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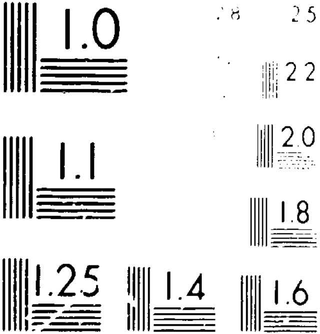
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UNITED NATIONS
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TECHNOLOGICAL INFORMATION PROFILE ON SOLAR ENERGY APPLICATIONS*.

prepared by

A. Takla**

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** UNIDO Consultant.

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Note

As a result of the energy crisis attention has increasingly been focused both by developed and developing countries on non-conventional sources of energy which culminated in the subject being reviewed at the international level by the United Nations Conference on New and Renewable Sources of Energy, held at Nairobi in August 1981.

The present study, which is complementary to DTT Series No. 5, Technology for Solar Energy Utilization, published in 1978, reviews applications of solar energy, which must be considered as one of the most promising and important renewable sources of energy and which has a great potential in developing countries as it is relatively abundant in most of them. Although there is still a great deal of technical development to be done before solar energy will become competitive with conventional sources of energy, prospects for installations in remote areas are very promising; as a matter of fact, quite a few are already in operation in a number of developing countries. Because of the complexity of solar technology and the rapidly changing state-of-the-art as investments in R + D programmes are promoted, this study purports in no way to be exhaustive. However, it is intended to alert government departments and private entrepreneurs in developing countries to the main areas of application of solar energy. The study is complemented by a Directory of Solar Equipment Manufacturers, Volume I, Developed Countries, UNIDO/IS.340. A Directory of Solar Research Institutes in Developing Countries is also presented, UNIDO/IS.341.

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BACKGROUND INFORMATION

Objectives and Scope of the Study

Utilization of solar energy is growing rapidly and thousands of solar manufacturing firms are already in existence. Manufacturing flat plate solar collectors is very popular, however, lifetime efficiency, esthetic and production costs differ very much from one producer to the other. Solar concentrators are produced in hundreds of places in the world, but they are still less popularized than the flat plate collectors. Other solar equipment is mainly taken from the conventional industry with or without relevant adaptation. In the category of equipment used both in solar and conventional equipment the following may be mentioned: pumps, fans, compressors, heat exchanges, absorption machines, storage tanks, piping, fittings, electric motors, control and measurement devices.

This may be explained by the fact that the same fluids are utilized in solar and conventional equipment: steam, water, air, LPG, freons and that at the outlets of solar collectors the characteristics of the fluids may be similar in the two cases: temperature, pressure, volumic mass, viscosity.

In the field of solar photovoltaic systems, the situation is different, the producers of semiconductors, and especially silicon, are very limited and assemblers of solar cells and arrays are still in limited number whilst large scale production does not so far exist. UNIDO has presented in the Development and Transfer of Technology series (1), a general survey on the development of solar energy utilization in developing countries, a selected number of papers on solar applications and the recommendations of the Expert Group Meeting held at Vienna 14-18 February 1977 on the existing solar technology and the possibilities of manufacturing solar equipment in developing countries.

This study complements and updates the UNIDO document mentioned above on solar energy. It contains in particular new chapters on solar photovoltaic systems, solar air conditioning systems, solar laboratories and a compilation of sources and specifications of solar equipment and systems. The main objectives are to provide to developing countries a practical tool for undertaking

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(1) DDT Series no. 5 (ID/202) Technology for Solar Energy Utilization.

preliminary reliable evaluation of solar equipment and solar systems, also to provide them with reliable information on sources and specifications of solar equipment and systems.

Accurate techno-economic evaluation of a system is a very long and complicated operation. The degree of accuracy depends mainly on the input data which are generally very difficult to define. The large number of variables and their interaction make the conclusions approximative and dependent upon the reliability of the assumptions used.

The following are the major factors to be considered when carrying out a feasibility study of a solar project;

- Objective of the project;
- Climatological conditions;
- Kind of solar application.
- Scope of the project;
- Location;
- Local conditions regarding available data, facilities and personnel;
- Daily and/or seasonal heat storage.
- Lifetime of the equipment;
- Available investment for first cost installation and availability of foreign exchange.

It is recommended to utilize the UNIDO document: Manual for the Preparation of Industrial Feasibility Studies. UNIDO, ID/206, United Nations New York, 1978, in undertaking the feasibility study.

In this study, which does not introduce present value calculations and does not discuss in detail all the aspects of the considered project, an attempt is made, however, to utilize and define simplified equations, rather than complicated programmes requiring computer processing.

The approach will be generally based on considering specific case studies and discussing them in order to arrive at practical conclusions and recommendations.

Applications of solar energy go from the simple direct utilization of the collected heat to the conversion of solar radiation to mechanical and electrical energy. Applications in the field of solar cooking, solar drying and solar water desalination, since developments have been limited, are not discussed.

Future of Solar Energy Utilization and Solar Equipment Manufacturing in Developing Countries

It is very difficult to predict the scope of solar energy utilization in the long-term. It depends on a large number of uncontrollable variables ranging from the availability of energy to success in developing new techniques and materials capable of reducing sharply the present high cost of solar equipment systems.

The ambitious aims of governments, in terms of replacing a "relatively high" percentage of their consumed conventional energy by solar energy, are often found to be unrealistic or at least very optimistic by scientists, economists and technicians working in the field of industries in connection with solar energy development. For example of such a situation see Chapter I of the findings of the American Physical Society Study Group[2].

With the fast development of solar collectors, a large utilization of solar energy equipment is expected in the field of domestic water heaters, space heating and solar drying. However, much less utilization is expected in the field of solar air conditioning even when this application is associated with domestic water heating and space heating. Solar refrigeration, when the collected heat is used to evaporate directly the refrigerant (without utilizing a vapour compressor) may have only a "passable" development in the medium-term as the ammonia-water absorption machines are still under development and the Water-Lithium Bromide absorption machines, which are commercially available, are not adequate for temperatures under zero degrees centigrade which limits their utilization. Intermittent solar refrigeration systems, if not using an external source of mechanical or electrical power, may deliver only a very small quantity of ice, for example, and they are not expected to undergo a major development in the near future.

Converting solar energy to mechanical energy through central tower receivers is not expected to have a promising future. This type of plant is still in the R and D stage and the cost is still in the high range of US $10,000 - 30,000 per installed kWe. A substantial reduction of the cost is not really expected as the output power is approximately proportional to the heliostat's area and the economy of scale does not apply.

Smaller solar thermal power plants of the farm system type in the range of 1 - 10 kw may develop successively. This range of power may meet a part of the mechanical/electrical energy needs in rural areas.

The cost of this type of plant is expected to be reduced substantially in connection with the cost reduction of solar collectors and with manufacturing in series successful prime movers. There is no reason for solar engines in this range of power when produced in series to have a cost much higher than diesel engines of equivalent power. In this regard it seems that solar prime movers associated with flat plate collectors, which do not have very efficient selective surfaces, will have much less success than those associated with concentrating collectors. The control system of solar engines when coupled to electric generators is still complicated and costly if constant speed is required.

The most promising application of solar energy seems to be the photovoltaic system. Apparently it will be possible to produce solar generators with a cost in the range of US $1500 - 2000 (1981) per kWe peak by the end of this decade. When solar photovoltaic systems become economically feasible, other solar applications such as refigeration, air conditioning, assisted water desalination become almost automatically feasible.

The future of solar equipment manufacturing in developing countries depends mainly on the development of engineering industries in the field of pumps, fans, compressors, electric motors, heat exchangers, sheet metal products, measurement and control devices, etc. When such industries are successful there is every possibility of manufacturing profitable solar equipment for solar systems which would be feasible in the country concerned.

A serious projection of "solar industries" in developing countries is not possible as studies should be made of individual cases. In terms of photovoltaic equipment it is unwise to make a judgment at present since techniques are still being developed.

I. PHOTOVOLTAIC SYSTEMS

Solar photovoltaic cells

Principle

The photovoltaic (PV) effect used in solar photovoltaic cells may be defined as the generation of electromotive force by the action of photons (light energy particles), at or near the p-n junction of a semiconductor. More simply, it is the creation of charge carriers within a material by the absorption of energy from incident ionizing radiation. Such photovoltaic conversion can be realized in all semiconductors but the most efficient are those that yield the highest current-voltage rate for the visible part of the sunlight spectrum. The efficiency of conversion depends on wavelength and temperature.

Direct and diffuse solar radiation may be converted into electrical energy by the photovoltaic effect. This is because, due to the barrier layer, solar cells have diode characteristics even in the dark: a diode is a one way potential barrier. In all cases photons transfer their energy directly to the electrons: this explains why this photovoltaic process does not depend on the heat.

To illustrate the PV effect, we consider, for example, what happens in a monocrystal of silicon (Si). This crystal has normally four valence (peripheral) electrons. If a small number of atoms of phosphorous, antimony or arsenic are introduced each photon will replace a Si atom. As the phosphorous has five valence electrons, one of them is free to move in the material: and the crystal is then said to be negatively doped: type n (negative). The process of doping is the introduction of an impurity in a crystal, either by diffusion from the surface at high temperature or by ion implantation at low temperature.

Conversely, if a small number of boron or gallium atoms, which normally have valence electrons, are introduced in the monocrystal, a hole is created; the monocrystal is positively doped and is described as type p (positive).

If an already doped type p monocrystal disc is then doped n on one of its faces, a p - n junction is set up and an electric field created. A junction in a crystal is a very thin zone in which an electrical current flows from the p type to the n type, in case of a p - n junction and conversely in the case of a n - p junction.

If a photon hits a p - n or n - p boundary it may dislodge an electron from a silicon atom creating a hole. When an electron is excited it may recombine with a hole or migrate to the edge of the semiconductor to be collected. In the presence of the electric field, the electrons are swept in one direction and the holes in the other. Holes thus move towards the p side and electrons towards the n side. These two contrary movements generate a photocurrent.

