium nitrate (in bags)	72 GJ/t (N)	ICI "Nitram" process	25
2.14	Ammonium sulphate	69 GJ/t (N)		6
2.15	Diammonium phosphate	68 GJ/t (N)		6
2.16	Compound fertilizers	23 GJ/t	Overall value from 1968 U.K. I/O Table	6

ENERGY NETWORK INPUTS (cont.)

ITEM No	PROCESS OR COMMODITY	E.N.I.	COMMENTS	SOURCE REF
	I.C.I. compound fertilizers			
2.17	No.1A (15:15:21)	16 GJ/t	Packaged for use	25
2.18	No.2 (22:11:11)	20 GJ/t		25
2.19	No.9 (9:25:25)	14 GJ/t		25
2.20	NO.5 (17:17:17)	18 GJ/t		25
2.21	Potassium chloride	9.6 GJ/t (K)		26
2.22	Potassium chloride	9.7 GJ/t (K)	In U.K. from Europe	6
2.23	Potassium chloride	7.5 GJ/t (K)	In U.K, from Cleveland Potash Ltd.	25
2.24	2-4 D	94 GJ/t		6
2.25	M.C.P.A.	130 GJ/t		20
2.26	Paraquat	460 GJ/t		20
2.27	DDT	101 GJ/t		6
2.28	Water	4 MJ/m^3	Overall U.K. water supply from 1963 and 1968 I/O Table	4
2.29	Water	7.3 MJ/m^3	Industrial water supply	27
2.30	Irrigation pumping	3 MJ/m^3	Calc. from Nebraska data (ground water supply)	12
2.31	Irrigation pumping	12 MJ/m^3	California, total irrigation supply 1972	23
2.32	Irrigation pumping	9 MJ/m^3	Israel; includes lifting water 200 m to the distribution system	28
2.33	Irrigation	0.11 GJ/ha.y 7.6 MJ/m^3	Total cost from Hong Kong system incl. piping, maintenance etc.	29
2.34	Capital cost for new irrigation schemes	80 GJ/ha	Typical value from world survey of costs from 10,000 to 500,000 acre schemes converted to J by J value of GNP $	15,16
3.	Packaging materials			
3.1	Paper	32 GJ/t	Overall paper in Aust.; excludes fuel value of the paper	7
3.2	Paper	27 GJ/t	Excl. fuel value of paper, and forestry operations	30
3.3	Paper	39 GJ/t	Incl. forestry operations and package fabrication	32
3.4	Paper -unbleached Kraft	47 GJ/t		31
3.5	Paper -corrigated boxes	41 GJ/t		31
3.6	Paper and board	36 GJ/t	Overall figure from 1968 I/O Table	4
3.7	Glass	18 GJ/t	U.S.	32
3.8	Glass	22 GJ/t	U.K. 1968 (plate glass)	30
3.9	Polystyrene	70 GJ/t	Direct energy use in process only	31
3.10	Polyethylene	160 GJ/t		31
3.11	Polypropylene	168 GJ/t		31
3.12	Polyvinyl chloride	119 GJ/t		31
3.13	Rolled steel	54 GJ/t	From virgin ore incl. mining (U.S.)	31
3.14	Zinc	72 GJ/t	From virgin ore incl. mining	30
3.15	Aluminium sheet	290 GJ/t	From bauxite incl. mining (U.S.)	31
4.	Construction materials and fabrication			
4.1	Pig iron	4.2 GJ/t		31
4.2	Steel-crude	38 GJ/t	U.K. overall 1968 (includes scrap)	30
4.3	Steel-finished	48 GJ/t	U.K. overall 1968 (includes 50% scrap)	30
4.4	Steel-finished	23 GJ/t	U.K. 100% scrap	30
4.5	Copper	72 GJ/t	U.K. from ore	30
4.6	Cooper	9 GJ/t	U.K. from 100% scrap	30
4.7	Aluminium	327 GJ/t	U.K. from ore	30
4.8	Aluminium	10 GJ/t	U.K. from scrap	30
4.9	Cement	6.4 GJ/t	Direct process-energy only	33
4.19	Cement	7.9 GJ/t	U.K. 1968	30
4.11	Cement	9.1 GJ/t	U.S. data	34
4.12	Cement	5.6 GJ.t	U.K. 1968, overall value from I/O Table	4
4.13	Concrete	1.8 GJ/t	Direct process-energy only	33
4.14	Plaster	3 GJ/t	U.K. 1968	30
4.15	Plaster board	66 MJ/m^2	U.K. 1968	30
4.16	Bricks	1.8 GJ/t	U.K. 1968	30
4.17	Stone	3 GJ/t	U.K. 1968, overall value from I/O Table	4
4.18	Swan Wood	6.5 GJ/t	U.K. 1968	30
4.19	Plywood	54 MG/m^2	U.S. 1963, overall value from I/O Table	5

ENERGY NETWORK INPUTS (Cont.)

ITEM NO	PROCESS OR COMMODITY	E.N.I.	COMMENTS	SOURCE REF
4.20	Synthetic rubber	148 GJ/t	U.K. 1968	0
4.21	Paints	0.7 GJ/gal	U.S. 1963, overall value from I/O Table	5
4.22	Automobile	64 GJ/car	U.K. 1968 overall value from I/O Table	4
4.23	Automobile	126 GJ/car	U.S. 1968	35
4.24	Farm tractor (per rated H.P.)	11 GJ/HP	U.S. 1954	36
4.25	Vehicles and machinery	79 GJ/t	U.S.	38
5.	Energy requirement for energy	This section gives the total primary energy required to deliver 1J of energy in various forms to the final consumer.		
5.1	Black coal	1.024 J/J	from U.S. 1963 I/O Table	1
5.2	Black coal	1.042 J/J	U.K. 1968	37
5.3	Black coal	1.022 J/J	from U.K. 1968 I/O Table	4
5.4	Coke	1.181 J/J	U.K. 1968	37
5.5	Oil from petroleum	1.208 J/J	from U.S. 1963 I/O Table adjusted for imports	1
5.6	Oil from petroleum	1.134 J/J	U.K. 1968	37
5.7	Natural gas	1.169 J/J	from U.S. 1963 I/O Table adjusted for imports	1
5.9	Natural gas to industry	1.032 J/J	U.K. 1972/73	25
5.10	Natural gas	1.233 J/J	U.K. 1971/72 (excl. exploration and drilling)	37
5.11	Town gas	1.545 J/J	U.K. 1963	
5.12	Electricity	3.870 J/J	from U.S. 1963 I/O Table	1
5.13	Electricity to industry	3.633 J/J	U.K. 1974	25
5.14	Electricity	3.968 J/J	U.K. 1971/72	37
5.15	Electricity	2.95 J/J	from U.K. 1968 I/O Table	4
5.16	Electricity	3.33 J/J	Australia 1972 (incl. hydroelectricity)	7

PHOTOBIOLOGICAL ENERGY CONVERSION

- a practical proposition?

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INTRODUCTION

Awareness that reserves of such fossil fuels as petroleum and natural gas will be severely depleted within a generation has led, in the last few years, to a re-examination of our future energy resources and needs. With growing objections to the hazards of nuclear fission, and fusion still very remote, there is a strong case for concentrating our efforts on the most abundant and widely available renewable energy resource - solar energy. Several ways of utilising solar power have recently been proposed (NSF/NASA, 1972; Australian Academy of Science, 1973) and many of these could be suitable for Australia, where there are many areas offering long periods of cloudless, sunny skies.

One method which has recently been advocated both in Australia and overseas (Chedd, 1975) is to utilise the photosynthetic mechanism of green plants whereby carbon from the atmosphere (CO_2) is "fixed" in the form of reduced carbon compounds. Harvesting of these plants and their conversion into a more useful form of fuel is therefore a way of harnessing solar energy.

Is this a practical proposition? Is it the most efficient way of utilising the resources involved (sun, fertiliser, land, water etc.)? These are some of the questions which have concerned us at the Energy Research Centre at Sydney University and which we have attempted to answer by defining and characterising in some detail possible systems of photobiological energy conversion - a term which we use to describe the complete process of growing, harvesting, transporting and chemically converting plant dry matter.

Of course, the use of photosynthetic materials as an energy source is not new; firewood is the oldest form of fuel known to man and was undoubtedly the most important single energy source until less than one hundred years ago. For example, figures for the U.S.A. (Schurr, 1960) show that in 1880 firewood still supplied over half the national consumption whilst, in Australia, for 1973-74, firewood contributed only 1.4% towards primary energy consumption (Gartland, 1975). However, wood is still the most important fuel in many of the less developed countries; for example Tanzania still derives over 90% of its fuel from wood or wood charcoal (Vahrman, 1974).

There is little merit, today, in using specially grown photosynthetic material as firewood. Although this has been advocated in the U.S.A. (for producing electricity) it would not be suitable for Australia where we are well endowed with coal resources but lack supplies of liquid fuels. At any rate the utilisation of dry matter in this way represents an unnecessary intermediate step since solar radiation could be used directly to raise steam in stationary boilers. Thus the best system of photobiological energy conversion seems to be one which concentrates on the production of liquid and gaseous fuels, such as alcohol, oil and methane.

SOURCES OF PHOTOSYNTHETIC MATERIAL

Potential sources of photosynthetic material can be divided into two groups: organic wastes and energy crops. The most important organic wastes in Australia (shown in Table 1) are urban refuse, sawdust and bark residues from sawmills, and straw. The first two may cause considerable local waste disposal and pollution problems but the total quantity, in energy terms, amounts to only 7% of our current consumption of oil, assuming (quite unrealistically) 100% efficient conversion of these wastes to oil. Thus wastes cannot be considered as significant contributors to our energy needs although the processing of them (in situ) to various fuels can be an economic and environmentally attractive method of disposal. Cereal straw is generally not a disposal problem since it is usually burnt in the fields (in areas of heavy soils) or ploughed in as mulch (in sandy soil areas). However, it too can be used as an energy source and we have examined elsewhere (McCann and Saddler, 1975a) the possibility of converting straw to either pyrolytic oil or methane. This study has highlighted a general observation applicable to organic wastes, namely that large scale utilisation of waste materials is only economic if the opportunity cost of waste purchase is negative (or very small). Since a significant cost is necessary to harvest and transport straw to a central processing point (see Table 2), then the processing of it to fuel is uneconomic given the current energy price structure. A much better proposal would be to utilise the cereal straw where it is produced i.e. on the farms. This is discussed in more detail later on.

