Solar and Wind Power for Remote Areas and Rural Communities*

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POWER SUPPLY FROM EXISTING CENTRAL POWER STATIONS

In countries where the generation of power is heavily centralised in existing thermal power stations based on coal or oil fired plant often the main reason for considering the alternative of local power generation from renewable sources is simply the high costs associated with the extension and maintenance of the power grid system. The costs associated with small grid extensions will vary widely from country to country and will be heavily dependent on the particular system used, the length of connection required, the type of terrain traversed, and the usage pattern and load factor at the supply point.

Although power charges in large systems for many countries are likely to lie in the range of US$0.07-0.15 these days, it should be realised that remote area power costs are likely to be in the range of US$0.20-2.00 if the power is generated from stand-alone diesel generator sets. In Austra-

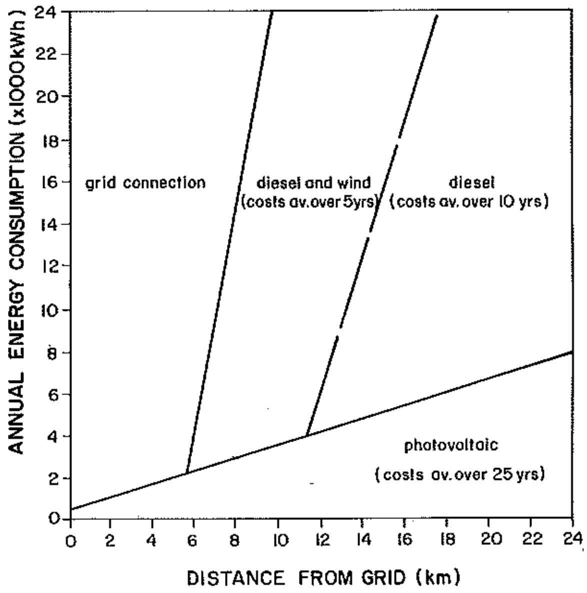

Fig. 1 Remote areas – cost effective options for electricity generation.

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lia, for example, where large connection distances are commonplace, a connection cost of US$-28 000 has been estimated to equate to an electricity supply cost of US$0.45/kWh.

The basic technologies associated with extensions of grid systems have been well documented and the costs associated with such work can be relatively easily estimated. The cheapest system in use is known as the single wire earth return system (SWER), in which a single steel wire is operated at 10-20 kV, with a step down transformer being used to provide up to 20 kW at 240 V AC. Because of safety factors these lines are often limited in length to about 20 km total length. If there is a requirement for a longer connection, it may be necessary to use more sophisticated and hence more expensive equipment. It is already possible, therefore, to compare the solar photovoltaic, diesel, and wind systems with the conventional distribution alternative, using the input parameters of distance in kilometers from the existing power grid and the user level of annual energy consumption as shown for Australian conditions in Fig. 1. A layout of the conventional single wire earth return system (SWER) is given in Fig. 2.

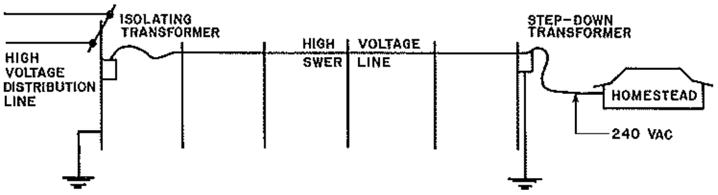


Fig. 2 Remote electricity grid extension.

AVAILABILITY OF CONVENTIONAL AND RENEWABLE ENERGY RESOURCES

If one eliminates the possibility of grid connection to the main power grid on the basis of technical feasibility or cost effectiveness, the range of supply options open to remote areas include the following:

- small-scale diesel or petrol generator sets,
- micro or mini hydro power systems,
- geothermal power generation using organic Rankine cycle plant,
- solar thermal systems based on flat plate collectors, solar ponds, or concentrating collectors driving various types of engines,
- solar photovoltaic systems,
- wind aerogenerators, or
- hybrid systems using several of these options together (Fig. 3).

It should be noted that virtually all hybrid power systems using solar and wind energy in tandem with conventional engine generators should be designed to incorporate battery storage for load smoothing. The only exception to this rule would be in the case of solar water pumping or solar ice making when the storage element can be built-in to the process in the form of water reservoir storage or ice storage.

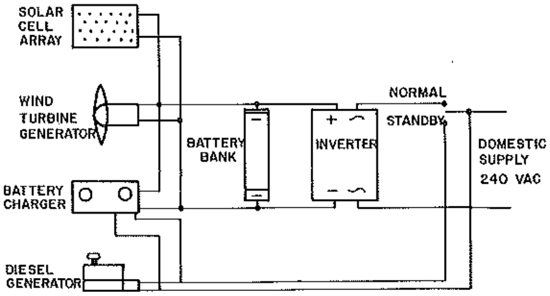


Fig. 3 A hybrid power supply system layout.

Resource Assessment

For an accurate assessment of the economic viability of solar and wind systems it is vital that accurate and long-term measurements should be available for prospective sites.

As part of the preparation for the first World Conference on New and Renewable Sources of Energy, held in Nairobi in August 1981, the World Meteorological Organisation (WMO) was commissioned to produce two definitive volumes on solar radiation and wind measurement and prediction. These volumes (*WMO Technical Note 72* and *WMO Technical Note 75*) include full and detailed instructions on the setting up and maintenance of small micro meteorological stations for these specialized measurements, and also provide invaluable advice on the selection and maintenance of suitable instruments and associated data logging equipment. In any country the local Meteorological Bureau should be the agency responsible for the maintenance and upkeep of the equipment and the requisite radiation and wind records.