The electrical energy thus created is proportional to the light intensity and to the junction area, the photocurrent however, does not depend on the applied voltage. The creation of hole-electron pairs alone is not sufficient to set up an electric current. For that the following conditions have to be realized. The number of charge carrier pairs has to exceed the number that normally exists at the given temperature. A region of heterogeneity (a region separating two zones of opposite charge carriers) has to exist within the material to keep opposite charges separated until they are allowed to recombine by flowing through the external circuit. The life time (the average time between electron - hole pair creation, and recombination) of holes and electrons has to be sufficient to reach the collection point.

The three types of p - n junctions used in solar cells are:

- The homojunction;
- The metal semiconductor barrier;
- The heterojunction, which is composed of two different materials: semiconductors - a semiconductor and a metal, or a semiconductor and an electrolite.

The arrangement of the above junctions depends on the technology used. For example: the front side of the p-n junction is covered with a semiconductor lattice to collect the electrical energy and the rear side completely metallized. Typical characteristics of solar cells are given in Figures I, II and III.

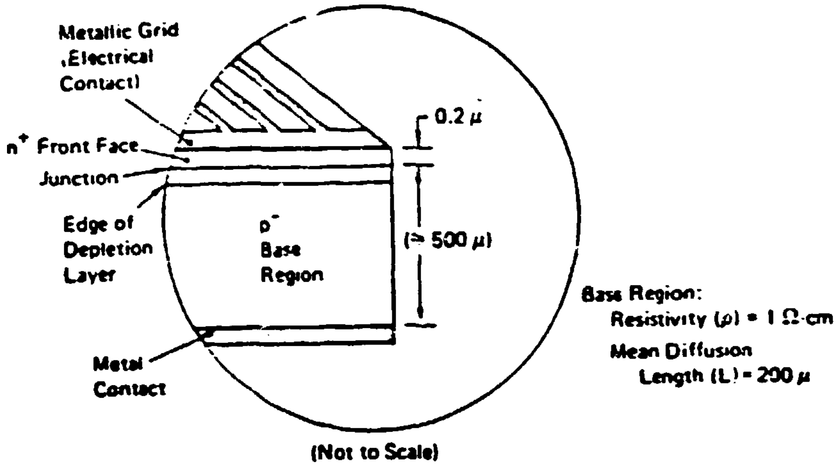


Figure I. Physical characteristics of a typical N^+/p solar cell

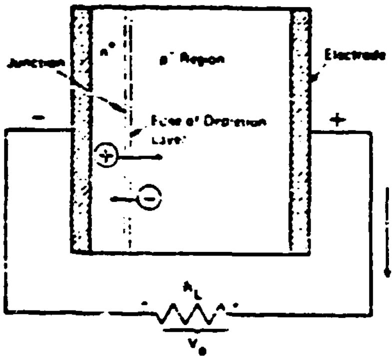


Figure II. Illuminated solar cell with an external load

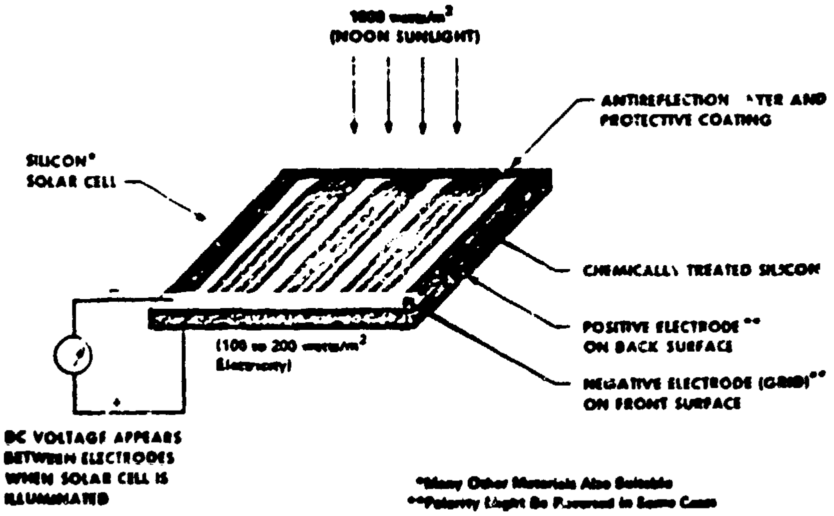


Figure III. Direct conversion of sunlight into electricity--simplified representation of solar-cell operation!

Source: Energy for Rural Development, National Academy of Sciences, Washington D.C.1976, pp.88,92.

Characteristics of solar cells

The characteristics of a solar cell are defined by its I - V intensity-voltage curves which depend on its design, its materials, the insolation and the temperature. The reference temperature is in general 25°C. The extracted power decreases with the rise of temperature, for example, the losses in case of silicon cells are in the range of four per thousand per degree celsius of temperature rise over the reference temperature. The following curves extracted from a SOLAREX Catalogue give examples of

- typical I - IV characteristics;
- a spectral response;
- I-V as a function of the insolation;
- I-V as a function of the temperature.

The terms AMO, AMI, Isc and V_{oc} and peak watt, refer to:
AMO: air mass 0, solar light outside the atmosphere;
AMI: air mass 1, maximum light on the ground at sea level;
Isc: short circuit intensity;
V_{oc}: open circuit voltage.
Peak watt: the amount of electricity produced by a solar generator at noon time on a sunny day.

The efficiency of a solar cell is defined as the ratio between the maximum electric power which can be extracted at the peak time (VxI) max in the curves at the reference temperature and the incident power.

Figure IV shows an example of the displacement of the maximum power point (VxI) in the case of a silicon solar cell. The optimization of the product IxV corresponds to a voltage Vm slightly smaller than the Voc. The optimization can be achieved by supplying an external voltage or by connecting the solar cell to a load resistance. (See also Figure V for a Spectral Response and Figures VI and VII for Typical Current/Voltage Curves).

Solar Photovoltaic Systems

A solar photovoltaic system consists of:

- The solar generator (s);
- The storage generator; and
- The charge control system.

Solar Generators

Solar generator components:

A solar generator or array is a sum of several panels which are connected in series and parallel combinations and mounted generally on a rigid frame. A solar cell is the smallest electric unit.

TYPICAL TEMPERATURE CHARACTERISTICS

Solarex photovoltaics operate reliably between -65°C and 125°C, and will tolerate exposure to 250°C for 30 minutes and short excursions to 300°C without significant degradation.

Since temperature changes affect cells' current and voltage oppositely, power output varies little with temperature.

VOLTAGE	increases by decreases by	2 mV °C	Below above	25°C
CURRENT	increases by decreases by	25µA cm^2 °C	above below	25°C
POWER	decreases by increases by	0.3% °C	above below	25°C

Source: Solarex Data Sheet 3004-3, 1979

Current is directly proportional to insolation; operating voltage is attained at relatively low insolation. Open circuit voltage (V_{OC}) is typically 0.55 V, with maximum power available at approximately 0.45 V.

Typical Solarex photovoltaics are responsive to a broad segment of the spectrum, and therefore produce energy under tungsten or fluorescent illumination as well as during clear or overcast conditions.

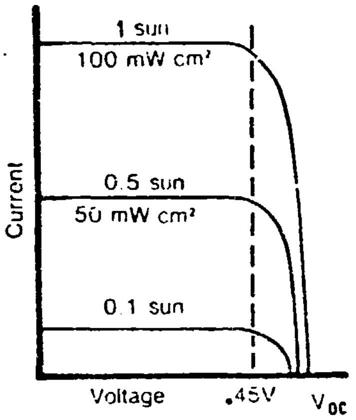


Figure IV. Typical I-V Characteristics

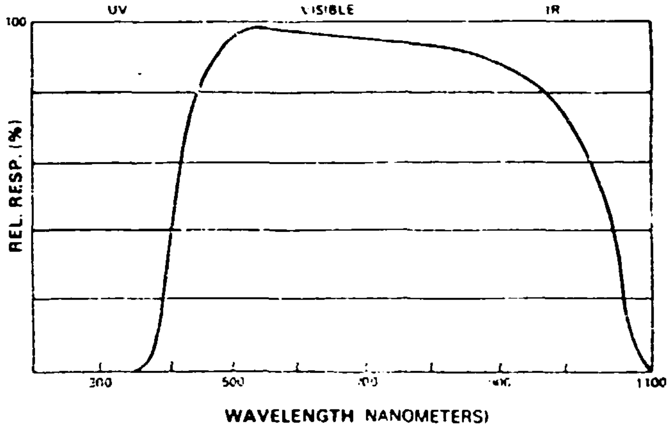
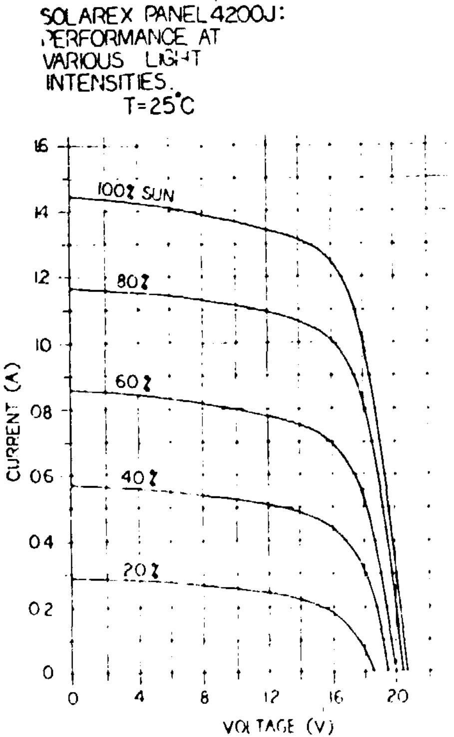


Figure V. A Spectral Response

SOLAREX TYPE 4200J UNIPANEL®

TYPICAL CURRENT/VOLTAGE CURVES



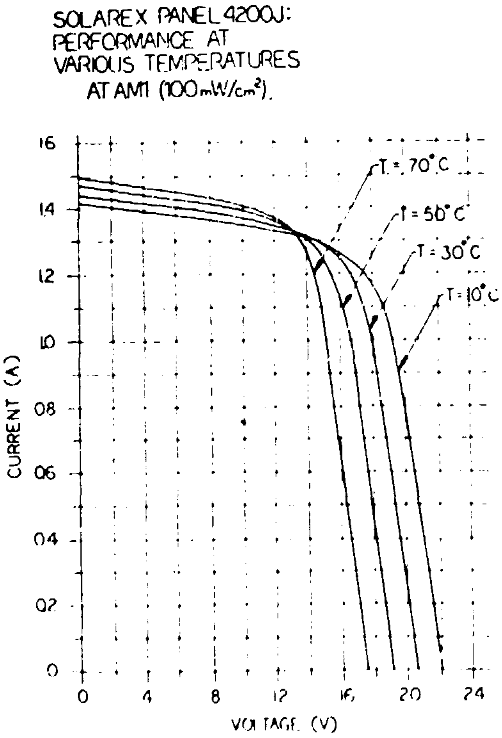


Figure VI. I-V as a Function of the Insolation. Figure VII. I-V as a Function of the Temperature.