ENERGY CROPS

Since organic wastes cannot make a major contribution to our energy needs we decided to examine the possibility of creating extra photosynthetic material by the cultivation of "energy" crops. Obviously there is a very wide choice possible here but the final selection of five contenders was based on the following selection rules:

(i) Crops must be capable of giving high yields in order to minimise the costs of land purchase, land preparation and harvesting which rise steeply as cropped area increases;

(ii) Yield should be assessed in terms of total dry matter that can feasibly be harvested;

(iii) Harvesting must be spread over most of the year so that processing plant can operate on a continuous basis thereby eliminating vast storage requirements or under utilisation of equipment.

For Australia, with its large tropical regions, these criteria point to tropical field crops as the obvious choice; in southern Australia where the climate is temperate, tree crops would be best.

On this basis, five crops were selected for detailed assessment. Four of these are tropical crops: Cassava (tapioca, manioc), kenaf (an annual fibre crop), elephant grass and sugar cane. Cassava produces both starch (from underground tubers) and cellulose (leafy tops), kenaf and elephant grass yield mainly cellulose,while sugar cane produces both sucrose and cellulose. The fifth crop is *Eucalyptus* species which would be grown in the temperate regions using short rotation forestry practice. A coppicing species (with the ability to grow from a cut stump) would be used, and harvesting would be carried out every eight years or so. After two or three coppice rotations, the trees would be replaced with seedlings.

Having selected the most suitable crops, several further ground rules can be established for successful crop production:

(i) There must be either a moderately large, reliable and fairly uniform rainfall or alternatively, irrigation;

(ii) The land should be reasonably flat, well drained and at least moderately fertile;

(iii) Extensive mechanisation will be necessary to reduce labour costs;

(iv) Mineral nutrients used by the crop, which generally pass through the chemical processing intact should be recycled to the cropped area either via irrigation channels or "rain guns".

This latter criterion is particularly important for tropical Australia where the cost of transporting fertiliser from the southern producing sites is considerable. The cost of urea on the Ord for example is nearly twice the cost of urea in Brisbane (the source of supply). The question of fertiliser is particularly interesting: so long as moderate to heavy applications are necessary to sustain high yields, photobiological energy conversion cannot really be considered a completely renewable energy source, for the process relies on exhaustible secondary ingredients (phosphate fertiliser) for its successful realisation.

Estimates of the cost of growing the five crops in various areas of Australia are given in Table 2; further details are given elsewhere (Saddler and McCann, 1975b). Eucalyptus was assumed to grow under rain fed conditions in southern Australia and cassava under irrigation in Northern Queensland. Kenaf costs are for the Ord River (Wood and Angus, 1975), elephant grass for the Burdekin delta in Central Queensland (Stewart and Rawlins, 1975) and sugar cane data are presented as a range covering various areas of Queensland (Ferguson, 1975). All costs are at prices prevailing at the end of 1974. Caution should be exercised in comparing the costs since there are some differences in the bases of calculation. The costs derived by us (cassava and eucalpytus) include the full cost of irrigation water and a 7% discounting factor on all capital items.

Energy costs are also given in Table 2. For straw, cassava, and Eucalyptus, the energy costs of the following items are included: direct fuel use, manufacture of machinery, maintenance of machinery and transport of all materials from a large urban centre. For kenaf and elephant grass, very rough calculations were made on the basis of the items indicated by the cost calculations of the respective authors; the figures should therefore be regarded as indicative ones for the purpose of general comparison only.

CONVERSION TO FUEL

Having grown and harvested the photosynthetic material, one has a choice of three major processes for converting it to liquid or gaseous fuels. These are fermentation to ethyl alcohol, bacterial fermentation to methane and pyrolysis to oil.

Ethyl alcohol is produced by hydrolysing either starch or cellulose and then fermenting the resultant sugars. Thus the "back-end" of the process is common to all raw materials, but a different "front-end" is required, depending upon whether starch or cellulose is used. Hydrolysis of starch is much the easier (and cheaper) process; we estimate that using current batch technology, cassava alcohol could be produced for $250/tonne in a large process plant (100,000 tonnes/yr). This may be compared with current prices of $275/tonne for alcohol as an industrial solvent. Hence it is possible now for cassava alcohol to compete with either molasses based or petroleum based alcohol. However, from Table 3, one can see that its use as a fuel may be some way off, depending upon changes in the energy price structure and Government excise policy. Further improvements to the antiquated alcohol fermentation technology are possible given adequate research, so that a future notional price for cassava alcohol could be about $215/tonne. Further cost reduction still would be possible given yield improvements and we may yet see a return to the production of ethylene from agricultural based materials and the establishment of an agro-chemical industry in Northern Australia (see later section).

Alcohol from cellulose, however, is much more expensive because of the great chemical stability of ligno-cellulose. If an acid hydrolysis process is used, concentrated hydrochloric acid is required and this means expensive acid-resistant vessels and large amounts of steam. In fact such a process would consume more energy than it produces ($\simeq$3.5:1) so that by no stretch of the imagination could it be considered as a contributor to our overall energy requirements. Enzyme hydrolysis is even more expensive and it too results in a negative energy yield due to the large amounts of energy required in fine grinding and pre-treating the raw material. Thus the prospects for producing alcohol from cellulose using presently forseeable technology are not good. Indeed, alcohol from cassava starch gives a positive net energy yield only because most of the energy used in the process comes from burning the cellulose in the stems and leaves of the cassava plant.

METHANE

Ligno-cellulose can readily undergo anaerobic bacterial fermentation to produce a "biogas" containing 70% methane (by volume) and 30% carbon dioxide. The cost of methane produced in this way from straw in an industrial plant would be about 0.42c/MJ (see Table 3), assuming use of the slurry residue as a livestock feed. This cost compares favourable with towns gas but is about four times the notional price ($1.15/10^{9}J) for ex-pipe line gas from the Cooper basin in South Australia. Energy yield (defined as N.U.E.P.† efficiency) is about 34% or even lower (12%) if any of the residue by-products are required in dry form. Similar efficiencies would be obtained with other cellulosic material e.g. Eucalyptus wood, but the cost would be greater because of higher raw material costs.

PYROLYTIC OIL

Pyrolysis of photosynthetic material can readily be carried out to produce a mixture of oil, char and gas. The relative proportions of each vary with different raw materials and process conditions. Basically, the material is shredded and dried to a powder, then flash pyrolysed at about 500°C. All of the gas and up to two thirds of the char are recycled to provide heat for the process, leaving

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† defined as 100 $\frac{\text{external utilisable energy-secondary energy input}}{\text{primary energy input (raw material)}}$

pyrolytic oil as the main product; this could be used as a fuel oil. This process has the highest energy efficiency (52%) of all the processes considered, mainly as a result of the reaction being carried out dry; large volumes of water do not need to be heated as is the case with the other processes. Table 2 shows that pyrolytic oil costs about twice the current price in Australia of No. 6 fuel oil (from petroleum) on an energy content basis.

ENERGY FROM CROPS?

The results we have obtained suggest that liquid or gaseous fuels produced by photobiological processes are likely to be considerably more expensive than alternatives such as petroleum fuels or natural gas, which are currently available in Australia. If the prices of fossil fuels continue to rise, photobiological fuels will become more competitive; their cost will also rise, but less rapidly, since at current prices inputs of fossil fuels and electricity account for only 10-15% of the cost of photobiological fuels. In Australia, photobiological fuels will also have to compete with synthetic fuels produced from our large coal reserves. As can be seen from the figures in Table 3, the estimated cost of syncrude (oil) from coal is considerably less than the estimated cost of the cheapest photobiological oil. Although this difference partly refelcts the cost reductions and economies of scale that are being achieved by the current intensive development programme on synthetic fuels from coal,

coal also has some major inherent advantages when compared with photosynthetic material. It has a much lower unit cost, particularly from the large open cut mines in Queensland, and it can be supplied in large quantities at the mine with very low transport cost, compared with crop material which must be gathered from a wide area.

Of course supplies of coal will eventually be exhausted, but for Australia this is a long term prospect compared with the short term prospect of depleted oil reserves. The Joint Coal Board has assessed in situ reserves of black coal in Eastern Australia to be not less thant 215,000 million tonnes which may yield around 100,000 million tonnes of saleable coal (Pratt, 1975). These figures include estimates of coal in unexplored areas as well as in areas which have been considerably tested by drilling.

Forecasts (Pratt, 1975) of black coal consumption for 1980 indicate a possible domestic and export requirement of 100 million tonnes per annum. In the same year Australian crude oil consumption may be around 40 million tonnes. Now assuming that all of our oil in 1980 was produced from coal via a Fischer-Tropsch process with a 25% efficiency, total coal requirements to satisfy our solid and liquid fuel requirements would be 260 million tonnes per year. Thus at 1980 rates of usage there would be enough coal to last about 400 years! Of course a superficial calculation like this doesn't take account of future increases in energy consumption (estimates vary depending upon population

endowed with the essential resources of fertile soil and reliable water supply than most people realise. Secondly, it is important to consider the most economically and socially desirable way of using these resources. The economic and natural resources needed to produce photobiological fuels can equally well be used for the production of food, natural polymers such as cellulose pulp or cotton, or industrial chemicals like alcohol.

For example, wood chips for use as a raw material in fuel production are identical with woodchips used as a raw material for a pulp mill. In 1974 the price of export woodchips was apparently $27 per tonne (Wood and Angus, 1975). If woodchips can be produced from an intensive plantation for $19 per tonne (Table 2) then obviously they will be used as a source of pulp until the market is saturated. Such intensive plantations offer a method of producing present and anticipated future Australian wood pulp requirements from a much smaller area than present plans allow for. A scheme like this could be set up on, for example, marginal dairying lands thereby allowing preservation of native forests which are currently being destroyed in a manner which is typical of the short-sightedness of most Australians.

A second example is provided by sugar cane. This is obviously a promising energy crop on the grounds of productivity alone; both sucrose and cellulose could be converted to fuel. However a plant manufacturing alcohol from sucrose at a cost of $250/tonne could only afford to pay $60 per tonne for the sugar. This is way below the long term price of sugar for use as food, let alone recent high spot prices. Theoretically Australia could convert the 75% of its sugar crop which is exported to alcohol for domestic energy supply but this would be enormously costly in economic terms and would pose untold strategic implications resulting from such an isolationist policy.