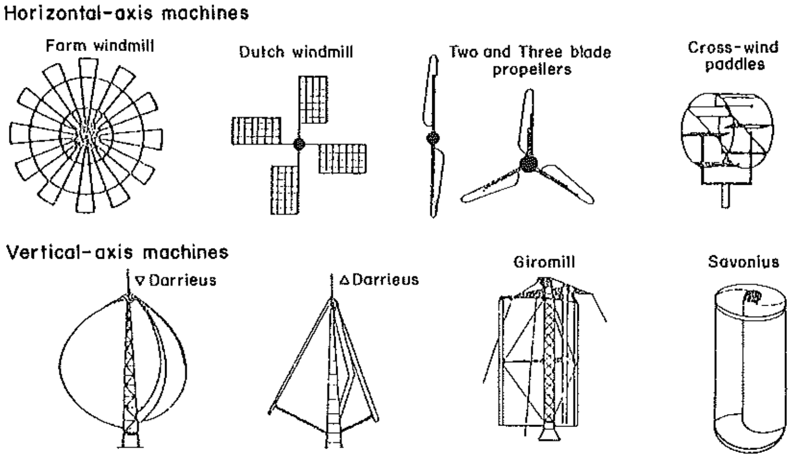
STATE OF DEVELOPMENT OF EXISTING TECHNOLOGY USING RENEWABLE ENERGY RESOURCES

Because of the breadth of the topic, it is not possible in this article to cover the entire field of power production from renewable sources of energy. Rather the emphasis will be laid on those technologies based on the solar direct route (photovoltaic conversion) or the solar indirect route (wind energy or solar thermal electric conversion). As explained earlier, the various options may be combined in many ways with diesel or petrol generator sets or with battery storage systems to give hybrid plant. This does not in any way diminish the importance of other renewable energy options such as micro or mini hydro or biomass derivative possibilities but should allow a fuller coverage of the solar and wind options.

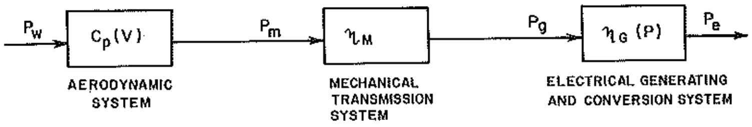
Wind Generators and Wind Power Systems

All wind generators convert the kinetic energy of the wind first into mechanical power at some rotating shaft and then to electrical power through a generator. As a general categorisation, commercial wind machines can be classed as small, ranging from a few watts to say 10 kW; medium, from 10-60 kW; and large, 60-300 kW. In addition there are some very large machines with power outputs in excess of 1 MW, at the demonstration level, at several sites worldwide.

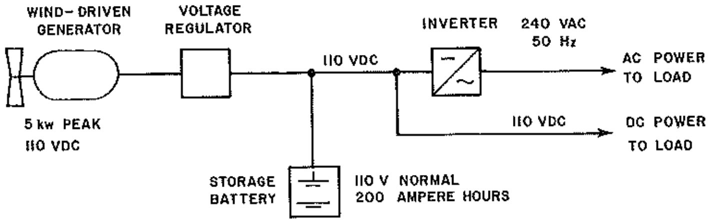
Modern aerogenerators produce AC electricity and come in two basic types – horizontal or vertical axis machines (Fig. 4). Most of the available commercial machines are of the horizontal axis type, with tower mounting and yaw control to continually face the rotor into the wind. The number of blades chosen for these machines is a compromise between high self-starting ability (indication of good performance at low wind speeds) and good efficiency at the higher operational speeds. A common choice is two or three blades if the annual power production is the dominant factor, and more blades if the most important factor is operation in a low wind speed regime (Fig. 5). Some vertical axis machines are now commercially available but they generally have lower conversion efficiencies than their horizontal axis counterparts. Advantages of this configuration, however, include the ability to operate with the wind from any direction, and reduced tower costs – as the heavier equipment items such as the gearbox and transmission can be ground mounted.



VARIOUS CONFIGURATIONS OF WIND ROTORS



WIND-ELECTRIC GENERATOR POWER CONVERSION SYSTEM



TYPICAL D.C. GENERATOR SYSTEM WITH INVERTER

Fig. 4 (a) Various configurations, wind rotors; (b) Wind-electric generator power conversion system; and (c) Typical D.C. generator system with inverter.

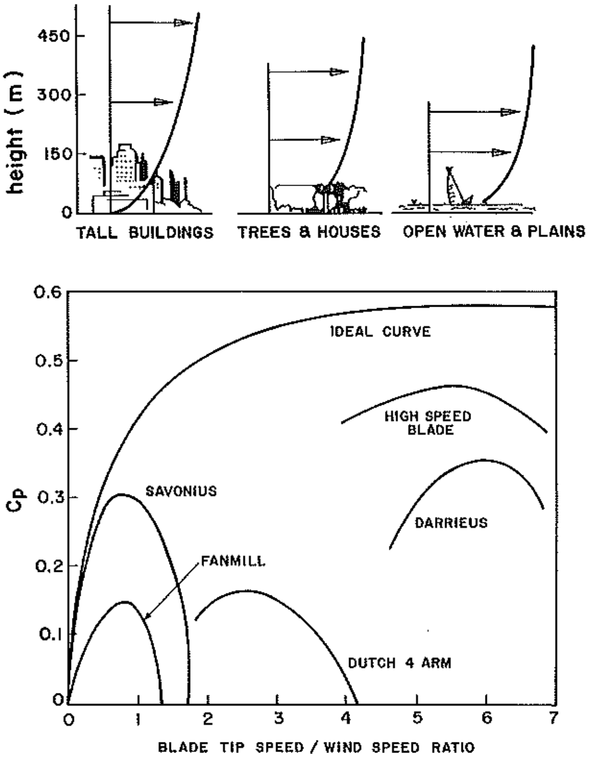


Fig. 5 (a) Wind speed profiles over different terrains; and
(b) Power characteristics of various wind machines.