A module is the smallest self-contained physical structure housing inter-connected solar cells and providing a DC electrical current.

A panel is the sum of several modules. (See Figure VIII).

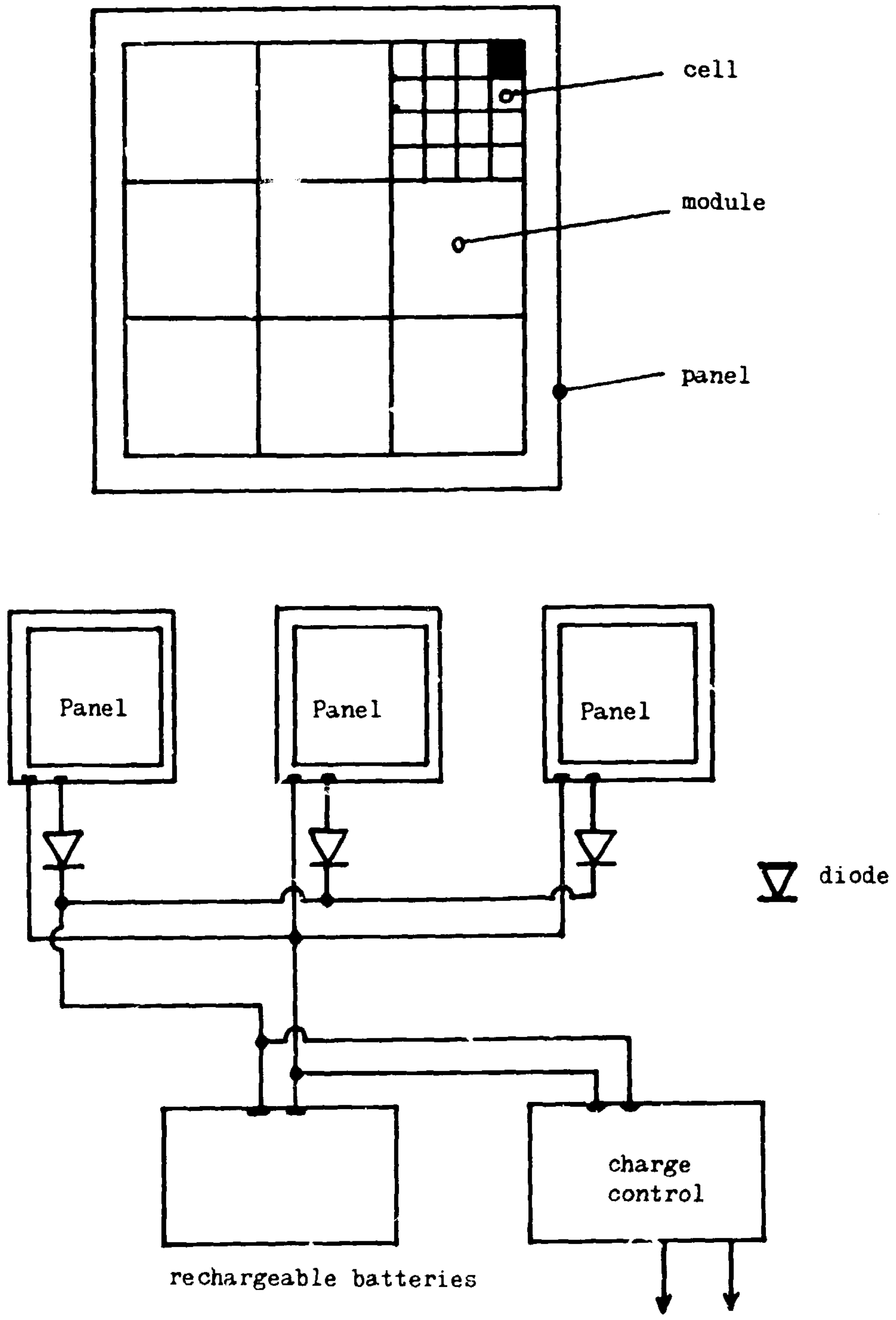


Figure VIII. Module housing inter-connected solar cells.

Each component of the solar generator has its own optimal efficiency, however, the optimal efficiency of the system does not correspond necessarily to the individual optimal efficiencies of the components. The output of the system, or the utilization point of the I-V curves, is defined by the requirement of the specific application. It may be specified in AH (ampere-hour) under a required voltage. Based on the solar map radiation at the considered site and taking into consideration the losses of the system, the amperage of the system may be obtained. The catalogues/directories of the manufacturers enable the designer to select adequate material.

Solar Generator Assembling

Connection of solar cells into series and parallel configurations permit the realization of panels with high current and voltage. The combination of panels into arrays with an adequate storage and control system permit the obtention of integral electrical systems up to several megawatts.

Solar generators are modulary assembled of a certain number of identical panels having the same power and voltage. The power of solar panels may range from a fraction of a watt to hundreds of watts. The nominal voltages are multiples of 1.5 volt: 6, 12, 24 and 48 volts D.C. The direct current may be converted, if needed, to alternative current.

The polarity of the voltage can be reversed by reversing the used p-n structure. Standard production cells are n-p types, with the negat terminal on the light-sensitive cell surface and the positive terminal on the cell back. Reversed types may be also obtained from the majority of manufacturers.

When connecting a solar generator to rechargeable chemical batteries, its working voltage should be compatible with the batteries' voltage. In lead acid batteries, the normal voltage of the cell is 2.1 volt and it increases to 2.4 volts during the charging cycle. The solar generator should then be assembled to give 2.1 volt in closed circuit and 2.4 volts in open circuit. Generally the open circuit voltage of a solar cell drops by less than 10 percent for a light intensity, dropping down to 80 percent.

Solar Modules Production

At the present stage of solar modules production, the materials mainly used are:

- Semiconductors;
- Aluminium, reinforced plastics, fibre-glass, metallurgical silicon and graphite may be utilized for structural substrate;
- Tempered or borosilicate glass for transparent structural superstrate;
- Polyvinyl butyral as a laminating material behind the glass;
- Soft silicon as transparent envelope;
- Adhesives: silicons, acrylics, epoxies and fluorocarbons;

Materials of construction should be able to resist the degradation which may result from severe climatic conditions and atmospheric effects (oxygen, salinity, moisture). Materials should also meet the requirements of mechanical resistance, resist sand erosion and allow easy cleaning.

Different candidate materials are under development or in an advanced stage of research; a large effort is made to develop cheaper materials and reduce the quantity of these materials (smaller thickness for example).

All semiconductors may be theoretically used in solar cells. However, only three types of solar cells have already been used in space applications: silicon, cadmium, sulphide and galliumarsenide. However, the silcon ones are still the only cells commercially available at present. The combination of materials and configurations permit the obtention of large varieties of solar cells.

Solar Silicon Cells: Silicon Plates

Thin silicon plates (wafers) are now available, in diameters up to 8 cm and thickness of about 300 microns. Plates of square or rectangular form obtained from ribbons (monocrystalline sheets) are also produced. These forms lead to an important economy in the cost of materials and give a higher packing (fill) factor: 0.9 instead of about 0.7. This will reduce the area of the panels and in consequence the supports and foundations. Ribbons techniques in addition to higher packing factors also permit the automation of of the production.

In thin film plates (the term thin refers to the method of preparation and not to the thickness of the film), the active layers are polycrystalline or disordered films deposited or formed on a substrate (support). These active layers go from grains of about 1 mm^2 cross section and 100 micron thickness of silicon to materials of microscopic dimensions based on amorphous (non crystalline) silicon. The thickness of thin films are generally lower than 10 microns. Techniques such as vapour phase, liquid phase and molecular beam epitaxy can be used for both high pure silicon and polycrystalline silicons. Figure IX following shows automized production of solar cells.