The plain fact is that the world is desperately short of food and natural fibre. To use the resources of soil, water, fertiliser etc. to produce fuel crops instead of increasing food production is economically crazy and morally reprehensible especially when the potential producing countries such as Australia and the U.S.A. are already so profligate in their use of energy. Thus the main conclusion of this study is a negative one: large scale production of energy by photobiological means would not be sensible in Australia (and probably not in any other country either).

AGRO-INDUSTRIAL COMPLEXES

One of the most worthwhile and exciting prospects that our study has highlighted is the potential that agro-industrial complexes have for developing Northern Australia. These complexes make use of all parts of a crop in a number of process plants which are integrated with each other and with the land from which the raw material comes. Energy production is likely to form only a small part of an agro-industrial system, as an outlet for those parts of the plant for which a more valuable use cannot be found. This is currently the practice in the sugar industry, which burns bagasse (the residue from cane processing) to provide all the energy used by the sugar mills.

A good example of an agro-industrial complex is shown in Figure 1; further details can be found elsewhere (McCann and Saddler, 1975c). Here cassava is processed to provide starch, glucose, single cell protein, alcohol etc. from the tubers and leaf protein concentrate and bagasse from the tops. Studies we have carried out for the Ord River show that this could be a very attractive scheme, particularly for starch, dextrose and ultimately alcohol production.

All of the energy for steam requirements would come from combustion of the bagasse (or tops if leaf protein concentrate is not extracted) and waste material from the processing could be used to generate methane before returning the nutrients to the soil. In this way the complex would almost be self-sufficient in energy.

Whilst large-scale versions of the complex would be necessary in Australia so that high labour costs could be absorbed, the technology is straight forward so that small scale versions could be constructed in developing countries out of simple equipment. This could be of great importance in those parts of Africa and South America where cassava is the staple food of the rural masses but protein deficiencies are rife.

ALTERNATIVE TECHNOLOGY

We indicated earlier our studies had shown that the gathering together of organic wastes for processing in a large central plant is uneconomic; it is far better to utilise these wastes at their source. In the case of cereal straw and other on-farm wastes there are distinct advantages both for the farmer and for villages in developing countries, in utilising these wastes in an anaerobic digestion system.

An example of such a system is depicted in Figure 2 where a scenario situation for a pig/cereal farm is given. This sized farm (270 lb/day dry solid) is probably the minimum sized practical scheme which is viable. The combination of 2/3 pig effluent and 1/3 cereal straw optimises the carbon/ nitrogen ratio, resulting in about 7 ft^3 of biogas per lb of dry solid. Part of the gas produced would drive a gas engine (which would drive an AC-DC generator), the engine cooling water being used to maintain the digester temperature. The remainder of the gas could be used for heating, cooking and as a liquid fuel substitute (when compressed to 3000 psig) for such machinery as tractors.

Like agro-industrial complexes the system would make use of all of the farm waste in a system generally ascribed to Chan (1972). Such a system (shown in Figure 3) would provide humus or soil conditioner, algae, fish, ducks and irrigation water in addition to valuable methane.

There is a chronic shortage of fuel at the local village level in less developed countries while at the same time large quantities of organic waste are often being produced. Schemes such as the one above are slowly emerging but they are generally hampered by a lack of basic scientific understanding. Overcoming this problem is one of the best ways that developed countries such as Australia, can contribute to the needs of the less developed countries. Indeed we believe that the greatest potential for photobiological energy conversion lies not in grandiose schemes to provide even more energy for wasteful consumption in developed countries, but in more modest efforts to make efficient use of organic wastes to achieve some improvement in the conditions of the masses of people in less developed countries.

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TABLE 1: AVERAGE ANNUAL PRODUCTION OF ORGANIC WASTES IN AUSTRALIA

Cereal Straw	20.6 x 10^{16} J per annum
Sawmill wood waste (sawdust and bark)	3.6 x 10^{16} J " "
Urban organic waste	5.0 x 10^{16} J " "
Total consumption of petroleum 1973-74	124 x 10^{16} J " "

TABLE 2: CHARACTERISTICS AND COSTS OF POSSIBLE ENERGY CROPS

Material	Location	Yield assumed (te/ha/yr)	Growing and harvesting cost ($/te)	Transport Cost ($/te)	Total Cost ($/te)	Energy Input (MJ/te)
Cereal Straw	Gunnedah District, NSW	1.6	3.90	4.50	8.40	540
Cassava - tops	far north Queensland	12	24.50	3.50	28.00	870
- tubers		17.5	31.00	3.40	34.40	1210
Eucalypt chips	south east Australia	16	17.40	1.50	18.90	760
Kenaf (1)	Ord River, W.A.	30	34.40	1.50	35.90	~2800
Elephant grass (2)	Burdekin Delta, Queensland	68	15.60	2.25	17.90	~840
Sugar Cane (3,4)	Burdekin Delta Queensland	44	16-21	2	18-23	

Sources:
(1) Wood and Angus (1975)
(2) Stewart and Rawlins (1975)
(3) Yield from Stewart (1975)
(4) Cost from Ferguson (1974)

TABLE 3: COSTS OF PHOTOBIOLOGICAL FUELS

FUEL	RAW MATERIAL	PROCESS	COMPARATIVE COST ($\$/10^9 J$)	N.U.E.P. efficiency (%)
Alcohol	Cassava	Enzyme hydrolysis/Batch fermentation	8.4	17
Alcohol	*Eucalyptus*	Acid hydrolysis/Batch fermentation	13.4	-180
Alcohol	*Eucalyptus*	Enzyme hydrolysis/Batch fermentation	20.1	<0
Methane	cereal straw	Bacterial fermentation	4.2	34
Methane	*Eucalpytus*	Bacterial fermentation	5.5	34
Pyrolytic oil	cereal straw	Flash pyrolysis (Garrett process)	3.3	52
Pyrolytic oil	*Eucalyptus*	Flash pyrolysis (Garrett process)	4.3	52
Syncrude from coal (Nicklin, 1975)		-	1.2-1.9	-
Kuwait crude oil ($10 US per bbl)		-	1.25	-
Petrol (76c/gall)		-	4.8	
No. 6 fuel oil ($75/tonne)			1.7	
Natural gas (Cooper Basin)			1.15	