In isolated remote area locations the only practicable solution is likely to involve a wind generator with appropriately sized battery storage and back-up diesel generator to ensure a secure supply. In such a system, a rectifier will be used to convert 240 V AC to 110 V DC for battery charging, and an inverter and transformer to convert 110 V DC from the batteries back to 240 V AC for appliance use.

At any given location it is possible to calculate the maximum power output from a wind turbine by knowing the average wind speed, the wind speed distribution, and the technical characteristics of the wind system prescribed.

Generally the power density can be expressed as:

$$\frac{P}{A} = 0.5\, r\, V^3,$$

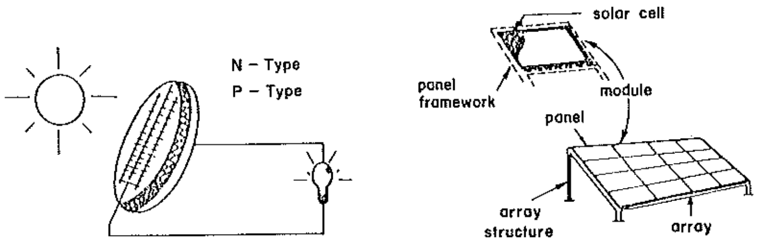
where P = power output in W
A = blade swept area in m^2
r = air density in g/L
V = wind speed in m/s.

Using typical sea level atmospheric conditions, this gives P/A as: $0.6125\ V^3\ W/m^2$.

It should be noted that, as P/A is directly proportional to V^3, very small changes in wind speed can cause rather large variations in power density. This indicates that a good knowledge of the wind speed characteristics at a given site is essential for correct design sizing. Installation of a wind machine rated at high wind speeds in a low average wind speed regime will inevitably result in a reduction of the power output. In addition an inability to match the machine power output to the actual local demand pattern may result in large amounts of power being dumped in high wind speed periods.

Solar Photovoltaic Power Systems

Photovoltaic cells fabricated from single crystal, polycrystalline or amorphous silicon are usually mounted in a solar cell panel sized to produce a reasonable peak power output level under conditions of maximum solar radiation. The output voltage is typically of the order of 0.5 V, and the output current is governed predominantly by the cell area and the intensity of the sunlight. Panels may be wired together to form solar cell arrays designed to match the required power, voltage and current requirements of the particular load application (Fig. 6).



PHOTOVOLTAIC CELL OPERATION LEVELS OF SOLAR ELECTRICITY GENERATION

TYPICAL CURRENT – VOLTAGE CURVE TYPICAL POWER – VOLTAGE CURVE

Fig. 6 (a) Photovoltaic cell operation; (b) Levels of solar electricity generation; (c) Typical current – voltage curve; and (d) Typical power – voltage curve.

The output of a solar panel is well matched to the task of battery charging, as it is the current rather than the voltage which varies with radiation intensity. It should be noted that the power produced is highly dependent on the cell operational temperature, with a voltage (and hence power) drop of 0.4% for every 1°C temperature rise. As some of the incoming radiation is absorbed by the cells and transformed to heat, raising the panel temperature above that of the surrounding ambient air, it is important to ensure adequate natural cooling for flat plate solar cell arrays, and it may become necessary to design forced draught cooling systems for concentrating or tracking arrays.

A maximum power point tracker (MPPT) is a device often fitted to photovoltaic arrays to ensure that the maximum energy can be extracted from these cells by electrically manipulating the voltage and current outputs. These devices are most commonly used when there is a specific requirement to control the hourly, daily, weekly or monthly energy output. If these temporal variations are not important, then a simple control of the output voltage may well be sufficient.

DC and AC Power Systems

DC power can be used to power lights, universal motors and other resistive loads. Most systems employ a voltage regulator to protect the battery and the load appliance from excessive over-voltage conditions. This regulator connected between the battery and the array dissipates any excess energy when the battery bank is fully charged. A DC circuit also includes a "blocking diode" between the array and the battery to prevent a current flow at night from the battery to the array at the expense of imposing a voltage drop of about 0.75 V in the normal solar induced current flow (Fig. 7).

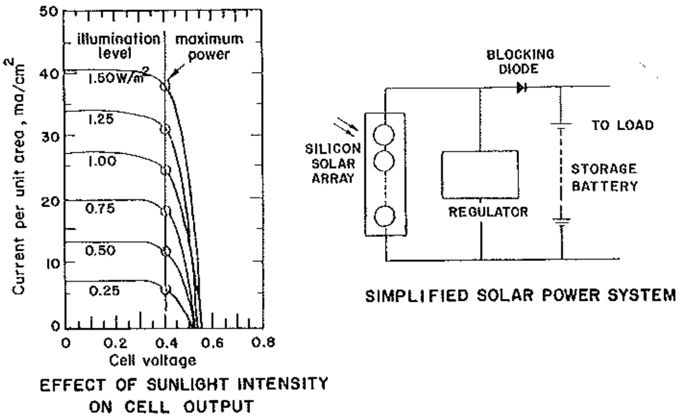


Fig. 7 (a) Effect of sunlight intensity on cell output; and
(b) Simplified solar power system.