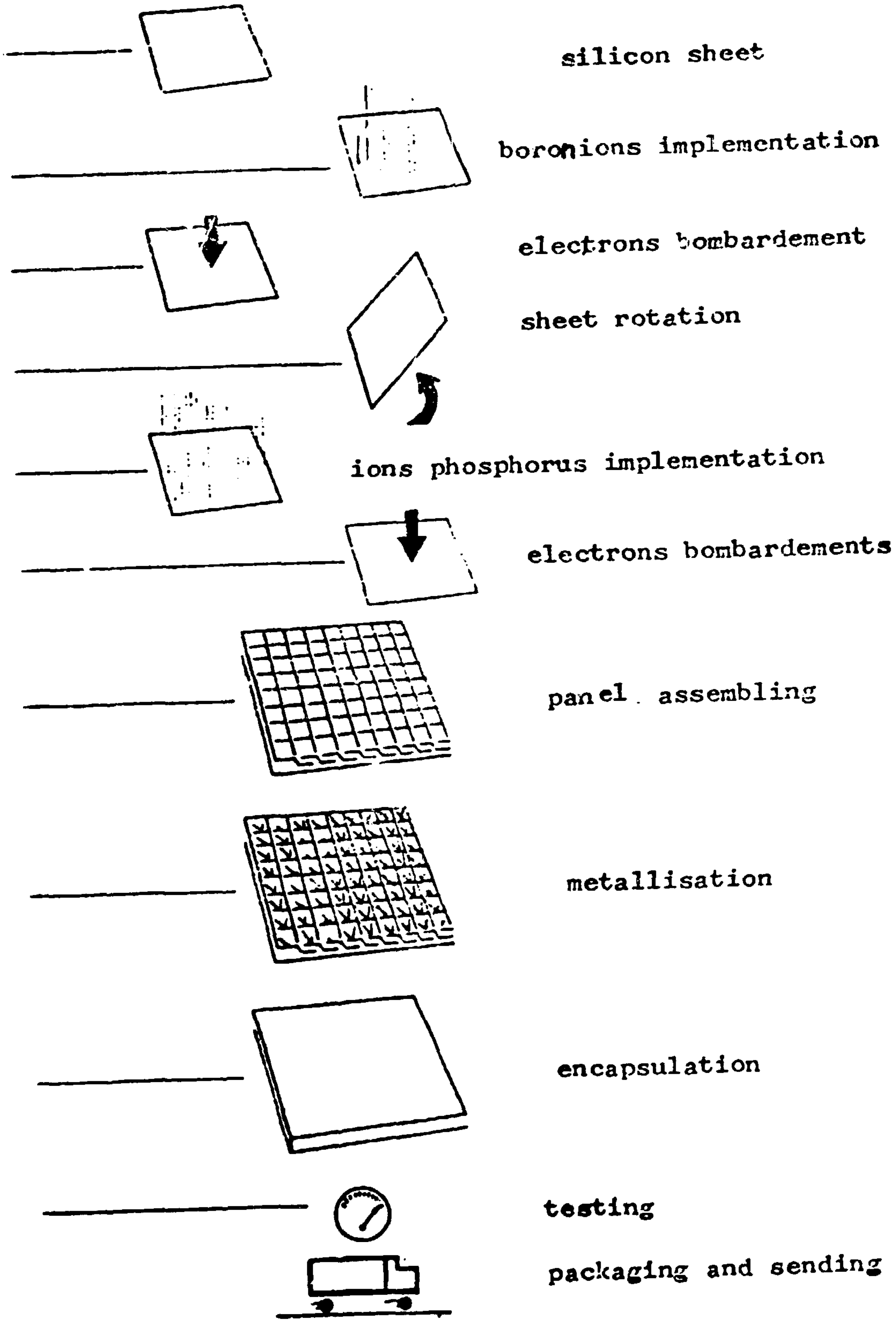


Figure IX. **The automized production line of solar cells of the SPIRE Corporation (USA)**

Source: Solaire 1 Magazine (France) Bimonthly, 57 rue Escudier, 92100 Boulogne, France.

Silicon Production

Two grades of silicon are at present produced:

- Semi-conductor quality, currently produced via the Siemens process;
- Solar grade quality, (solar energy silicon) less pure and much cheaper.

Silicon may be obtained from:

(a) Metallurgical silicon by synthesis of Silan, Si Hcl_2, UCC, Union Carbide Corporation process;

(b) The reduction by Zinc vapour of $SiCl_4$ silicon tetrachloride, BCL, Battelle Columbus Laboratory process;

(c) The deposition of H_2 Si Cl_2;

(d) The reduction by sodium of Si Fl_4 Silicon tetraflouride.

- Union Carbide Corporation UCC process: the following extracts are made from Yaws et al paper:
new technologies for solar energy silicon, cost analysis of UCC silan process: solar energy (ref.6), vol. 22. pp 547-553 we extract the following passage:
" The profitability results indicate a sales price of 9.88 $/kg of silicon (1975 dollars) at a 20 per cent DCF return on investment.
This new technology for producing polysilicon shows good promise for meeting the cost goal of $10 per kg of silicon material (1975 dollars) for solar cells".

Battelle Columbus Laboratory BCL process: From Yaws et al paper: cost analysis of BCL process, ref.(6), vol. 24. pp. 359-365 (1980), we extract the following passage:
"The profitability results indicate a sales price of 14 S/kg of silicon (1980 dollars) at a 7.5 per cent DCF rate of return on investment after taxes.
This new technology for producing polysilicon shows good potential for meeting the goal of providing lower cost material (in the range of 14 $/kg, 1980 dollars) for silicon solar cells".

Cells Encapsulation

Solar cells are fixed or encapsulated within the modules by one of the three main techniques(2). (See Figure X).

- Substrate bonded
- Superstrate bonded
- Laminated (rigid and flexible)

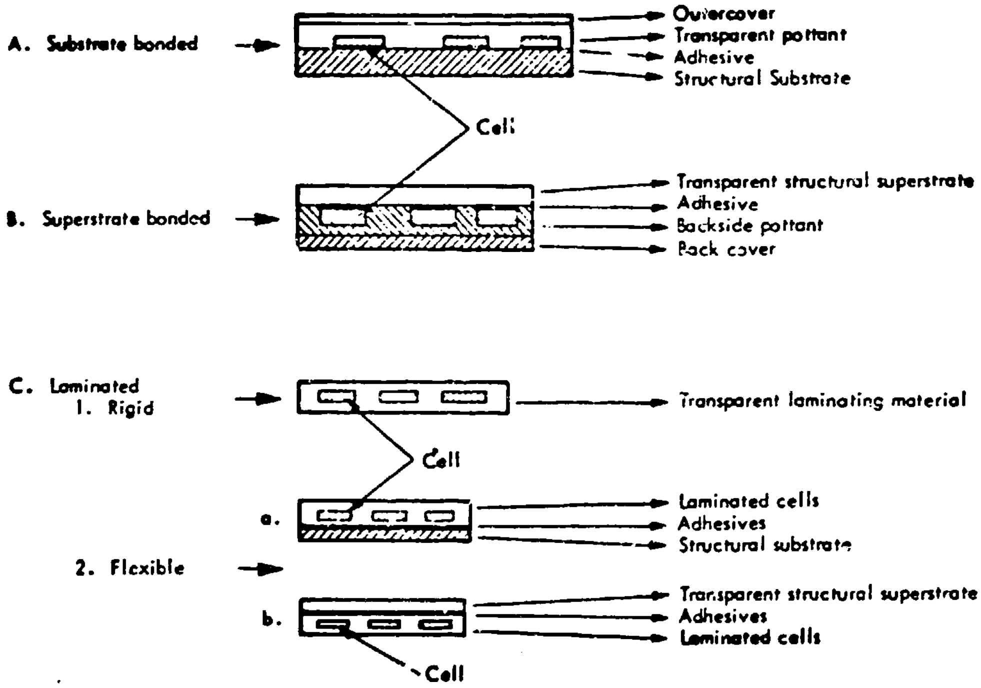


Figure X. Flat module design classifications.

Source: Cuddihi, Solar Energy, Vol.22., pp. 399;396 (1976).

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(2) Substrate design means that the cells are bonded to a structural substrate, the superstrate design means that the cells are bonded to a transparent structural superstrate, and the laminated design means that the cells are wholly encased within a laminating material. Furthermore, if the laminating material is sufficiently rigid and self-supporting, it needs no further mechanical support, but if it is flexible (low-modulus) material, additional mechanical support from either a substrate or transparent superstrate is needed.

The fragile silicon plate is bonded by adhesives to the substrate and protected on the front by a transparent layer. All materials used in the construction of solar modules should be selected in order to avoid stress during the high number of thermal cycles. This would otherwise lead to mechanical rupture or cracks. This condition requires that the thermal expansion coefficients of the different materials shall be very close one to the other. Over a period of 20 years, their expected life, transparent materials should maintain their transparency and mechanical properties under long exposure to the severe atmospheric conditions and sunlight. In this context, glass has unchanging optical and mechanical properties, but this is not always the case with plastic materials which may be darkened by a long exposure to the sunlight and their mechanical properties may not be stable. However, fibre-glass, certain acrylic resins and certain polyurethane products are both weather-proof and reliable.

Tedlar UV films offer good ultraviolet screening, but the required thickness is relatively high and this increases the cost \$ (0.50/m^2 for 25 micron thick film in 1978). Acrylic films may be adequate technically and economically. Transparent materials should not attract dust since heavy dirt may screen the light. Pollution otherwise has little effect on the performance of the solar cells.

Tandem Solar Cells

The tandem solar cells aim at obtaining a higher efficiency. They are based on the idea of converting solar radiation by steps through two or more solar cells built of materials with different energy gaps. The largest gap receives first the radiation, the next cell absorbs the major part of the remaining energy and so on.

Two arrangements of cells are used:

- Several independent p-n homojunctions;
- Integrated tandem solar cells (ITSC) which is equivalent to the connection of the cells in series.(see Figure XI)

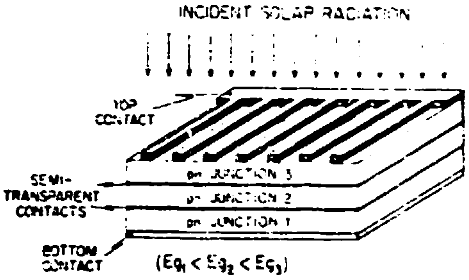


Figure XI. Schematic representation of the typical geometry of a three-element integrated tandem solar cell (ITSC) device. Many variations of this basic structure can be conceived, including heterojunctions and metal-semiconductor junctions.

Source: Vecchi, Solar Energy, vol.22, Pergamon Press.

LOFERSKY, Proc., 12th Photovoltaic Specialists Conference, Baton Rouge, Louisiana (1976)[27], has confirmed a previous work of Wolf, Energy Conv. 11,63 (1976) stating that it is possible to obtain 44 percent efficiency at AM1 of Si tandem solar cells. Lofersky has also proposed general arrangements for tandem solar cells with independent p-n homojunctions.

"Vecchi in his paper, Solar Energy, Vol.22, page 383-388 has concluded:

> "The economic feasibility of producing ITSC devices depends upon many factors. First of all, it is necessary to have the availability of a large assortment of semiconductors with different energy gaps in order to choose the right materials for each specific system, In this respect, continued research on compound semiconductors (II-VI, III-V, I-III-VI_2, II-IV-V_2, etc.) may yield in the near future numerous materials over a wide range of energy gaps. In addition, as more heterojunctions and metal semiconductor solar cells are developed, greater flexibility in the design of ITSC devices will be possible. For instance, hybrid combinations of pn homojunctions, heterojunctions and metal semiconductor cells could be used to make an ITSC device. Numerous possibilities can be conceived, and continuing developments on new materials and production methods may make ITSC devices very attractive solar energy converters. Furthermore, the better match that is made to the solar spectrum reduces substantially the radiation energy lost by thermalization [3,6] and therefore ITSC devices should be seriously considered for operation with concentrator systems."