FIGURE 1: CASSAVA AGRO-INDUSTRIAL COMPLEX

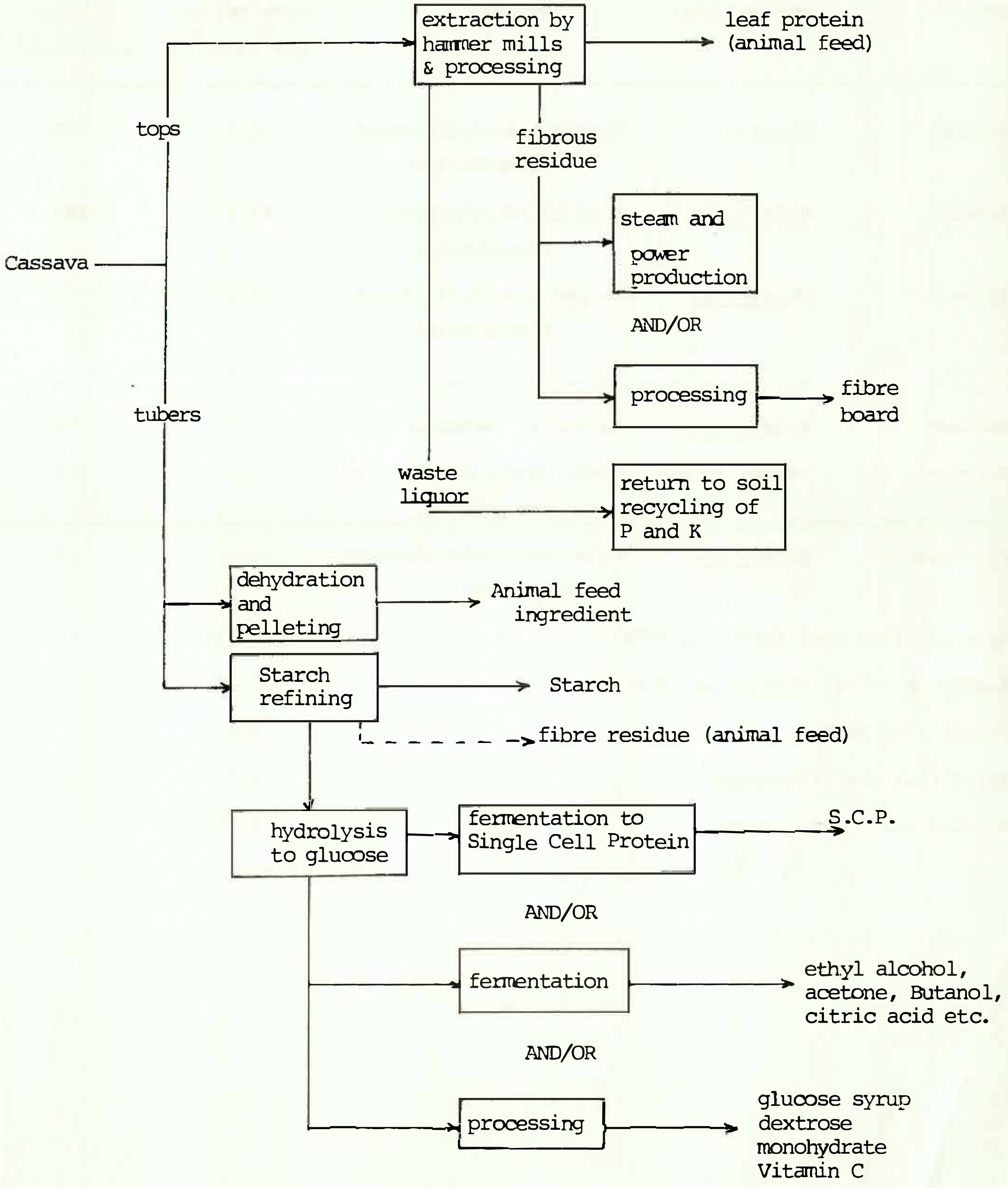
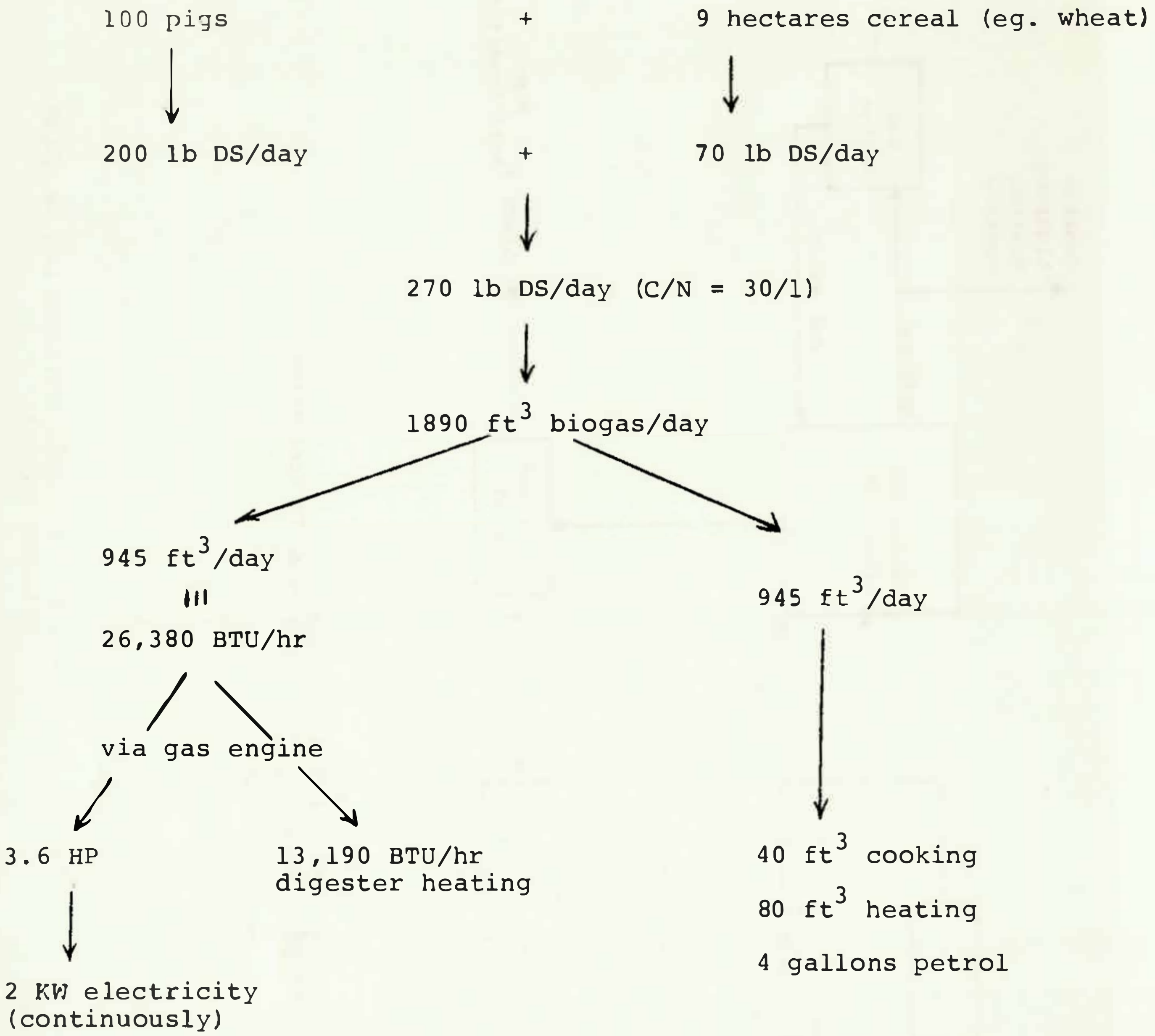


FIGURE 2: POSSIBLE ANAEROBIC DIGESTION SCHEME



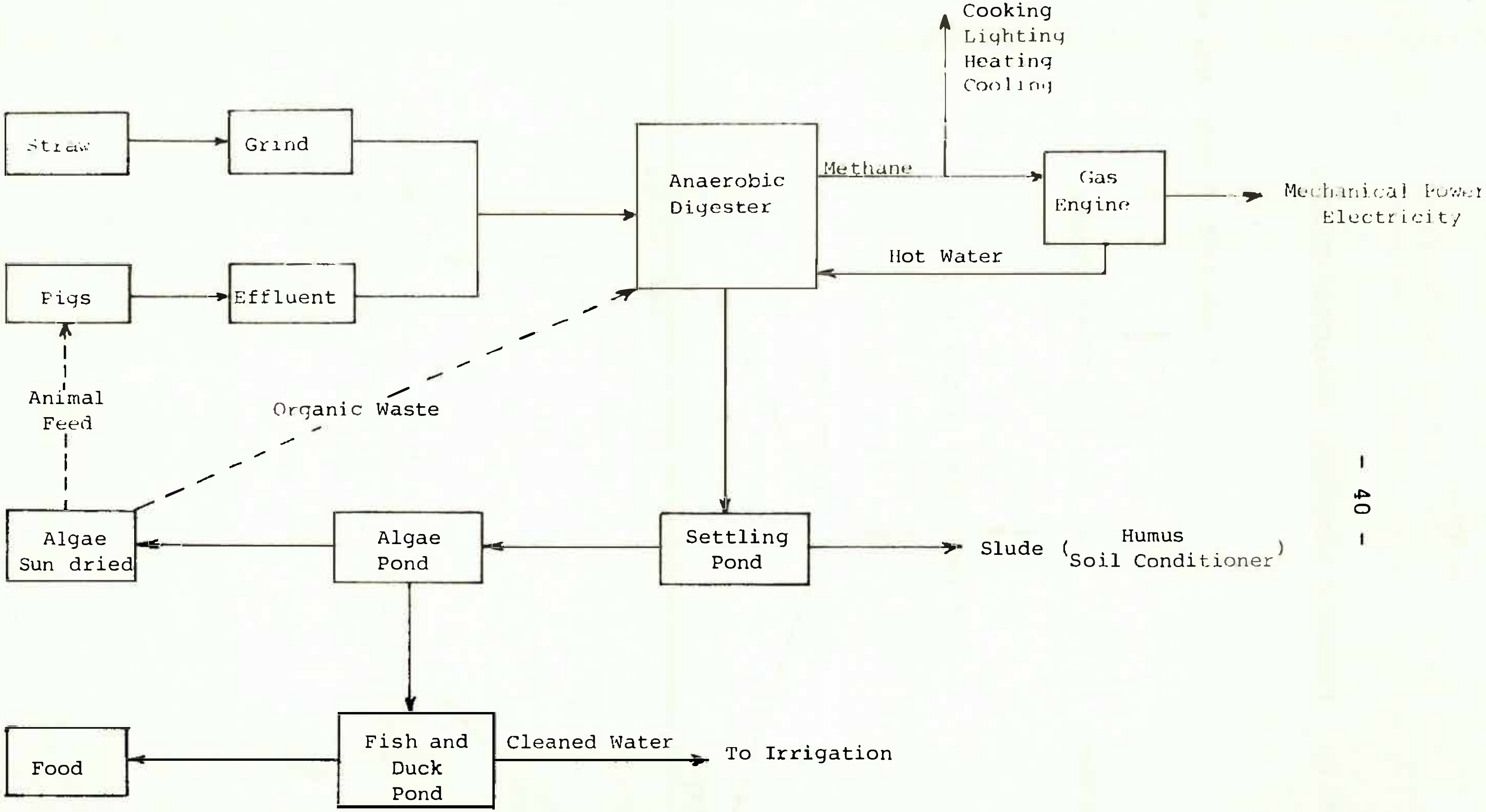


FIGURE 3: SCHEME FOR TOTAL UTILISATION OF FARM OR VILLAGE WASTES

THE ENERGY COST OF PROSPECTIVE FUELS - WITH PARTICULAR REFERENCE TO FUELS FROM "RENEWABLE" SOURCES

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SUMMARY

The energy cost for prospective fuels is discussed. These fuels include those derived from solar energy, either directly and or through crops, coal and uranium. For a fuel to be renewable there must be a net energy output and all resources used in the production must be totally recycled or be practically inexhaustible. The prospects of renewable fuels from solar energy are not good, the exceptions being methane produced by anaerobic fermentation from crops, and low grade heat from solar collectors. Large reserves of coal and current technology precludes the immediate use of nuclear reactors in Australia. Coal then must again be the predominant energy resource if the importation of energy is to be restricted. Direct and indirect ways of producing fuels from coal are analysed. Substantial savings of coal could be made by investing coal energy into other energy producing systems, particularly those involving the utilisation of solar energy. The foreseeable future for solar energy may be as a means of extending fossil fuels rather than as a renewable fuel.

1. INTRODUCTION

Australia is a very rich country in terms of total energy resources. However petroleum provides about half of our current primary fuel and local sources are likely to be exhausted before the end of this century. For economic and strategic reasons, it is preferable that some substitute fuels be produced in this country. The prospects of possible substitute fuels depend on their relative price and convenience. Unfortunately, it is not possible to predict future prices with any certainty. On the other hand, the energetic efficiency with which fuels can be produced is much more predictable and, in the long run, fuels derived efficiently from abundant raw materials predominate. This paper examines the relative abundance and conversion efficiency of some prospective fuel sources.

Prospective fuels are considered here under two categories, potentially renewable fuels from solar energy either by direct conversion or through a photosynthetic route, and non-renewable fuels from coal and uranium. In an energetic analysis of the fuels the total energy cost of the fuel production system needs to be calculated. The total energy cost is defined as the calorific value of the raw material plus the energy cost of any other fuel used, together with an energy cost for other materials, machines, transport, and labour used in the processing. When data on energy used in a process is not available but the monetary cost is known then that cost has been converted to an energy cost using the energy equivalence factor (Ref. 1,2). This factor is the energy use associated with a unit value of production. In all cases except where indicated, the energy cost calculated from monetary cost is less than 10% of the total.