AC power is now most commonly used as, in addition to lights and other resistive loads, it is required to power the cheap electrical induction motors found in a wide variety of appliances. To produce AC power from the DC solar cell output an inverter is placed in the circuit before the load (Fig. 8). Such an inverter will produce a wave form approximating a sine wave with varying degrees of distortion depending on the quality and cost of the inverter chosen. The distortion of the output wave is known as harmonic distortion, and if this is too large it can induce overheating in some types of electric motor. Inverters should be carefully chosen to match closely the power demand of the load, as they are often extremely inefficient outside a narrow band of power limits.

Solar Thermal Power Systems

Several variants are possible on the technology of producing electrical/mechanical power from solar heat collection systems using thermodynamic heat engines. Of these systems the low temperature options based on fixed flat plate collectors (or solar ponds) tend to use organic working fluid Rankine cycle plant, and the high temperature options based on fixed (or tracking) concentrating collectors use either steam Rankine cycle or Stirling cycle engines (Fig. 9).

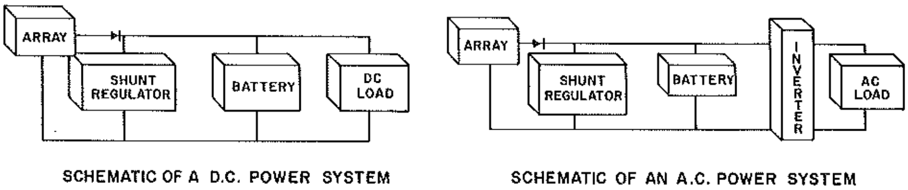
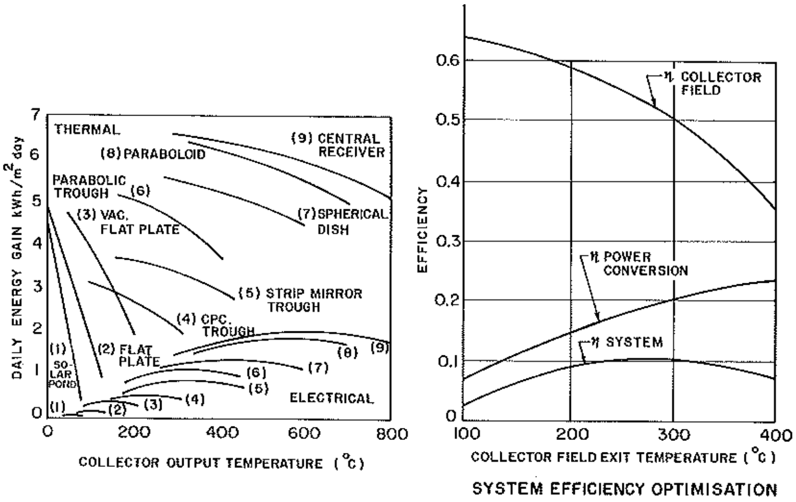


Fig. 8 (a) Schematic of a D.C. Power system; and (b) Schematic of an A.C. power system.



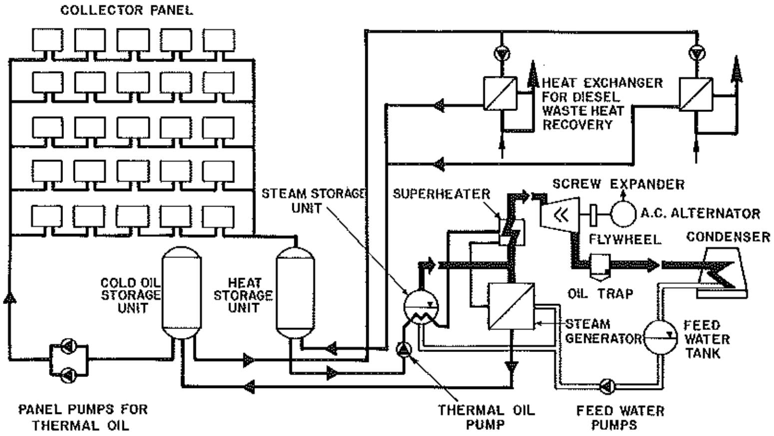


Fig. 9 (a) Collector output temperature (°C); (b) System efficiency optimisation; and (c) Typical block diagram of a solar/diesel power station. Plant output 83 kW_e; 212 kW_H exhaust heat recovery for 854 kW solar input.

As the basic operational characteristics of both non-concentrating and concentrating collectors have been well documented extensively elsewhere, the primary emphasis here will be laid on salt gradient solar ponds – a relatively new and untried method of collecting solar thermal energy (Fig. 10). In a later section on cost economics, inter-comparison of the various alternatives will be outlined.