Photovoltaic Cells and Optical Concentration

Optical concentration may be used for reducing the solar cells area per unit of power. Concentration factor at the present stage of development may go from 3 to 1000. The cells efficiency decreases with the increase of temperature, the cells should then be associated with heat rejection systems natural air cooling may be used up to a concentration factor of 30. When using water for cooling, an integrated system may be used: domestic hot water and space heating for example. Optical concentration supposes the utilization of sun tracking mechanisms. For a very low concentrating factor of about five, seasonally tilting tracking may be sufficient, for medium concentration factor one axis mechanism, and for a high concentration factor, two axis mechanisms are needed. As in conventional solar collectors, Fresnel Lenses, cylindroparabolic and paraboloidical concentrators of different materials may be used.

Theoretically, the cells efficiency increases with the concentration factor, however this is true only up to a certain value depending on the cell structure. This phenomena may be explained by the increase of the internal resistance of the cell which decreases the voltage. An example of this phenomenon is given in the following Figure XII. To improve the global efficiency solar tandem cells may be associated with the optical concentration.

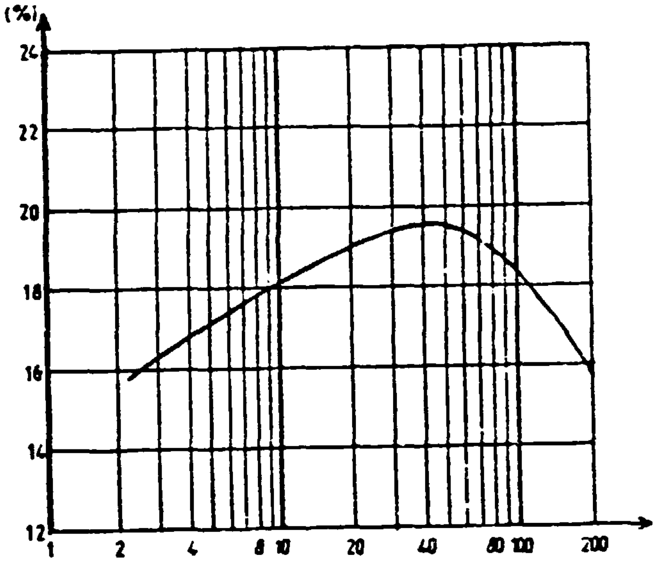


Figure XII. Curve of the efficiency versus the concentration factor for a General Electric silicon solar cell.

Source: **Solair 1. No. 12, page 31, Dec/Jan 1981.**

Cadmium Sulphide Solar Cells

The cadmium sulphide solar cells are produced from thin films of about 20 microns thick. The film is a polycrystalline Cd_2S of which the length of diffusion of the charge carriers is very small. This property allows the utilization of relatively high impurity up to 1000 ppm.

Figures XIII and XIV give examples of these cells[24/].

The back electrode is a metallized Kapton sheet on which is deposited by evaporation a thin film of Cds, type n. The upper part of this surface is then converted by chemical reaction into Cu_2 S type p. A metallic grid is afterwards deposited and the cell is protected by plastic coating.

The following characterizes type P 27 cells. (See also Figures XV, XVI and XVII).

"Dimensions: 62 mm x 27 mm (sensitive area: 27 cm^2).

Weight: 1.5 g.

Electrodes: gold-plated copper and matallized plastic.

Electrical characteristics at 25°C	AM 0 140 mW/cm^2	AM 1 100 mW/cm^2
Open-circuit voltage	435 mV	450 mV
Short-circuit current	695 mA	615 mA
Maximum-power-point voltage	360 mV	360 mV
Maximum operating power	220 mW	196mW
Conversion efficiency	6%	7.2%
Fill factor	70%	71 %

from 3,000 Å
to 10,500 Å

Mechanical characteristics:

Flexibility: capable of being wound around a pencil

Protection: the plastic seal protects from humidity, freezing and heat; the cells are resistant to chemical attacks

Exposure to electron and proton irradiation: no degradation, even at high exposure levels

Reliability: these cells are space qualified and they are perfectly suitable for terrestrial applications

These strong and flexible cells can easily be joined by welding or bonding into large, self-supporting surfaces. Series - or parallel connection permits custom-design of generators" [24].

R and D is aiming at automating the production by deposing the different layers by chemical spray on glass substrates.

Commercial production on a very small scale started in 1975 and reliability of Solar Cds cells is now accepted. However, this type of cell is not adequate for use with optical concentration.

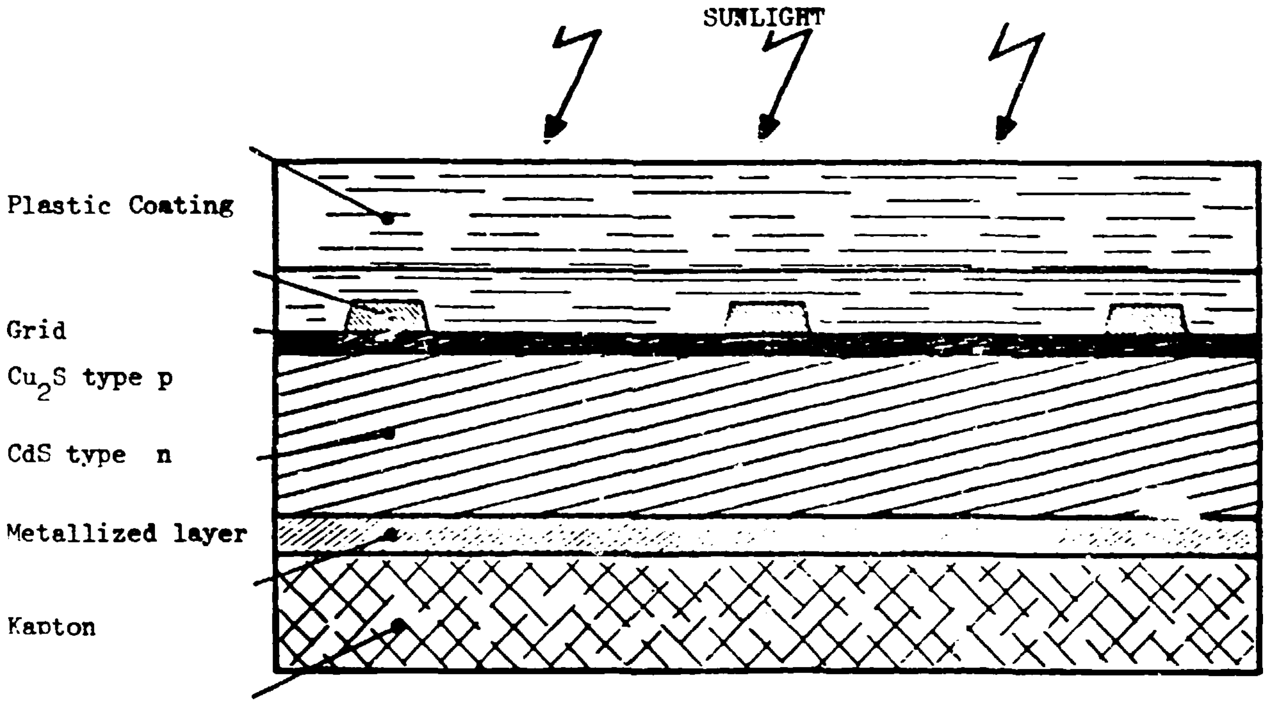


Figure XIII. Schematic cross section of a CdS Cu_2S cell.

Source: Besson, Onde Electrique, vol. 55, No.2 pp.21-24, 1975.

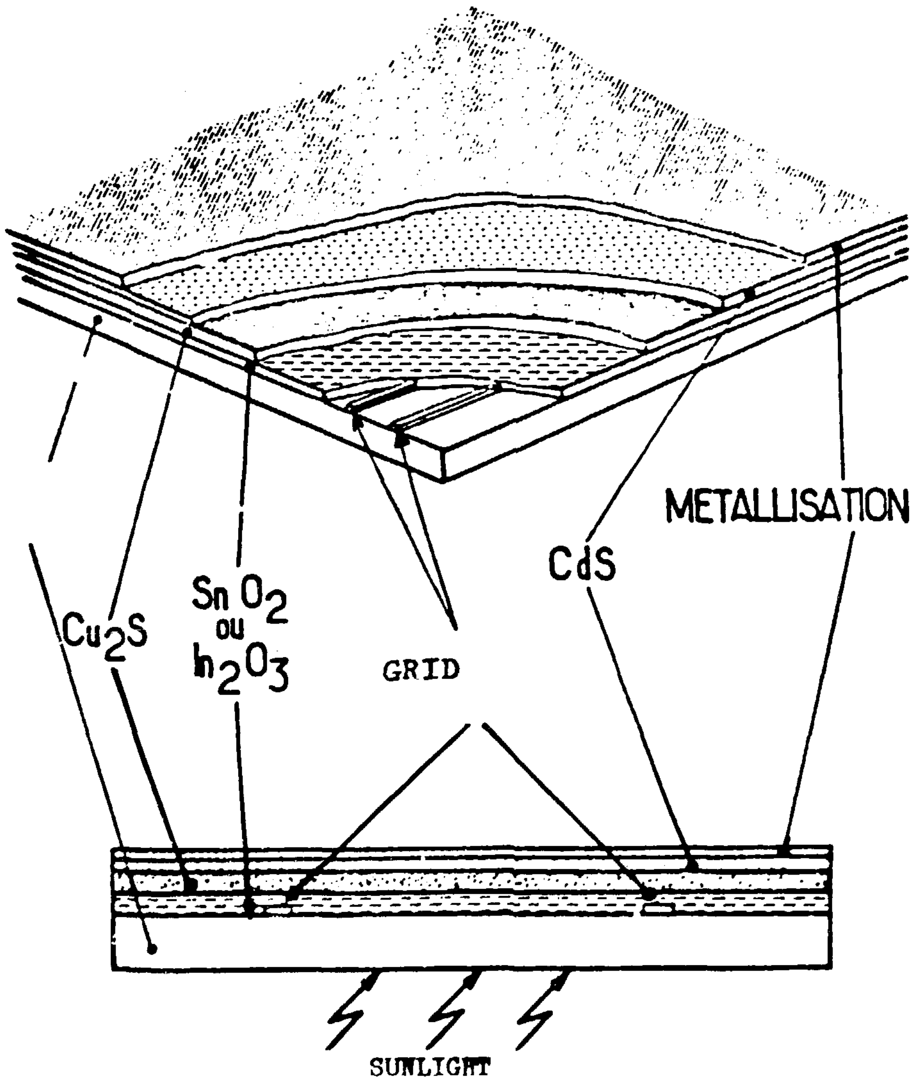


Figure XIV. Photovoltaic CdS cell realized by silk printing.