2. PRESENT DAY FUELS

Present day fuels are derived almost equally in energy terms from coal and crude oil with minor energy contributions from natural gas, hydroelectricity, wood and bagasse. In Table I it can be seen that the reserves for coal are substantial but that crude oil reserves are likely to be exhausted relatively quickly unless large new fields are discovered. Apparently natural gas has a long future but it is predicted that its use will increase 10 fold in the next decade; at that rate of consumption, the ratio of reserves to annual consumption will only be 40.

TABLE I

AUSTRALIAN PRIMARY ENERGY RESERVES AND CONSUMPTION (REF. 3,4)

	Reserves 10^{21}J	Consumption 1971/72 10^{18}J/yr	$\frac{\text{Reserves}}{\text{Consumption}}$
Coal	0.73	0.9	800
Oil	0.01	1.0	10
Natural Gas	0.04	0.1	400
Uranium (fission thermal)	0.30	-	-
Hydroelectricity (annual)	0.0001	0.06	1.7

Energy is required to convert the raw materials in the ground to fuels; Table II gives the fuel efficiencies with which fuels are produced in Australia. The fuel efficiency is defined as the energy in the product fuel expressed as a percentage of the total energy cost of the fuel. The efficiency for oil is lower than for coal and gas partly due to the energy cost of the fractionation of the crude oil into a variety of fuels.

TABLE II

PERCENTAGE FUEL EFFICIENCIES OF AUSTRALIAN ENERGY INDUSTRIES (REF. 2)

Coal	96
Oil	80
Gas	90

The long term use of coal is assured because of the large reserves and relatively low price which is a consequence of the efficiency with which the raw material is converted into fuel. Natural gas is a medium term resource that should maintain a relatively low price for some time, but petroleum fuels derived from local crude oil are only a short term prospect. Further supplies will have to come from new local discoveries, overseas, or from substitute fuels. The first source is unpredictable, whilst the second will involve economic and strategic problems. Substitute fuels are desirable for liquid petroleum fuels in the near future and for gaseous fuels in the longer term.

3. PROSPECTIVE FUELS

Prospective fuels will be discussed in two parts, the first covering possible renewable sources, and the second non-renewable sources. The prospective renewable fuels discussed are ones derivable from solar energy. This is an abundant source of energy for Australia because of its large area in or near the tropics. The non-renewable sources considered are coal and uranium, both of which occur in relative abundance, as is shown in Table I. For a variety of reasons discussed elsewhere (Ref. 3), other sources such as wind, tidal and geothermal energy, oil shales, and tar sands are of little interest for Australia in the foreseeable future.

(a) Fuels from Solar Energy

Fuels from solar energy offer a prospect of renewable fuels since the original energy source is time dependent, and its future availability is unaffected by its current use. In order for a fuel to be renewable, there needs to be firstly a net energy production, that is, the fuel produced must release more energy at its point of use than is required for the conversion processes of solar energy to the fuel. The production efficiency defined as the net energy produced expressed as a percentage of the product energy, must be positive. Secondly, other fuels and material resources used in the conversion processes must also be renewable either by recycling, or by being practically inexhaustible.

(i) Fuels from plants

Photosynthesis provides a convenient storage of solar energy. Australia, with relatively large land and water resources, and with a large agricultural economic base, is in a strong position to exploit solar energy via plants. The energetics of several ways in which plants may be converted to fuels are summarised in Table III.

Starch from cassava and cellulose from wood can be hydrolyzed to produce sugars. The majority of these sugars can be fermented to give ethanol, which when separated by distillation from the fermentation medium, can be used as a fuel. Similarly, ethanol can be produced from sugar molasses. In all cases, more energy is required to produce the ethanol than is contained in the product fuel; the production efficiency is negative. The major energy cost is in the distillative separation of alcohol from water. If a cheap (in energy terms) fuel is available, then the energy balance can be considerably improved. For instance in the conversion of wood to ethanol, if processing energy can be obtained through the combustion of extra wood, then a positive production efficiency of nearly 50% can be obtained after allowance has been made for the energy cost of growing and harvesting extra wood.

TABLE III

ENERGY EFFICIENCIES OF FUELS FROM CROPS (REF. 2)

Crop	Fuel Produced	Production Efficiency* %	$\frac{\text{Net energy}}{\text{Energy in crop}}$
Cassava	ethanol	- 44	-
Sugar Molasses	ethanol	- 3	-
Wood †	ethanol	- 64	-
Wood ‡	ethanol	49	0.13
Various	methane	50	0.41
Garbage	char, pyrolytic oil	41	0.35
Straw	char, pyrolytic oil	26	0.24
Elephant Grass	char, pyrolytic oil	20	0.16

* Production Efficiency = $\frac{\text{net energy}}{\text{product energy}} \times 100$

† Processing energy from conventional fuels

‡ Processing energy from the combustion of wood where possible, e.g. steam raising, electricity for processing.

Most plant organic matter can be anaerobically fermented to yield methane, a process particularly suited to matter with a high moisture content. The process functions best with plants which contain only small amounts of lignin and polyphenols. A large scale development in the U.S.A. (Ref. 5) is aimed at producing fuel gas from garbage and sewage wastes. Using data from this development, it has been estimated that methane could be produced from suitable crops with a production efficiency of about 50%.

Pyrolysis of crop and municipal wastes has been studied in the U.S.A. (Ref. 6), the energetics of this process is also given in Table III. It can be seen that this process has a positive production efficiency which is highest for garbage because it contains high calorific value wastes such as rubber and plastics. The efficiency is lower for a crop such as elephant grass than for waste such as straw because energy used for growing the crop has also been included. From what little information is available on hydrogenation studies on photosynthetic wastes and crops, it would seem that production efficiencies similar to those for the pyrolytic process can be expected, as is the case for the processing of coal.

The net energy output from the conversion of crops to a fuel is considerably lower than the gross energy of the harvested crop. Estimates of the amount of crop required to yield energy should be adjusted accordingly. In Table III, the ratio of net energy to the gross energy in the crop is given for production systems giving a net energy gain. The best system, methane from various crops, requires a crop yield 2½ times larger than would be thought necessary, based on the gross energy yield.

A national objective of 1 x 10^{18}J/yr of liquid fuel from plants has been suggested (Ref. 3). This could only be achieved by the cultivation of crops wholly or primarily as energy resources since the maximum possible contribution from present plant and animal wastes would be relatively small. It has been estimated that a potential energy of 2 x 10^{17} J/yr is available if all cereal straws were harvested (Ref. 7). However, when converted to ethanol, the net energy yield would be only about 3 x 10^{16}J/yr. Thus if all the cereal straw could be collected and processed, only 3% of the target liquid fuel could be produced. A similar figure would be achieved by processing forestry wastes; no other wastes are created on the same scale. In these estimates no energy cost has been deducted for harvesting and transportation. The estimates must thus be considered as being optimistic.

In order to approach the national objective, large areas of land would be required. If it is assumed that an average wood yield of 10 tonnes/ha/yr could be achieved from forestry, a value only achieved in plantation forests, the potential energy per hectare would be 1.6 x 10^{11}J, and the total area of 6 million hectares appears to be adequate to meet the national objective. However, if the net energy produced is only 13% of the potential energy, then 46 million hectares would be required. This is nearly equal to the total arable and pasture land under use in Australia. The competition for land use for the production of food and natural polymers would seem to preclude the use of such land areas for energy alone (Ref. 1).

A possible major contribution that could be made by energy crops may be in a way that will extend the useful life of our present fossil fuels. Consider plants as an indirect way of converting coal to gaseous or liquid fuel. Assume that the energy for growing the crop, harvesting and processing to a fuel is met by the use of coal. For the production of alcohol from wood, 1.64 kwh of energy input is required to produce 1 kwh of ethanol energy, in other words 0.6 kwh of ethanol energy could be produced from 1 kwh of raw coal. We shall see later that this fuel efficiency is comparable with that for the production of liquid fuels from coal directly. Starch crops such as cassava will give an even better fuel efficiency by the indirect route. The land area needed to make a significant contribution is then much smaller since it is the gross yield that is relevant. Thus liquid fuels from plants can be considered as making a substantial contribution to the liquid fuel supply, but only as a competitive process with other means of converting coal to such fuels.

When the production of methane from plants is assessed as a means of converting coal to synthetic natural gas (SNG) a very favourable conclusion is reached. For 1 kwh of coal used to supply the full energy cost of producing SNG from plants via anaerobic fermentation 2 kwh of gas are produced compared with 0.6 kwh of gas by the direct process. Green crops such as elephant grass have a gross yield as much as 1×10^{12}J/ha so that less than 1 million hectares of land would yield 1×10^{18}J of SNG. Thus the indirect conversion of coal to SNG has great promise, but will of course, not be of significant interest to Australia for some decades unless a policy of natural gas export is pursued vigorously.

Growing of crops and fermentation processes requires nutrients of nitrogen, potassium and phosphorous in suitable forms and other trace elements. In any high temperature process and combustion, much nitrogen would be lost, but can be replaced by the refixation of atmospheric nitrogen. Much more serious is the volatilisation of some of the non-renewable potassium and phosphorous and their converstion to insoluble salts. It is unlikely that a total recycle of these nutrients could be achieved when high temperature processes are involved in the conversion of crops to fuel, and thus these processes cannot be considered as totally renewable. Biological or chemical processes at low temperatures such as anaerobic fermentation and enzymatic or acid hydrolysis should preserve nutrients in a suitable condition for recycle, but little attention has been given to date to these aspects. In addition the utilisation of nutrients during cultivation is not high due to losses in run off and seepage water and to insolubilization in the soil. The possibilities of closing the nutrient cycle appear small.

Hydroponic systems such as the growing of algae appear to offer a solution to nutrient losses experienced in land agriculture and have the ability to utilise the diffuse sources in sea water, irrigation drainage water and sewage effluents water. Some algae have the potential to convert relatively efficiently solar energy to chemical energy, they can utilise a variety of organic and inorganic carbon sources including carbon dioxide, and some have the ability to fix atmospheric nitrogen. One possible further advantage of algae is their ability to produce liquid hydrocarbons thus obviating the conversion of carbohydrates to suitable fuels. Studies of such systems are being made within the CSIRO Division of Chemical Technology, but are not yet sufficiently advanced to allow accurate energy costings to be made.