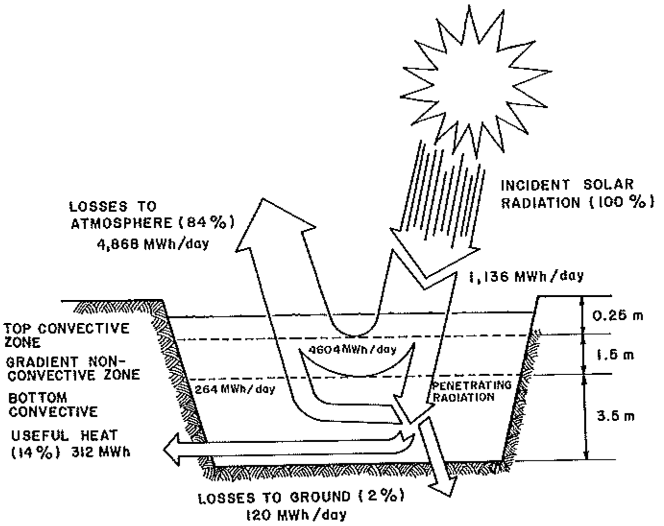


Fig. 10 The estimated energy balance for a MSP of surface area 1 km^2 (approximately 250 acres), designed to provide 5 mW base load. These calculations are based on experience obtained from operational ponds operated by an Israeli pond company and are made for a climate similar to that of the Perth region in Western Australia.

Solar Ponds

All natural bodies of water collect solar radiation and convert it directly to heat by absorption, the collected heat is readily dissipated to the atmosphere by surface convection, evaporation, and long-wave radiation at the pond surface, thus limiting the temperature attained. In any pond constructed as a "solar pond," artificial means of suppressing internal convective mechanisms and surface barriers to minimise surface heat effects are incorporated.

Most of the current experimental and developmental solar ponds, and the commercial operational ones are of the liquid density gradient convection-suppression type. This density gradient is formed using a saline gradient in which salt concentration, and hence density, increases with depth (Fig. 11). The most commonly used salts are sodium or magnesium chloride, although considerable work has also been undertaken using natural compound salt solutions such as those formed in the Dead Sea (Israel) or in solar salt works in other parts of the world. In practice, the saline solar pond generally splits itself into three distinct regions:

i. the top convective zone (TCZ) formed by wind and wave action,

ii. the gradient non convective zone (NCZ) for thermal insulation, and

iii. the bottom convective zone (BCZ) for heat extraction.

There are now available simple and reliable design tools for sizing solar ponds based on local

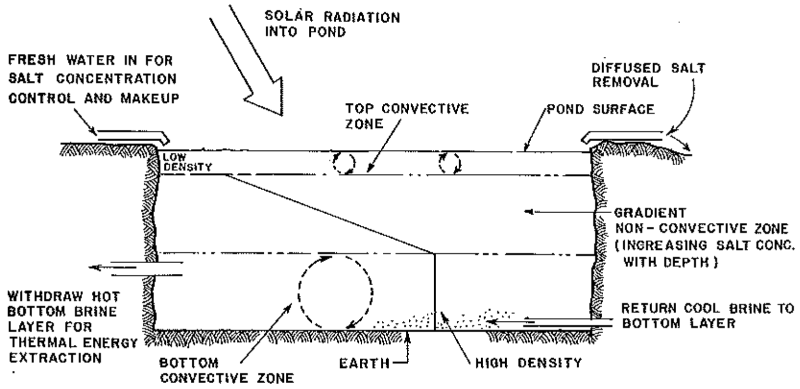


Fig. 11 A schematic of a meromectic solar pond, showing the essential features of its construction.

environmental conditions, micro meteorological data and system load demand. For detailed design calculations, it will always be necessary to have site-specific data for soil thermal conductivity, surface wind direction and speed, and preferred pond configuration. The actual depth utilised for the pond depends on the regional climate, and the climate will in turn strongly affect the amount and temperature level of the heat collected.

Some desirable characteristics of the ideal solar pond site are as follows:

- minimal requirement for earth moving such as exists in a 2 m to 5 m deep salt lake bed,
- free or low-cost salt locally available in large quantities,
- free draining dry soil with a low water table at the site,
- adequate water supply for establishing and maintaining (surface washing) the salt pond,
- soil which is readily compactable and with strong cohesion for construction work on site,
- a climate of high global irradiation, ambient temperature and humidity in a low wind speed regime,
- an ecologically acceptable method for recycling and/or disposal of brine solutions,
- a steady load requirement for process heat and/or electrical power.

It should be stressed here that the availability of low-cost suitable salts will strongly affect the overall cost economics of salt gradient solar ponds. Ideally the salts should have the following properties:

- adequate solubility with salt solubility increasing with temperature (Fig. 12),
- salt solution as transparent as possible to solar radiation,
- salt readily available close to site to minimise harvesting and transportation costs,
- salt solutions should be ecologically acceptable.

Practical factors affecting the overall efficiency of the salt gradient solar pond include:

- establishment and maintenance of the salt gradient including surface washing and brine injection,

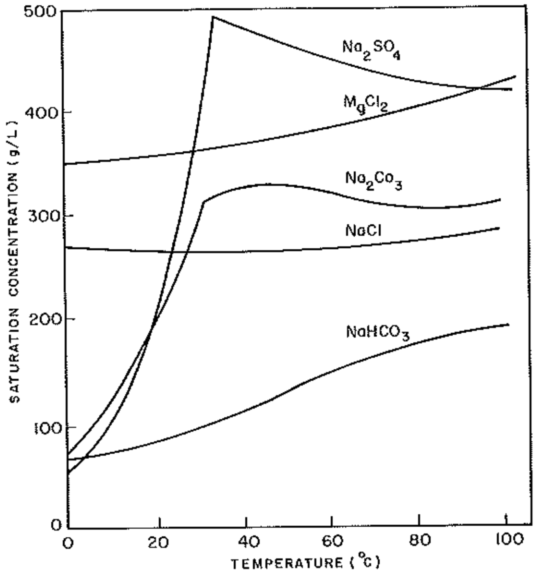


Fig. 12 The solubility and its variation with temperature of various candidate salts for solar ponds.