Source: Ibid.

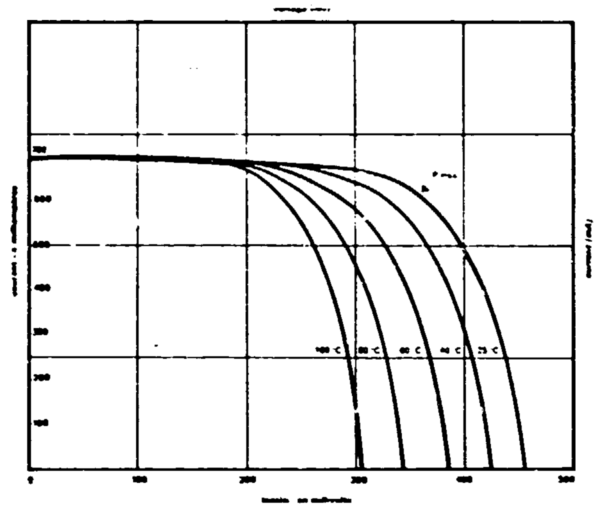


Figure XV. Characteristics as a function of temperature under solar simulation (140 mW/cm2) - Type P 27.

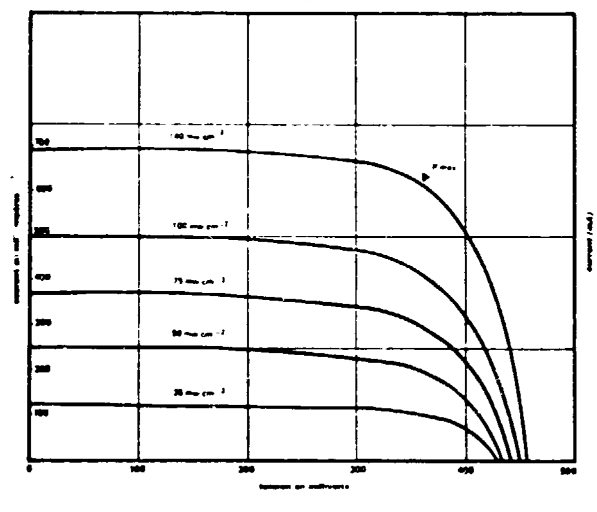


Figure XVI. Characteristics under different illumination - Type P 27.

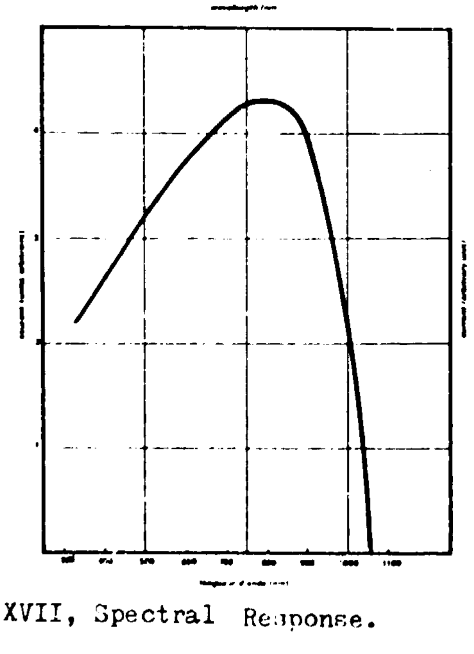


Figure XVII, Spectral Response.

Electricity Storage

The commercial feasibility of PV systems is subject to a large number of factors, among these storage represents a major one when the total produced electricity is not utilized instantaneously.

Electricity may be stored in chemical rechargeable batteries (lead-acid for example of which the cost is in the range of $30-40/kWh or in dry batteries of which the cost is about 20-30 times higher. Such costs will result in high costs per stored Kwh and become rather bulky.

To illustrate the importance of the electricity storage problem when a continuous need of electricity exists, a relatively sunny country is considered and it is assumed that the sun may not appear for 100 hours. This means that for a permanent load of 1 kw, a 100 kwh has to be stored which represents an investment of about $3,000 per installed kwe. Another problem is the relatively short lifetime of the chemical batteries which is in the range of 2 - 5 years, depending mainly on the design, material and operation conditions.

Techno-economic Evaluation

The silicon solar photovoltaic system is still the only system available commercially. However, the commercial availability of CdS solar systems is expected within a few years.

The production of PV systems is progressing at a fast pace; it is approximately doubling every year. The world production was around 1000 kW (peak) in 1978. The cost of the solar PV system is still in the range of $US 10,000 - 15,000 kWe. However, ambitious national programmes are aiming at increasing the production and reducing the cost by 10 to 15 times. The planned programme of the Department of Energy (DOE) in the USA is aiming to produce PV systems for less than $US 1000 kWe. The technical feasibility of PV systems is already demonstrated, but this is not the case for the commercial feasibility. However, the development of new materials and techniques of production are very promising.

According to H. Durand[26], the expected cost for peak kilo watt will be about $2000 around 1985 and about $1000 around 1990. (see Figure XVIII).

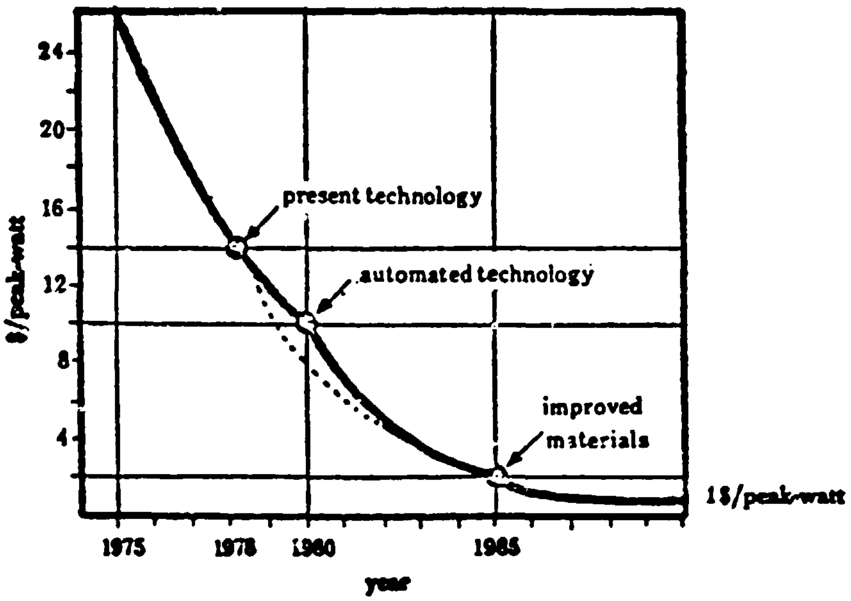


Figure XVIII. Expected price trend for photovoltaic panels.
Source: H. Durand, Phil. Trans. Royal Society, London A.295, 1980.

The expected cost reduction may be achieved by utilizing smaller quantities and cheaper materials for semiconductors, substrate and encapsulation, improving the efficiency and automating the production.

In the case of silicon solar cells the cost reduction may be obtained by:

- Saving on materials, which may be achieved in the case of monocrystalline cells by increasing the diameter of the wafer and decreasing its thickness. Current research is aiming at diameters up to 20 cm and thickness down to 200 microns. It is expected to obtain $1m^2$ of cells of 1 Kg of silicon. Obtaining cheaper silicons is expected by new technologies: ribbons, chemical epitaxial films, semi-crystal and coating from the melt. These new technologies may, within a few years, reduce sharply the cost of materials;

- Improving the efficiency which is in the current commercial terrestrial silicon cells in the range of 12-15 percent. This value is relatively low compared with the 23 percent theoretical conversion efficiency under maximum illumination at AMI. However, an 18 percent actual efficiency is expected shortly ;

- Utilizing new arrangements: tandem solar cells and optical concentration;

- Utilizing thin films technologies. The thin films may be obtained by depositing in a vacuum process very thin films (this technique is not limited to the silicon materials) of amorphous silicon on cheap substrates. The thickness of the films may be in the range of some microns. This technique allows the utilization of large scale areas, the reduction of the cost of interconnections and the automation of the production.

In the Institute of Energy Conversion at the University of Delaware, a machine that can deposit a thin film of photoelectric material (not limited to silicon) on a moving substrate, one meter wide, is already under utilization for research purposes. Carlson, in the RCA laboratory at Princeton is anticipating in six years time, to reach a commercial prodution of depositing under vacuum process a mixture of hydrogen and silane on substrates, which may be glass plastics or aluminium.

Boeing Aerospace in the United States of America is currently producing thin-film solar cells from copper indium selemide Cu In Se2 and CdS on a special low-cost substrate. The produced cells are of 1 cm^2 area and 5 microns thick. Boeing has at this stage announced 9.4 percent efficiency for the cells.

When the thin film technology is technically and commercially feasible the problem of cost reduction will be transferred from the photoelectrical materials and their processing to the other components of the solar cells and array: substrates, interconnections, encapsulations, supports and foundations.

The various thin film technologies are still in the development stage and it is difficult to say what will be the achievements within the coming five to ten years in silicon matters of reaching 10 percent efficiency for amorphous silicon, if the ternary compound is stable and gives the expected higher efficiency.

The most ambitious national programme in the field of photovoltaic systems is that of the United States. The allowed budget in the 1978-1979 period was $125 millions. The Departmen of Energy (DOE) has distributed the research activities between several institutions:

SERI:	Research on materials: Polycrystalline silicons, thin films CdS and AsGa.
Jet Propulsion Technology:	Improvement and development of new techniques of production.
SANDIA Laboratories:	Systems and subsystems studies: NASA, MIT, SANDIA and Aerospace Corporations: Market studies.