(ii) Direct conversion of solar energy

The author is unaware of any data that have been published with regard to the energy costs involved in the production of photovoltaic cells for the direct conversion of solar energy to electricity. In order to assess them projected costs have had to be converted into energy costs. The estimates are thus subject to a large degree of uncertainty. The purification of silicon, for use in the cells will be energy intensive so that it is suggested that estimates based on an average energy equivalence will underestimate the energy cost.

An optimistic projection for the cost of solar cells to produce electricity is $400/kw (installed) with an equal sum being required for suitable storage to smooth the fuel supply. This capital cost is equivalent to an energy cost of 17,000 kwh/kw (installed). The annual output at a load factor of 20% would be 1750 kwh. Thus with an annual allowance for maintenance equivalent to 5% of the initial energy cost there would be no net energy gain in the first twenty years of the installation. If the system involved the conversion of electricity to hydrogen with an energy conversion efficiency of 43% and a total solar and electrolytic cell cost of $1200/kw installed, then over 20 years the ratio of total energy produced as hydrogen to energy cost is about 0.3. This superficial assessment of solar cells indicates that a thorough review of the energetics should be undertaken.

A significant Australian development has been that of solar collectors at present being used extensively for heating domestic water supplies but with a potential for supplying low grade heat to industry. It has been estimated (Ref. 8) that the capital cost for collectors with a thermal output of 1 x 10^{18}J/yr would be \$2.3 x 10^{10}; solar collectors cost about $50/kw installed and have a collector efficiency of 35%. If it is assumed that the total annual energy cost is 10% of the installed energy cost then the total production energy cost is only 20% of the thermal energy produced. Obviously the low grade heat produced cannot be used to produce the solar collectors which are fabricated from glass and metal but there is an opportunity to save enormous quantities of high grade fuels currently used to provide low grade energy; for instance, electricity is used widely for domestic water heating and room heating. Each kwh of heat from electricity requires about 3 kwh of coal, but if the same amount of coal was used to construct solar collectors 15 kwh of heat would be obtained. However, high grade heat is required for the construction of solar collectors and the conversion of low grade to high grade heat is thermodynamically inefficient. It may well be that even these devices cannot be considered as truly renewable.

(b) Non-Renewable Fuels

(i) Fuels from coal

There are now processes being developed for the production of gaseous, liquid and solid fuels from coal that are environmentally more acceptable than existing processes. It is reasonable to suggest that Australia with its huge reserves of coal could produce substitute fuels from coal to replace petroleum fuels in order that the present fuel use structures be maintained. The energetic efficiency of production of some possible fuels are given in Table IV, the figures being based mainly on data from the IGT Symposium on clean fuels from coal (1973) (Ref. 9). The fuel efficiencies

TABLE IV

ENERGETIC EFFICIENCIES OF GASEOUS AND LIQUID FUELS FROM COAL (REF. 2)

Fuel	Process Route	Production Efficiency † (%)	Fuel Efficiency ‡ (%)
Low BTU gas	Winkler gasifier	52	59
SNG	Winkler gasifier methanation	74	58
Methanol	Winkler gasifier catalytic reactor	75	42
"Syncrude"	Hydrogenation	76	57

† Production Efficiency = $\frac{\text{net energy}}{\text{product energy}} \times 100$

‡ Fuel Efficiency = $\frac{\text{product energy}}{\text{energy cost}} \times 100$

are significantly lower than the 80% value for petroleum fuels since additional processing steps are involved. Thus in order to produce 1 kwh of liquid fuel from coal 1.75 kwh of coal is required compared with 1.25 kwh of crude oil. The reserves of coal must therefore be discounted by 30% when considered as substitute petroleum energy. At the present rate of consumption with similar fuels to those now being used solely produced from coal, the ratio of coal reserves to consumption reduces from 800 to 300. Even with an anticipated tripling in local energy demand, and large scale exportation, coal can still be considered as a long term resource, but more efficient ways of using it should be pursued.

The two presently favoured fuels from coal, SNG and "Syncrude" have the best production and fuel efficiencies. There are still problems to be overcome on a commercial scale, but the processes are close to being economically competitive with petroleum fuels in some parts of the world. The "Syncrude" which can be produced is dissimilar to petroleum crude and adjustments in liquid fuel uses, especially with the lighter grade fuels, will need to be made.

(ii) Uranium

With current technology, uranium provides a comparable energy reserve to that of coal. On a world scale, Australian uranium represents some 16% of the total proven reserves, but only if the fast breeder reactors were developed commercially would the uranium reserves represent a major energy resource ! In other words uranium as used in todays commercial reactors is only a minor world resource, but would be capable of providing some 30% of Australia's proven energy reserves. However uranium like coal has its major use in the generation of electricity, and since Australian coal reserves for this use are very extensive, there is no economic reason at the moment to replace coal with uranium.

An energetic analysis of a nuclear reactor has been made (Ref. 2), based on data published by Chapman (Ref. 10) (see Table V). With a rich ore a high production efficiency is attainable. The energy cost for fuel processing, capital installations and materials is only a little above the total allowance for distribution losses and power used by the electrical industry. When a lean uranium ore has to be processed the energy required has a profound influence on the overall production efficiency, a factor which may limit the role of nuclear fission in energy production. There is obviously a grade of uranium ore below which, with current mining and enrichment technology, there is no net output of energy.

TABLE V

ENERGETIC EFFICIENCY OF A 1000 mW(e) STEAM GENERATING HEAVY WATER REACTOR

	Rich Ore (0.3% uranium)	Lean Ore (0.007% uranium)
Electrical output	620	620
Net output	457	134
Production Efficiency *	74	22
Fuel Efficiency *	40	33

* See Table IV

The use of high grade ore appears to be very efficient, but if the production efficiency of electricity by the SEC of Victoria is calculated on the same basis, a value of 78% is obtained. Thus the production of electricity in nuclear fuel power stations is no more efficient than in fossil fuel power stations. The fuel efficiency of the conversion of potential energy into electrical energy for nuclear power stations is about 40%, again very similar to fossil fuel power stations. If only low grade ore is available the fuel efficiency is lower. No allowance has been made in the analysis for the disposal of nuclear wastes or for any possible energy savings from recycling unspent uranium fuel. To this extent, the analysis in incomplete, but such further allowances are unlikely to improve the efficiency figures for rich ore.

Nuclear energy thus appears to have no advantages in efficiency over coal or oil energy in the production of electricity. Since Australia has large reserves of coal, there would appear to be nothing gained by the direct substitution of nuclear power for fossil power. However if nuclear reactors are thought of as a means of converting fossil fuel indirectly to electricity then a positive contribution can be made. For instance, if the energy costs of processing the uranium ore to fuel, for heavy water and for capital installations, are met from fossil fuels then for each kwh of fossil fuel used some 3.7 kwh of electricity are produced. The uranium ore is treated here as a material used in the conversion of fossil fuel rather than a fuel in its own right. When fossil fuels are converted directly to energy in a modern power station then only about 0.3 kwh of electricity is produced from 1 kwh of fossil fuel. Thus a substantial reduction of coal usage is possible by generating electricity in nuclear power stations but this is unlikely to be of interest in Australia for some time.

4. DISCUSSION

Renewable or replaceable fuels offer a promise for the conservation of fossil fuels and ultimately of the steady state economy. In the preceding analysis, possible renewable fuels from solar energy have been analysed.

The direct conversion of solar energy to electricity or hydrogen with photovoltaic cells needs to be closely analysed from an energy point of view. Thermodynamic analysis of the purification of materials and construction of the cells would give a clear indication of the possibilities of achieving a net energy gain from such systems. Energetically and economically these devises are orders of magnitude away from large scale commercial use.

The most favourable use of solar energy at present is low grade heat collection with solar collectors for water heating. Much high grade energy use could be replaced by these devices; a suitable pricing policy would bring large fossil fuel savings. There could be savings of all fuels if the devices were developed for drying, air conditioning and low pressure steam generation.

Energy via photosynthesis in the form of crops has been shown to be doubtful on energetic grounds when liquid or gaseous fuels, comparable with present day fuels, are required. The areas of land required to grow sufficient biomass are very large, and there are doubts on the recycling or replacing of the resources needed to grow and process the crops.

Two immediate positive roles for solar energy via plants are foreseen. The first is through the integrated use of crop resources (Ref. 1) and the second is as a means of indirectly converting coal to liquid and gaseous fuels more efficiently than can be done by direct processes.

Integrated use is likely to remain a minor national use of solar energy. However an important contribution could be the insulating of agricultural production from inflating energy costs. Already two large industries are operating in a way which integrates energy production with food or natural polymer production. The first is the sugar industry in which the residual sugar cane bagasse from the sugar extraction is burnt to raise sufficient steam to meet all thermal and electrical requirements of the sugar mill. The other is a large timber conversion industry based at Mt. Gambier where all on site energy requirements are met by burning waste wood. McCann and Saddler (Ref. 11) recently detailed a possible agro-industrial complex based on cassava in which a substantial contribution to the energy required for processing could come from the waste cassava bagasse.

In a CSIRO study of the utilisation of kenaf as a source of paper pulp and animal feed products, one option is to use the core of the stalk, which contains poorer quality fibre, as an energy source. With this strategy, 90% of the energy required for the crop processing and nitrogenous fertilizer production could be provided, these being the major energy costs. The study was based on the growing and processing of the kenaf in the Ord River Irrigation Area where fuel costs are high. A study of the economics showed that this option was a break even prospect. If energy becomes relatively more expensive, such integrated use of crops may become commonplace in the tropics where extended periods of harvest mean that agricultural residues are attractive.

The use of crops to give an efficient conversion of coal, and other non-renewable energy resources, to liquid and gaseous fuels should not be overlooked. Table VI shows that the production of SNG indirectly gives much higher product energy than does the direct way. Here more energy is obtained in the product than exists in the original coal, the extra energy coming from solar energy stored in the crop. With liquid fuels the advantage is not so pronounced, but ethanol is a much more suitable fuel for transportation than are methanol or any fraction from "Syncrude". In addition, the technology of each step in the indirect methods are fully developed, whereas there are still obstacles to be overcome in the direct processes. The land area that would be required to make a significant contribution to Australia's energy is very large, a significant portion of the land presently used for agriculture but it is much more realistic than that that would be required if a renewable fuel system were being pursued.

One further possibility now being actively pursued within the CSIRO Division of Chemical Technology is the utilisation of plants that produce hydrocarbons either naturally or by stimulation. The object is to avoid the high energy cost of conversion of carbohydrates to liquid fuels.