- reduction in the gradient degradation effects of surface winds and waves by wind control baffles or floating barriers,
- maintenance of adequate pond clarity to allow adequate penetration of sunlight to the bottom convective zone.

Practical operational collection efficiences of solar ponds have ranged from a low of 10% to a high of 20%.

An indication of a typical thermal balance on an operational solar pond is given in Fig. 13 for a climate zone equivalent to that experienced in Perth (Western Australia). This is based on an expected pond water clarity corresponding to that allowing 20% of incident radiation to pene-

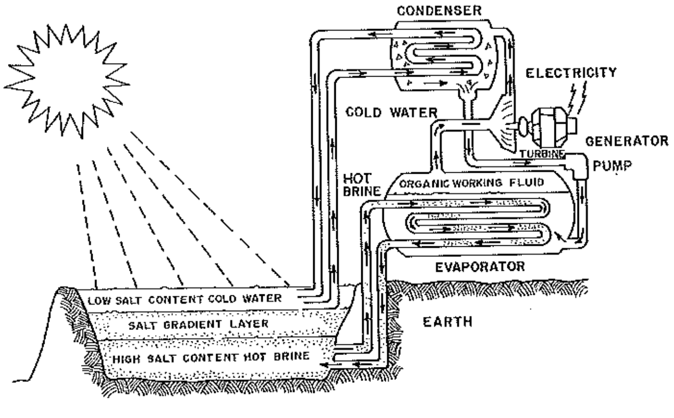


Fig. 13 An illustration of the method used to generate electric power from a MSP via an organic fluid Rankine cycle engine.

trate to a depth of 2.5 m.

To generate electrical or mechanical power the solar heated brine from the bottom convective zone is withdrawn from storage and passed through a heat exchanger forming the evaporator element of the organic Rankine cycle engine. After the work is extracted from the working fluid by an expander (generally screw or turbine) the vapour is condensed in the condenser which is cooled by water from a cooling tower circuit or by water from the top convective zone of the pond (Fig. 13).

An estimation of the overall system efficiency from incoming solar radiation to electrical power is likely to yield figures in the range of 1% to 2%.

Hybrid Systems, Storage and Power Conditioning

As mentioned earlier, the possibility often exists of combining two or more of the individual power producing technologies in a hybrid plant – the aim being to produce a more efficient or a more cost-effective system. Generally such a hybrid power plant will entail more sophisticated and hence more expensive control equipment for regulation of the system operation and to provide a good matching of the plant output to the load demand characteristics. Some typical configurations would include, *inter alia:* diesel/wind; diesel/photovoltaic; photovoltaic/wind; and diesel/photovoltaic/wind. Each of these options may be considered with or without battery bank storage, although it is safe to say that all systems relying heavily on input from solar and/or wind will benefit substantially from the smoothing provided by adequate battery storage.

With all battery banks the cell life is highly dependent on the rate of discharge, the boost facility provided, the type of battery used, and the level of maintenance provided. Boost charging is necessary at least once per month to ensure complete conversion of the plates, and batteries should be of the deep discharge pure lead pasted plate type. Typically a design figure of 3-5 days demand is used when sizing the electrical storage sub-system for wind or photovoltaic arrays.

Inverters of high efficiency (90% overload range) are now commercially available for 240 V AC supply at various power outputs, such as 1 kW, 10 kW, and 20 kW.

ANALYSIS AND PREDICTION OF LOADS FOR SYSTEM SIZING

The first important step in determining the size of the solar or wind system required for any particular application is to obtain as accurately as possible the likely system load characteristics. These should include, where possible, an accurate estimation of the average and peak loads as well as any special requirements for acceptable voltage variations of the equipment to be used. For all solar and wind systems, including battery storage – but particularly for photovoltaic systems (which the capital cost is highest), it is vital to specify these loads accurately. An undersized system will not be able to cope with the required charging and will eventually lead to total battery discharge , whilst an oversized system will be prohibitively expensive on capital cost and will also lead to the provision of excess powers and a need for "dumping" energy.

Often a survey of current demand pattern in a remote location is confused by the additional "false loads" which are put on the system in an attempt to provide adequate loading of an engine generator set.

Peak Load

The peak system load is reached when several appliances, such as water pumps, refrigerated storage systems, etc., are switched on simultaneously. This peak load rating is increased and becomes particularly noticeable when the motor starting loads are included (see attached table of typical running and starting loads.)

Average Load

If the availability of power is required for 24 hours a day, as is the case if an effective food cold store system is contemplated, then the total amount of power required each day is often described as the average over that 24-hour period, (e.g. a typical load of 10 kW per day is often expressed as 10 000/24 W continuous over that daily period, or 417 W average load).

Relationship Between Peak and Average Load

Often in power supply terms the relationship between peak load and average load is used to qualify the type of load profile on a particular installation. The ratio of average load to peak load is known as the "load factor" of the system, and is an important parameter in system sizing and design. An installation for a remote area power system with a low load factor will be essentially different to that for one in a central locality with a high load factor.

In the remote system considered above, the load factor may be as low as 0.04, as compared with a centralised large diesel generator system with a distributed load where the load factor can be as high as 0.70.