A large number of national and international meetings have discussed Solar PV Systems and it is felt that one of the most reliable evaluations of these systems and the R and D in the USA is the study carried out by the American Physical Society Study Group on Solar Photovoltaic Energy Conversion, published in January 1979, from which the following extract is taken:

"PV Systems: A Perspective

1. It is unlikely that photovoltaics will contribute more than about 1 per cent of the U.S. electric energy produced near the end of the century. Central power production is the most extensively studied and clearly perceived long-term, large-scale application of PV for this country. Barring unforeseen rises in the cost or availability of fuels, prices for 12-16 per cent efficient flat plate modules or concentrator arrays of about 10-40c per peak watt (W_p) in 1975 dollars will be required to compete with the projected cost of coal-generated electricity (about 45-70 mills/kWh levelized busbar cost in the year 2000.

2. It is anticipated that only a small fraction of the electricity generated after 1990 will be based on gaseous and liquid fuels. Therefore photovoltaics will not significantly reduce the use of these fuels. The major effect of photovoltaic generation will be a displacement of some combination of coal and nuclear fuels.

PV Systems: Technical Issues

3. Because of the cost associated with encapsulation, foundations, support structure, and installation of PV array fields, there is a large economic penalty for the use of low-efficiency cells. To compete in the U.S. central power generation market, even zero cost PV cells must have a limiting minimum efficiency. The use of modules with efficiency as low as 10 per cent will probably require substantial reduction in these other costs, even if the modules themselves are inexpensive.

4. The minimization of materials usage in the overall PV system must be emphasized. New designs for PV systems should be tested against the availability of materials at high rates of construction of generating capacity, because political or economic developments might produce a need for accelerated rates of deployment. Some current designs, in addition to being extremely expensive, would make major demands on U.S. ability to supply certain materials in sufficient quantity.

5. Energy storage would be necessary if photovoltaics came to supply more than about 10-20 per cent of electrical energy in a typical region.

Silicon Technology

6. Silicon-based PV is the reference technology for both flat plate and concentrator systems. It provides a vehicle for evaluating systems, with known bounds on performance and manufacturing costs and with extensive field experience. Flat plate silicon module costs using technology now foreseeable will approach the price range of 50 to 77 c/Wp. This price range will not produce electricity competitive with projected coal central power generation, but it does offer important insurance value against unexpected energy price rises and would permit the growth of a significant expert market to developing countries.

7. Efforts to reduce the cost of silicon sheet from sliced single-crystal material should be emphasized becuase of the importance of high efficiency in minimizing systems costs in both flat plate and concentrator applications. With current technology the cost per unit area of cells fabricated from cast semicrystalline silicon or ribbon growth is slightly lower than that of cells make from Czochralski material. This does not offset the highter systems costs associated with lower efficiency. Current ribbon growth efforts should be continued because of the potential for possible advances, particularly in cell efficiency.

8. Silicon cell performance currently falls below theoretical limits for reasons that are not adequately understood. Innovations in cell design and processing technology that can lead to improved efficiency and lower cost should be supported.

Concentrators

9. An especially promising approach to competitive PV is the use of novel concentrators and high efficiency cells. Recent concentrator designs indicate that there is a real possibility of substantial reductions in structural cost, particularly at high concentration.

10. There are a number of possible ways of making cells with efficiencies of 25% or more. Such cells, although too expensive for flat plate systems, would be highly desirable for concentrators. Promising routes include GaAs-GaAlAs cells and the development of integrated multicolour cells.

Thin Films

11. Highly disordered thin films are typically characterized by large defect concentrations and short lifetimes compared to those found in single crystals. Despite this fact, there are cells with efficiencies near 10 per cent (e.g., Cds/Cu_2S).

12. Thin films could form the basis of an inexpensive cell technology. Work to develop this potential for low-cost power generation will include the search for new materials and research exploring basic phenomena in thin film and prototype crystalline systems.

13. As in other flat plate systems, effective application of inexpensive, presumably low efficiency cells requires innovation in other than cell related costs. Low cost encapsulants, support structures, and installation that maintain the structural integrity and chemical stability of the cell are required.

15. Because functional interfaces are necessary and often limiting features of PV devices, fundamental research on their structural and electronic properties is of particular importance. The programme should address semiconductor heterojunctions,Schottky barriers, semiconductor/liquid interfaces, grain boundaries, and interfacial atomic structures on well characterized prototypes and systems of practical interest.

16. Semiconductor/liquid junction cells represent a rapidly advancing field (from 1 to 12 per cent efficiency in the last two or three years). Both basic and practical questions remain to be resolved. It is possible that understanding and manipulation of interfacial charge transfer kenetics at semiconductor/liquid junctions could lead to a system having significant advantages over an all solid state photovoltaic cell.

17. There are no nonbiological schemes for useful fuel production on the near-term horizon; but, since their theoretical efficiency is the same as for other photovoltaic systems, man-made systems could significantly surpass present natural photosynthetic efficiency. Research activities should emphasize the connection between photosynthesis and photochemistry, electrochemistry, and photovoltaic physics. Since the formation of conventional fuels requires processes utilizing two or more photons per fuel molecule formed, research efforts should be directed towards seeking out ways of doing this efficiently.

18. Until recently, the DOE funding formats have been too goal-oriented, over-managed, and too restrictive in other respects. R and D management styles and funding formats should reflect the long-term nature of the problem and the need to compete with other research fields for the talent essential to a successful PV programme.

Concluding Statements

19. The Federal programme should encourage a diversity of approaches to obtaining better PV systems, both in studies of all the present candidate technologies and in diligent searches for new ones.

20. Deployment should be limited to the scale necessary to generate field engineering and systems knowledge. Until a clear pathway to the PV future has been established, efforts to stimulate a large-scale low cost industry are premature.

21. A long-term and innovative R+D programme in PV is needed, which must include:

(a) the search for and development of new photosensitive materials;

(b) basic research on the interfacial phenomena that control photovoltaic conversion;

(c) investigation of non-biological methods for direct production of fuels from sunlight;

(d) development of novel photovoltaic technologies or devices (for example, bubble concentrators, encapsulants for flat plate cells, and noncell related structural materials) to aid in identifying the critical materials problems limiting performance and cost."

II. SOLAR THERMAL POWER SYSTEMS

General Information

Solar thermal power plants which convert solar energy to mechanical and then to electrical energy may be classified in different ways, for example:

- By the temperature of the working fluid. Under 100°C. when utilizing flat plate collectors and above 100°C. when utilizing concentrating collectors;
- By the thermodynamic cycle - Rankine, Brayton, Sterling;
- By the arrangement of the subsystems which constitute the system. Solar farm or distributed system and solar central receiver (tower) system.

Different working fluids are utilized in the expanders: butane, different freons, steam, benzene, toluene, etc. Different types of expanders are also utilized: reciprocating engines, screw expanders, rotating expanders, turbines, etc. All these types of expanders are adapted from the conventional industry where they are used as air compressors, in refrigeration industry, power plants, etc. These expanders have to be adapted to different temperatures, pressures, flow rates, speeds and working fluids.

A large number of subsystems and systems in different countries are now under development with powers going from a fraction of kW to thousands of kW however, a "real" commercial availability of appropriate systems does not at present exist.

The range of solar power plants needed in a country depend on the specific problems and situation of that particular country, however, it seems that in the majority of developing countries the major number of plants will be in the range of 1-10/20 kW and a much smaller number in the range of 20-50 kW. The need for solar thermal power plants is mainly in irrigation, electrical generation and some small industrial applications (cottage industry for example). The produced mechanical energy may be used directly to drive equipment such as pumps, compressors, wheat mills, cotton seed presses or to drive electric generators.

Although the need for solar central receiver plants in developing countries does not appear urgent in the short and medium term due to their uneconomic feasibility at this stage of development, a general idea about the on-going projects in this field is given. The information is mainly extracted from various sources [8, 10, 15, 30].

Examples of solar farm systems at low temperature working fluids have already been discussed in the UNIDO publication [31] and this chapter will treat mainly solar distribution systems at temperatures higher than 100°C.

Unfortunately no information is currently available to the author on important works in the Union of Soviet Socialist Republics (USSR) in the field of solar thermal power plants. Table 1 following gives the main characteristics, location and costs of the major projects which were under development in 1978.

Table 1. Solar-Thermal Electric Power Generation Projects in the Planning Stage (sample list)

	COUNTRY	FACILITY: LOCATION: DIRECTED BY	RATING: EFFICIENCY	DATE OF COMPLETION: COST ESTIMATE +)	MODE OF COLLECTION: CONCENTRATION RATIO	TRANSFER MEDIA/TEMP.: STORAGE/CAPACITY: PRIME MOVER
TOWER CONCEPTS	USA	BARSTOW S. CALIFORNIA DOE, CALIF. ED, ET AL	10 MWe 19 %	1980 ~200 Mio DM	1720 HELIOSTATS (40 m^2); ~500	WATER/ 510 °C; THERMAL OIL / 3 HOURS; STEAM TURBINE
	SPAIN	CESA 1 ALMERIA CEE	1 MWe 18 %	1980 ~32.5 Mio DM	275 HELIOSTATS (36 m^2); ~1100	HI TEC / 520°C; HI TEC / 3 HOURS; STEAM TURBINE
	(IEA)	SSPS-A ALMERIA, SPAIN DFVLR	0.5 MWe 15 %	1980 ~28 Mio DM	148 HELIOSTATS (40 m^2); ~300	SODIUM / 600 °C; SODIUM / 4 HOURS; STEAM TURBINE
	FRANCE	THEMIS 1 TARGASONNE CNRS; EDF	2 MWe 16 %	1980 ~34 Mio DM	380 HELIOSTATS (45 m^2); ~425	HI TEC / 430 °C; HI TEC / 6 HOURS; STEAM TURBINE
	(EEC)	- SICILY ISPRA	1 MWe 14 %	1981 ~12 Mio DM	727 HELIOSTATS (12 m^2); ~500	WATER / 510 °C; HI TEC AND STEAM/ 0,5 HOURS; STEAM TURBINE
	JAPAN	- SHIKOKU MITSUBISHI	1 MW	1982 ~14 Mio DM	HELIOSTATS (?);	WATER/ ;
DISTRIBUTED COLLECTOR	(IEA)	SSPS-B ALMERIA, SPAIN DFVLR	0.5 MW 8 %	1980 ~19 Mio DM	PARABOLIC TROUGHS; ~35	THERMAL OIL / 300 °C; THERMAL OIL + ROCKS / 4 HOURS; ORGANIC RANKINE TURBINE
	FRANCE	- CORSICA BERTIN	0.3 MW	1978 ~9 Mio DM	PARABOLIC TROUGHS; ~20	THERMAL OIL / 200 °C; THERMAL OIL + ROCKS / ?; ORGANIC RANKINE TURBINE
	USA	DWIF ARIZONA DOE	0.15 MW	1979	PARABOLIC TROUGHS; ~35	THERMAL OIL / 300 °C; THERMAL OIL + ROCKS/ 114 m^3; ORGANIC RANKINE TURBINE
	GERMANY	- KAIRO BMFT	0.01 MW 7 %	1978 ~5 Mio DM	PARABOLIC TROUGHS (200 m^2) AND HEAT-PIPE COLLECTORS (400 m^2); ~10 (PARABOLIC TROUGHS ONLY)	WATER / 250 °C; WATER / 3 HOURS (3 kWe); RADIAL FREON TURBINE
	GERMANY	- ALMERIA BMFT	0.05 MW 10 %	1979 ~9 Mio DM	PARABOLIC TROUGHS (300 m^2); ~10	THERMAL OIL / 250 °C; OIL + CAST IRON /~0.5 HOURS (3 m^3); 2-STAGE STEAM SCREW EXPANDER

+) Non-recurring cost elements included

Source: Documents of the International Symposium, April 1978, Cologne, FRG.
Organized by DFVLR on Solar Thermal Power Stations.
J.R. Gintz et al, page 19.