There are also other means with which to make coal reserves last longer. Each involve the investment of coal energy into another energy producing system, such as electricity via nuclear reactors or hydroelectricity installations. By far the best investment is in low grade heat solar collectors which are likely to return five times the invested energy over the lifetime of the collector.

The conversion of the nuclear energy of uranium to electricity in todays reactors offers no advantages of fuel efficiency over thermal power stations based on coal. In addition, there are operational and waste disposal hazards which cause concern, and their establishment requires

TABLE VI

ENERGY CONTENT OF FUELS DERIVED FROM 1 Kwh OF COAL

Fuel	Route	Process	Energy content Kwh
SNG	Direct	Winkler gasifier	0.58
SNG	Indirect	Crops Anaerobic fermentation	2.0
Methanol	Direct	Gasification and reaction	0.42
Syncrude	Direct	Hydrogenation	0.57
Ethanol	Indirect	Starch crop hydrolysis fermentation	0.69

large amounts of monetary and energy investment. For these reasons, and because of the large reserves of coal which are eminently suitable for electricity production, nuclear power reactors have no immediate place in the Australian fuel industry. We can afford to wait for improvements in nuclear reactor efficiency, fuel recycling and waste disposal, and for the possible development of breeder and fusion reactors. In the meantime, there should be a concentration of the best economic, environmental and social use of coal.

A final point about coal. There are no overwhelming technical reasons why coal has to be converted into synthetic petroleum products. Pulverised coal can be handled just as easily as oil or gas in power stations. Stationary engines do not need a gas or a liquid fuel, and land and sea transport can be powered by external combustion engines or turbines that will operate satisfactorily on powdered coal. The overall energy efficiency for electric cars is as good as petrol driven cars, the inefficiency in the power station being matched by the inefficiency of the internal combustion engine. If coal is converted to synthetic natural gas for heating buildings, the overall efficiency is no better than if electricity is used to provide the heat. Thus more work should be aimed at the more direct uses of coal with less concentration on conversion processes which aim at turning coal into petroleum.

If there comes a time when coal resources are dwindling and other non-renewable energy sources have not been developed, solar energy will predominate. Since solar energy used directly, in the form of tides or wind, or through crops, is a diffuse resource, it is likely that society will have to be restructured into smaller and more widespread communities. Civilisation probably would need to revert to lower population levels and a less energy intensive society. Solar energy does not seem to offer a renewable intensive energy resource on which present day advanced societies can be maintained.

5. CONCLUSION

An analysis of prospective fuels is incomplete without a fuel energy balance being made; this has been done for possible renewable fuels based on solar energy and for fuels from uranium and coal.

For a fuel to be renewable, there must be a net energy output in its production and all resources used in the production must either be totally recycled or be practically inexhaustible. For the solar energy systems discussed the prospects of satisfying these criteria are not good.

Possible renewable fuels from crops were examined, the production of methane by anearobic fermentation is the only system to have the potential of satisfying renewability criteria. In all systems studied the land area required for a substantial contribution to the supply of energy in Australia is much higher than is apparent. The demand for food and natural products is likely to preclude a large energy production.

Energy from the sun via plants already makes a contribution to energy supply through integrated production systems in the sugar and timber industries. Such integrated production of food, natural products, and energy would become more commonplace, particularly in the tropics, if energy became relatively more expensive.

The direct use of solar energy in the generation of low grade heat in solar collectors gives a high net energy return. Alternative high energy sources are required for the construction of the collectors.

Preliminary analysis of photovoltaic cells as a means of obtaining renewable fuel from solar energy indicate that present and prospective construction techniques will be too high in energy cost.

The reserves of coal are so extensive that there is no urgent need to consider nuclear reactors for the generation of electrical power. Moreover with current technology, the efficiency of power generation is no better for uranium than for coal.

In order to restrict the importation of energy coal will have to again become the predominant energy resource. Substitution of coal for oil could be by the production of synthetic petroleum fuels, by the conversion of machines to direct use of coal, or by the investment of coal energy in other fuel production systems.

The foreseeable future for solar energy may be as a means of extending fossil fuels rather than as a renewable fuel. If coal provides the energy input in such fuel production systems as methane or ethanol from crops, electricity from uranium, or low grade heat from solar collectors, then the fuels are produced with more net energy than when coal is converted directly to comparable fuels.

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The Limitations of Hydroelectricity in Australia

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Summary

The Australian continent as a result of its low relief and latitudinal position is overall the driest in the world. The mean elevation is about 300 m, with three-quarters of the area lying between 200 and 500 m, and the average annual runoff is 344×10^9 m^3. Whilst the highest runoff rates occur from the higher elevations, rates are also high in the tropical lowlands and so the total estimated potential hydroelectric power is only about 800×10^9 MJ or 230×10^9 kWh. This is less than one-third of Australia's present total energy consumption. The high potential areas in Tasmania, the Snowy Mountains and North Queensland, have been developed to an annual output of 50×10^9 MJ. The total economic development is unlikely to exceed 120×10^9 MJ.

The Kimberley Coast of N.W. Western Australia offers very considerable opportunity for tidal power and an economic potential of 3000×10^9 MJ per annum has been suggested. This resource, because of its fluctuating nature and physical location, would require transformation to a more usable form by coupled pumped-storage hydroelectricity and/or conversion to chemical energy.

Hydroelectricity cannot be expected to make a signifcant contribution to Australia's gross energy requirements although its flexible character improves the efficiency of other forms of electrical energy production.

Introduction

Solar energy is the driving input to the hydrological cycle and the potential energy possessed by surface runoff by virtue of its elevation above the base level, sea level usually, derives from solar energy. We may define a theoretical hydroelectric potential as the summation of product of surface runoff and elevation for each unit of surface area, this energy in the natural condition being dissipated in erosional processes.

Australia, by virtue of its position on the Australian tectonic plate, consists mostly of plateaus and peneplains of low relief and low elevations. The mean elevation is approximately 300 m and three-quarters of the continent's surface lies between 200 and 500 m, and only 1% exceeds 1000 m, with a maximum elevation of 2230 m. Further because of its latitudinal position and low relief it is the driest of all continents with an annual average rainfall of 430 mm and average runoff of 40 mm compared with the world land surface averages of 660 mm and 300 mm respectively. Australia therefore has a very low hydroelectric power potential on a per unit area basis, and is also low on a per capita and total resource basis (see Todd (1970), Table 7-22).

The greater part of Australia is also further handicapped for economic development of any hydroelectric potential by the great irregularity of runoff. McMahon (1973) has examined a group of flow records from all parts of the continent and shows that the coefficient of variation of the mean annual discharge varies from over 1.6 for the Nogoa River in Central Queensland to less than 0.20 for the King in Tasmania. McMahon also investigated the theoretical storage, as a proportion of the mean annual flow, to achieve a steady regulated flow of 50% of mean flow with a 5% chance of failure. The storage ratio for the Nogoa River is over 1.6 whilst for the King River it is 0.05.

There is also an annual cycle of runoff as a result of rainfall seasonality and/or snowmelt. An example of one of the major streams of northern Australia is the Burdekin River which has a mean annual discharge of 8 x 10^9 m^3 and in 1958 discharged 29 x 10^9 m^3 with a peak rate of 37,000 m^3 sec^{-1}. It also ceased to flow in the same year. Such irregularity requires large regulating storages which are also subject to large variations in stored volume.

Potential Hydroelectric Energy in Australia

The theoretical hydroelectric potential based on mean annual flow provides a basic index figure to compare different parts of Australia, and Australia with different continents. The ratio of possible economic development to theoretical potential then provides an indication of the problems arising from runoff variability and geomorphic characteristics.

Figure 1 shows a subdivision of the Australian continent into the major Drainage Divisions as determined by the Australian Water Resources Council, together with an indication of the areas of higher annual runoff. The Water Resources Council have provided a more detailed partitioning of the Drainage Divisions into some 243 individual basins for which estimates of mean annual discharge have been provided (A.W.R.C. 1975). For the purposes of this paper, basin discharges have been aggregated to groups indicated on Figure 1 and a weighted mean elevation adopted which can only be considered accurate to 30%. The product of mean discharge and weighted mean elevation have been summed for each Drainage Division as indicated and are given on Figure 1.

The areas of highest potential are the most difficult to estimate by these reconnaissance methods and some guidance has been sought from detailed studies (see Knight 1954, 1969; Nimmo and Shepherd 1956; Johnson et al. 1967; Hudson 1969; Dann 1969; Howard 1970; Jeffries 1972). The total Australian potential of 800 x 10^9 MJ or 230 x 10^9 kWh estimated here agrees with the figure of 250 x 10^9 kWh or 28,500 MW of Todd (1970) and 170 x 10^9 kWh for mainland Australia of Hudson (1969). Knight (1969) implies that the potential power of the higher parts of Tasmania is about 3 x 10^9 kW average capacity, this is about 70% of the Figure 1 estimate.

This theoretical hydroelectric potential for Australia may be compared with that of the United States which is 1060 x 10^9 kWh and Asia which is over 8000 x 10^9 kWh (from Todd 1970).

Economic Hydroelectric Energy Production

Hudson (1969) has suggested that the total economic development for conventional hydroelectric plant in mainland Australia will be only 40 to 60 x 10^9 MJ or between 6 and 9% of his estimate of the theoretical potential. The reasons for this remarkably low ratio are related to the requirement of economic development for reasonably large blocks of potential energy together with favourable topography. Most of the potential calculated in Figure 1 is too diffuse and/or irregular to be realized economically.

The three major areas of present economic development of hydroelectric power are Tasmania, the Snowy Mountains region and North Queensland, and we will briefly examine some aspects of these developments.

The present estimate of theoretical potential in Tasmania is 140 x 10^9 MJ and Knight (1969) considered the potential of the higher regions to be 94 x 10^9 MJ. Knight also stated that the estimated actual system capacity by 1975 would be 30 x 10^9 MJ and the probable maximum economic development would reach some 42 x 10^9 MJ. Thus the final actual development should realize about 30% of the theoretical potential of the whole island or 45% of the potential of the higher parts. Parts of the island are particularly favourable for hydroelectric development, and the control and diversion of the outflow from the Great Lake, the largest natural freshwater lake in Australia, from the Derwent to the Tamar Basin is outstanding. The effective fall harnessed to turbines through two power stations, Poatina and Trevallyn, is 955 m of the potential fall to sea-level of 1033 m or 92%. Regulated flow is effectively 100%.