Table 1.
Typical ratings, peak demands and total energy demands for several applicances

Appliance	Rating (watts)	Peak Demand (watts)	Daily Energy Demand (based on usage) (watt hours)
Light (high efficiency fluorescent)	10/20	20/40	80/160
Battery charger	600	600	2400
Electric fence	10	10	240
Radio	60	60	30
Television	100/200	100/200	30/60
Water pump	450	900	1000
Soldering iron	200	200	20
Drill	300	600	60
Fan	100	100	2400 (if used continuously)
Refrigerator	300	1500	1500
Food freezer	300	1500	1600
		= peak demand	= daily energy demand

Note: Any analysis should include consideration of all likely appliance loads and an estimation of the running time for each piece of equipment.

Capacity Factor

In addition to the term load factor, mention is often made of the system "capacity factor." This is a term which shows the net amount of energy delivered to the load compared to the potential amount of energy capable of delivery by the installed generating system. This distinction means that a diesel set which is run for a few hours each day may have a very low load factor but a reasonably high capacity factor, giving a relatively well matched system. Often in practice the high capacity factor is only achieved by using false or unnecessary loads, as explained earlier. These may be "dump loads" which are of no financial value and should not be taken into account when carrying out any financial analysis on the cost effectiveness of the plant. If this is done, then only a realistic capacity factor will be obtained, and this can be cross-compared with the load factor to see if there is a requirement for energy storage in the system. In a well designed remote engine generator set, it is advisable to aim for a capacity factor in excess of 0.8. At lower values the engine is not being properly utilised and excessively low capacity factors may even lead ultimately to engine damage.

Quality of Power Supply

Factors which need to be taken into account include possible fluctuations in supply voltage, frequency stability, and output waveform.

The choice between AC and DC systems is essentially one based on supply voltage, as all DC systems are in essence low voltage systems. In addition because of their inability to handle heavy loads, such as those imposed by refrigeration systems, the bulk of new systems installed are likely to be of the AC type.

For AC supply systems the frequency will be 50 or 60 Hz, but frequency control is not a critical parameter. Most motors and resistive appliances can tolerate a wide frequency variation and most modern control systems can maintain frequency stability to within 5%. It should be noted that sensitive electronic equipment may well require the provision of a small well regulated power supply.

Waveform control is more of a problem, and many systems may output a modified square wave. These may sometimes produce unacceptable motor over-heating or radio frequency interference. Pure sine wave is optimal but modified square wave with adequate filtering may prove acceptable for many systems.

SELECTION GUIDELINES FOR SOLAR AND WIND POWER GENERATING PLANT

For solar thermal systems based on solar ponds, or for flat plate solar photovoltaic arrays, there is no requirement for direct (beam) radiation as no concentration is involved in the conversion process. A general guideline is that the solar regime should be such as to supply a total daily radiation input in the order of 5 $kWh/m^2 day$ to the solar array. Allowing for a conversion efficiency of 10%, this would enable one to produce an output of 500 Wh/day from each 1 m^2 of solar array, or an output of 100 Wh from each $1m^2$ of solar pond surface area at 2% overall conversion efficiency from radiation input to electrical output.

For wind turbines a general rule of thumb, with conventional modern aerogenerators, is that a machine rated at 4.5 kW should produce in excess of 4000 kWh per year if sited in a region with 4-5 m/s annual average wind speed. At lower wind speeds the output will be substantially reduced, and it may be better to consider photovoltaic systems, particularly for low power requirements. However, it should be noted that designers are starting to produce efficient wind machines capable of starting and operation in winds from 2.5 m/s, which will greatly extend the usefulness of wind generator sets for inland areas remote from the good coastal wind regions.

It is fairly evident that it is not possible to make a final choice as to the best type of equipment in any particular location without carrying out a detailed technical and cost analysis of the options available; but a preliminary "feel" for the final solution may become evident from the preliminary resource assessment carried out at the site. In the case of solar thermal systems using concentrating collectors it is almost self-evident that they will have to be sited in regions not only of good total radiation level, as outlined earlier in this section, but also at sites where the ratio of beam radiation to total radiation (i.e. beam plus diffuse) is consistently high. Such areas tend to be found in arid or semi-arid regions of the world, where it is not uncommon to have radiation of the order of 6 kWh/m^2 day and over 320 clear sky days per year.

In many cases, an economic study will help to highlight the potential advantages of hybrid systems and indicate the extra costs likely to be incurred with this type of plant.

POWER GENERATION COSTS

With the remote area operation of a diesel set it is not unusual for the operator to be totally unaware of the true costs of the electricity generated. The diesel engines are often run for short periods such as 4 or 5 hours per day, and are often ill matched to the required power demand, giving a low capacity factor and high electricity costs. The capital cost of the installed plant is often quite low, but the fuel costs are high due to problems with fuel transportation to remote sites. Typical total costs incurred by a small plant may range from US$0.70 to US$2.50 for each kilowatt-hour of energy generated.

For all forms of alternative energy systems, the true costs of the power generated must be calculated over the life-time of the system using what is known as "life-cycle" costing. To ensure a rational comparison of the possible systems a reasonable life-cycle time must be selected to balance the different replacement lifetimes of the individual high cost components. For example, if a mean system replacement life of 20 years is chosen this will be a compromise between the comparatively short life of a petrol or diesel driven generator set (3-5 years) and the long life of the photovoltaic array (currently taken to be of the order of 30 years). Often a lifetime of 20 years may be assumed, with allowance being made for the intermittent replacement costs of low-life equipment.

Rather than concentrating on the costs of supply, it is often better to assume that a fixed annual energy demand must be met by the installed plant, which should also be capable of meeting the peak power requirement. These two parameters, based on the calculated load demand, are then held to be constant for an intercomparison of different system configurations. This ensures that systems not capable of meeting the real-life demand criteria are not considered suitable, and also that any power generated in excess of the load peak demand is not given any financial credit in the analysis.

Engine fuel usage and fuel costs need to be assumed for use in any economic analysis. Although these will vary greatly from place to place, a diesel fuel cost of US$0.30 would appear reasonable for many locations and the fuel flow rate may be extracted from manufacturers' data for the appropriate engine chosen to match the system power demand. All battery bank storage conversion efficiencies can be assumed for simplicity to be in the order of 0.7, but care should be taken to check manufacturers' claims for performance on other system components such as inverters.

Capital Costs

Where possible, it is best to take current retail prices for all items of capital equipment and to ignore the effects of tax subsidies or other financial incentives to arrive at the first cross-comparison of different systems. These effects can be analysed separately, if so required, and will tend to help the high capital cost or capital intensive technologies.

Annual Costs

There will be many payments made over the life of a typical system, including a capital recovery charge and a fuel charge – annualised for simplicity, as are the operational and maintenance charges incurred. Payments which occur at regular intervals include items such as diesel generator replacement (based on 15 000 hours running) and batteries (based on 7 years life from field experience).

Simple Payback Analysis

Although it is tempting to take a simplistic approach and to calculate a simple payback period based only on the estimated capital cost of the equipment and the anticipated annual value of the fuel saved at today's prices, this can be very misleading as it ignores several important facts:

1. interest possible if the capital were to be invested elsewhere;
2. interest possible on the energy savings over the plant lifetime;
3. any inflationary effects within the economy.

These factors can, however, be taken into account using a life-cycle costing method over the estimated total life of the plant.

Present Value Concept

If one invests \$100 at 10% annual interest rates, then in one year the investment would be worth \$100 plus one-tenth X \$100 = \$110. Conversely the present value of \$110 in one years time at 10% prevailing interest rate would be only \$100, or expressed differently, the 'present value' of \$100 in one year with 10% interest is \$100 divided by 1.1 = \$90.91.

Similarly for a 2-year period with the interest calculated at a compound rate \$100 is worth \$100 X 1.1 X 1.1 = \$100 X 1.21 = \$121, giving a present value of \$100 divided by 1.21 = \$82.60.

So present value,

$$PV = \frac{S}{(1+I)} + \cdots + \frac{S_n}{(1+I)^n}.$$

This can then be extended, for as many years as desired, by finding the compound interest factor which is earned by \$1, and enables one to find the present value in today's terms of future cash earnings. In this way it is possible to directly compare future earnings and present expenditure loading to the concepts of life-cycle costing.

Energy Price Inflation Rate

If the price of energy is inflating at the general prevailing interest rate, then the present value of the energy saved in all future years can be made equal to the annual sum expected at the outlet. If, on the other hand, the energy price inflation rate (R) is greater than or less than the current interest rate (I), this has to be allowed for in the cost analysis of any energy saving scheme giving a savings per year of $S.

Then the present value,

$$PV = \frac{S\,(1+R)}{(1+I)} + \cdots + \frac{S\,(1+R)^n}{(1+I)^n}$$

$$= \frac{S\,(1+R)}{(1-R)}\left(1 - \frac{(1+R)^n}{(1+I)^n}\right)$$

$$= S\,(_{I,\,R,\,n})$$

Note: *A, I, R, n* values are tabulated in *The Energy Saving Guide,* George Helcke, Pergamon Press, UK, 1981.

Assessment of Cost Effectiveness

This can be carried out by a direct comparison of the invested capital cost with the sum of the annual savings given in present value terms. If the latter savings are greater than the capital invested, we say that the income is cost effective over that time span.

Net Present Value

The net present value,

$$\begin{aligned} NPV &= -\text{Capital Cost} + \text{Summed Present Value} \\ &= -C + PV \\ &= -C + \sum_{n=1} \frac{S_n}{(1+I)^n} \end{aligned}$$

For NPV greater than zero the system is cost effective and the scheme with the largest NPV is said to be most cost effective. When NPV = 0 we say that we have "broken even" and the time to this zero NPV is called the "breakeven point" or "payback period".

In general terms,

$$NPV = -C + \frac{(1+R)}{(1-R)}\left(1 - \frac{(1+R)^n}{(1+I)^n}\right)S$$

$$= -C + (A_{I,\,R,\,n})S$$

Choice of Interest Rate and Fuel Price Inflation Rate

As interest rates and fuel price inflation rates vary very widely, it is necessary to carry out a life-cycle costing using realistic estimates relevant to local conditions for any major energy investment in order to assess the economic viability (cost effectiveness in the local market place of the country concerned). Tabulations for use in discounted cash flow analyses can be found in a number of publications such as *Tables for discounted cash flow,* G.H. Lawson, D.W. Windle, Longmans, UK.

Wherever possible market prices should be used with discount rates equal to (or a function of) interest rates, and real benefits should be calculated in dollar terms for the financial appraisal. No account should be taken of any forms of taxation, subsidy or government incentives. Governments often use a common test discount rate (TDR) in the range of 7% to 10% which may be low for reasons of social preference. They may also in an economic appraisal use shadow (accountancy) pricing which will include fuel subsidies, tax effects, and real labour costs, etc.

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