Modern technology has allowed the artificial creation of a similar situation in the upper reaches of the Gordon, Serpentine and Huon Rivers. In the upper Gordon scheme three dams create a pool with an active storage of 12 x 10^9 m^3 or six times the size of the Great Lake. The active storage level is 308 m and the head obtained in Stage 1 is 186 m or 60%. The environmental impact of the water storage works for this scheme have been considerable and it may be expected that the future development of the remaining hydroelectric potential in Tasmania will be less complete.

In the case of the Snowy Mountains Hydroelectric Scheme very detailed analysis of potential and actual power realizations, and also the impact of environmental problems, are available in the literature (S.M.H.E.A. 1963; Johnson et al.1967; Dann 1969; Brown 1974). The power potential of the catchment area is 47 x 10^9 MJ, using a sea-level datum and an annual discharge of 3.6 x 10^9 m^3. Water is however discharged into the westward flowing streams, the Murrumbidgee and Murray, in order to make the water available for irrigation purposes at an effective base level of 300 m. This reduces the power potential by 11 x 10^9 MJ. Dann (1969) has quoted the actual annual power output at full development as 17.6 x 10^9 MJ or 50% of the potential above the 300 m base level. He also indicates that initial plans, which made more use of very high level storage, aqueducts and power stations, anticipated a development of two-thirds of the available energy. These high level developments were abandoned for a combination of economic reasons, related to small size of individual schemes and the changing role of hydroelectricity in overall electrical energy systems, and environmental and aesthetic reasons.

The development of hydroelectric power in Queensland has been discussed by Nimmo and Shepherd (1956) and their estimates only consider schemes in Drainage Division 1 which are estimated on Figure 1 to have a theoretical potential of 190 x 10^9 MJ. The subdivisions with the greatest potential are 1.1, 1.3 and 1.7, and present developments are concentrated in 1.2 and 1.3 on the Barron and Tully Rivers. Nimmo and Shepherd gave a total economic development of 400,000 kW at 50% load factor or 6.3 x 10^9 MJ. This appears a very low proportion of the theoretical potential but is caused by the seasonality of rainfall and runoff and the high coefficient of variation of annual runoff coupled with unhelpful topography. It may be noted that Figure 1 gives a theoretical potential of 150 x 10^9 MJ in Division 9, most of which is in Queensland, yet no economic schemes were proposed in this Division by Nimmo and Shepherd. Experience in Southern Australia suggests that if environmental considerations allow the development of very large storages a higher realization may be possible but it is unlikely to more than double the 1956 estimates to say 13 x 10^9 MJ.

The Role of Hydroelectricity in the Energy Situation

The changing role of hydroelectricity in the Australian electrical generation scheme has been well documented by Dann (1969), Hudson (1969) and Howard (1970). The trend through the construction of the Snowy Mountains Scheme was towards lower load factors, i.e. the ratio of actual energy generated to the possible output of the installed capacity in continuous operation. Thus the Guthega power station had a load factor of 27% while Tumut 3 power station has a load factor of 4%. In addition Tumut 3 power station has capacity to act as a pumped storage, returning water from the tailwater reservoir, Jounama pondage, the 150 m to Talbingo dam during periods of low demand and raising its effective operating load factor to 15%.

The great virtue of a large hydroelectric station is that it can act as a spinning reserve, i.e. it can be rotating at synchronous speed under no load, and take up full capacity in as little as 15 to 30 seconds in response to rapidly rising loads or failure of an element in a thermal power station. Howard (1970) suggests that by the year 2000 perhaps 20% of the generating capacity of the State Electricity Commission of Victoria will be in pumped storage hydroelectric schemes. At present approximately 30% of generating capacity is in hydroelectric plant although this provides less than 15% of total electrical energy. Evans and McCutchan (1971) suggest the percentage will decrease to below 9% by 2000 for the whole of Australia; this is of course influenced by the large block of power used in Tasmania which uses predominantly hydroelectricity and will continue to do so even in the year 2000.

Tidal Power

Tidal power is a renewable resource which is only partly connected with solar processes but is often coupled with hydroelectricity since it uses the machines and techniques of low-head hydroelectricity. The major published study in Australia is by Lewis (1963) and he points out that, like hydroelectricity, to be economically attractive large blocks of potential power must be available. The Kimberley coast of Western Australia has a series of very large inlets in which there is a mean tidal range in excess of 5 m which therefore meets the present minimum potential requirements. Lewis discusses a large number of schemes with some multi-stage suggestions. Evans and McCutchan (1971) assess the annual output from an aggregate of 25 favourable sites as 3000×10^9 MJ or four times the potential hydroelectric power and fifty times the actual possible hydroelectric power. Lewis (1963) suggested that the most favourable site for early development was Walcott Inlet with a capacity of some 80×10^9 MJ or more than the total capacity of all the economic hydroelectric schemes at full development. There is a real problem in conceiving of a market for this energy unless it were transmitted to the Pilbara Industrial Complex which already has ideas of basing its energy requirements on N.W. Shelf natural gas. If a hydrogen based portable energy system was developed then the tidal power could readily be used to produce hydrogen from seawater.

Conclusions

The combination of low relief and low and often irregular rainfall means that the hydroelectric potential of the Australian continent is very low. It would appear that the total economically available energy from hydroelectricity cannot exceed 70×10^9 MJ and about half of this comes from Tasmania. This is in contrast to New Guinea to our immediate north, where the hydroelectric potential exceeds 800×10^9 MJ (Rosenthal 1953; Todd 1970) and practical economic schemes appear to exceed 340×10^9 MJ (S.M.E.C. 1970).

The role of hydroelectricity, particularly pumped storage schemes, is very important in the economic use of large thermal plants. It may be attractive to develop hydroelectric plants with very little net energy production but very large installed capacities. It appears likely that the present ratio of machine capacity for hydroelectricity to thermal machine capacity of 1 to 4 will be maintained.

The related energy source of tidal hydroelectricity has a very great potential in Australia in the Kimberley area of Western Australia. The problem will be the transfer of that energy to present population and industrial centres.

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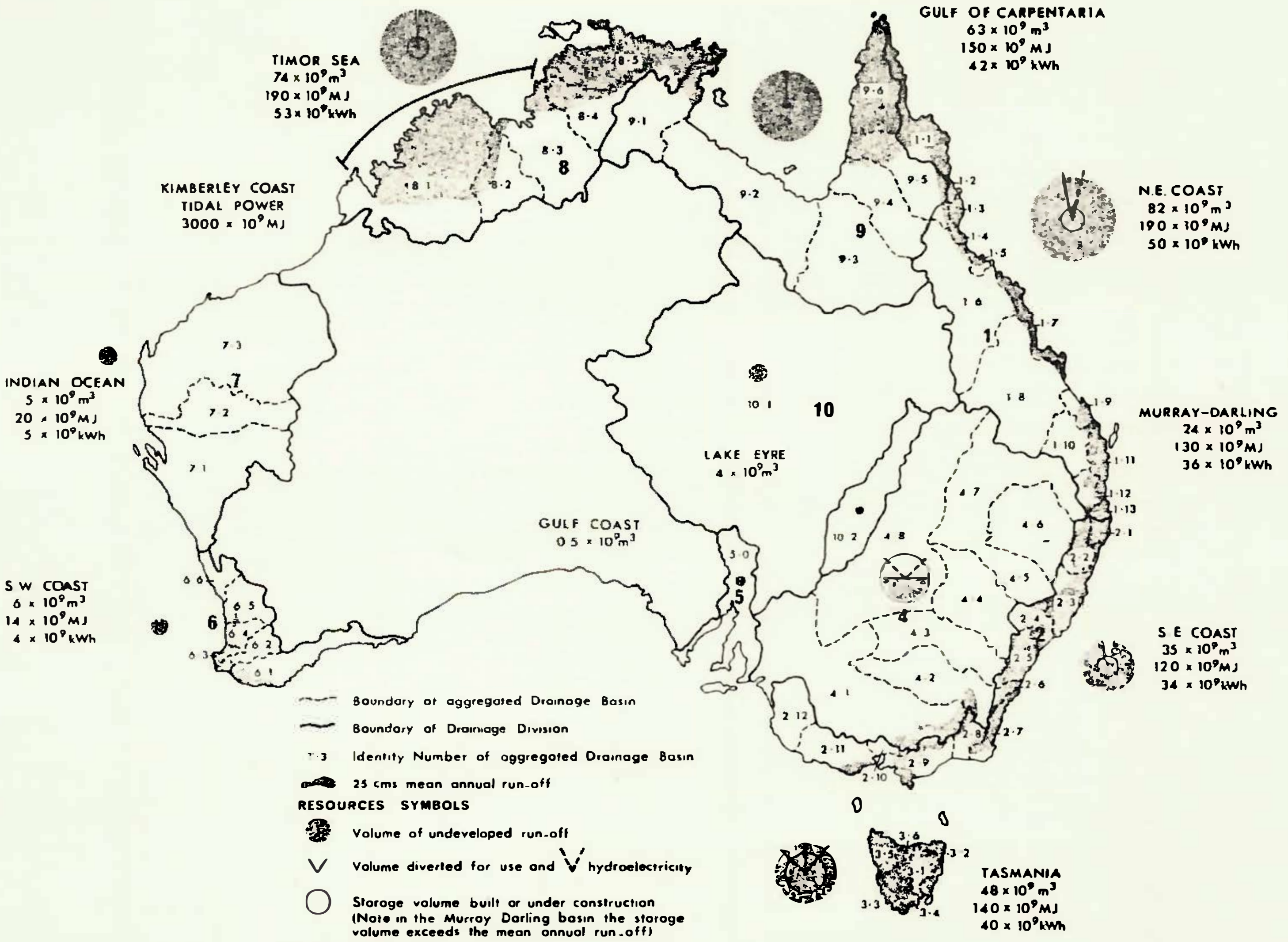
SURFACE WATER RESOURCES AND THEORETICAL HYDRO-ELECTRIC POTENTIAL



NOTE (1) Circle and section areas are proportional to mean annual volume

(2) Diversion volumes and power realization of Snowy R. included in Division 4

Fig 1