Central Receiver Solar Thermal Power Systems

A central receiver solar thermal power system consists of four principal subsystems:

- Solar collectors (heliostats);
- Thermal receiver and its support;
- Storage;
- Expander and electric generator.

The collector system consists of a large number of heliostats with two axis tracking systems. These heliostats are of different shapes, materials, dimensions and tracking systems. For example in the CNRS (France) THEMIS 2 MW central receiver project, the heliostats are of 50m^2 reflective area each and back silvered glass. The total reflective area is 17,500 m^2 and the land area 70,000 m^2 (25 percent coverage). In the McDonnel Douglas project in the USA, the heliostats are of 38m^2 reflective area each, the total reflective area is 66,780 m^2 and the coverage is 22 per cent. Figures XIX to XXV show different heliostat concepts and arrangements for energy storage.

The position of the tower and its height, the receiver and its characteristics are determined by the local conditions, the technology of materials, the cycle, the peak power, the storage system, etc.

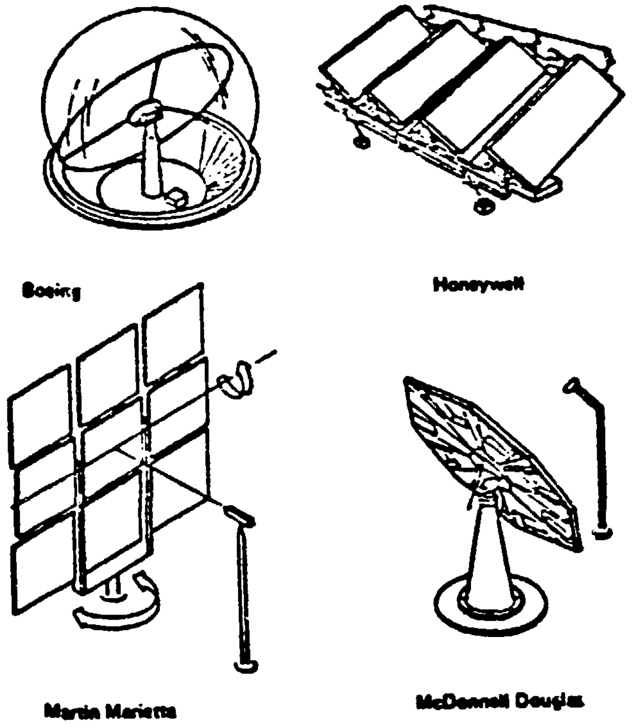


Figure XIX. Pilot plant heliostat concepts.

Source: Walton and Harris, development of a ceramic receiver for a Brayton Cycle solar electric power plant, Georgia Institute of Technology, USA.

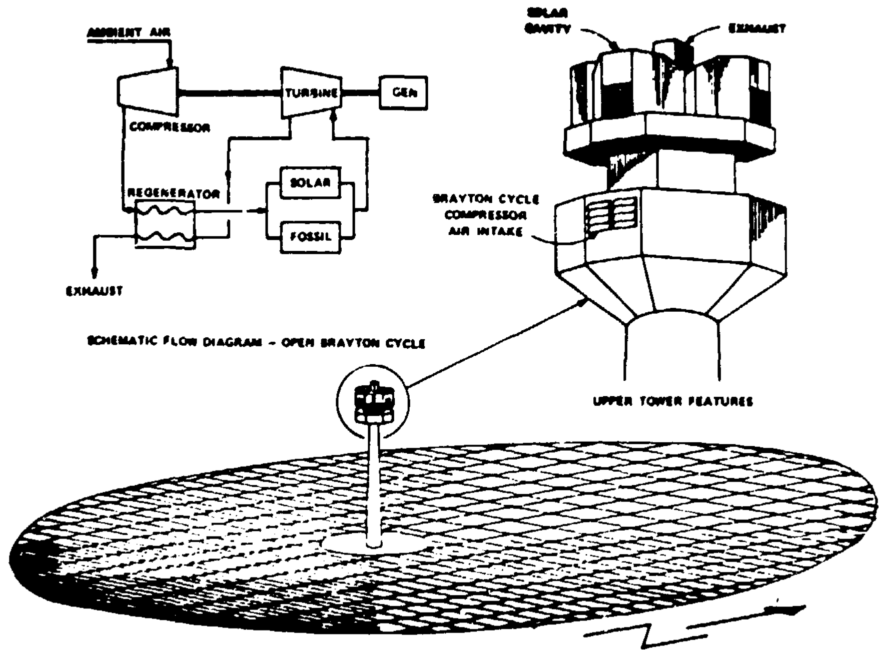


Figure XX. Perspective View of the Open Cycle Solar Thermal Central Receiver System.

Source: Ibid.

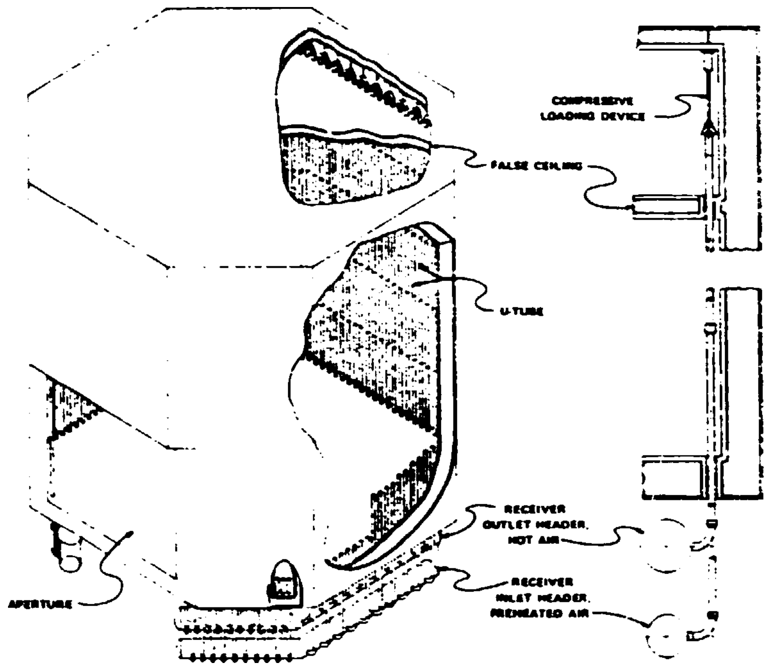


Figure XXI. Cutaway of U-Tube cavity type receiver heat exchanger.

Source: Ibid.

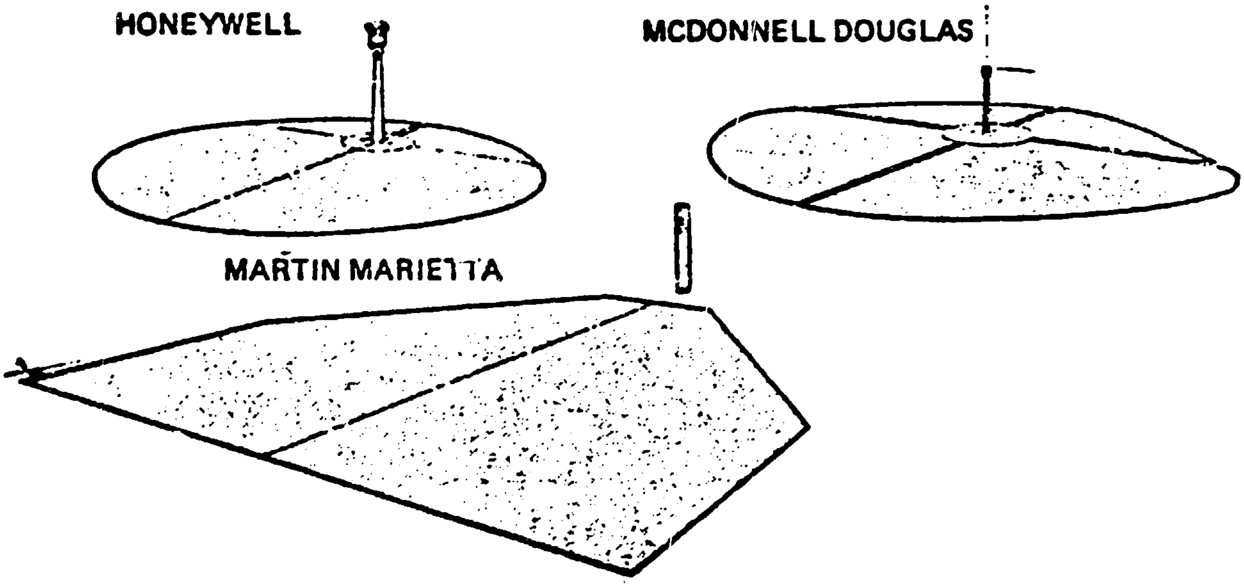


Figure XXII: Collector field layouts.

Source: Ibid.

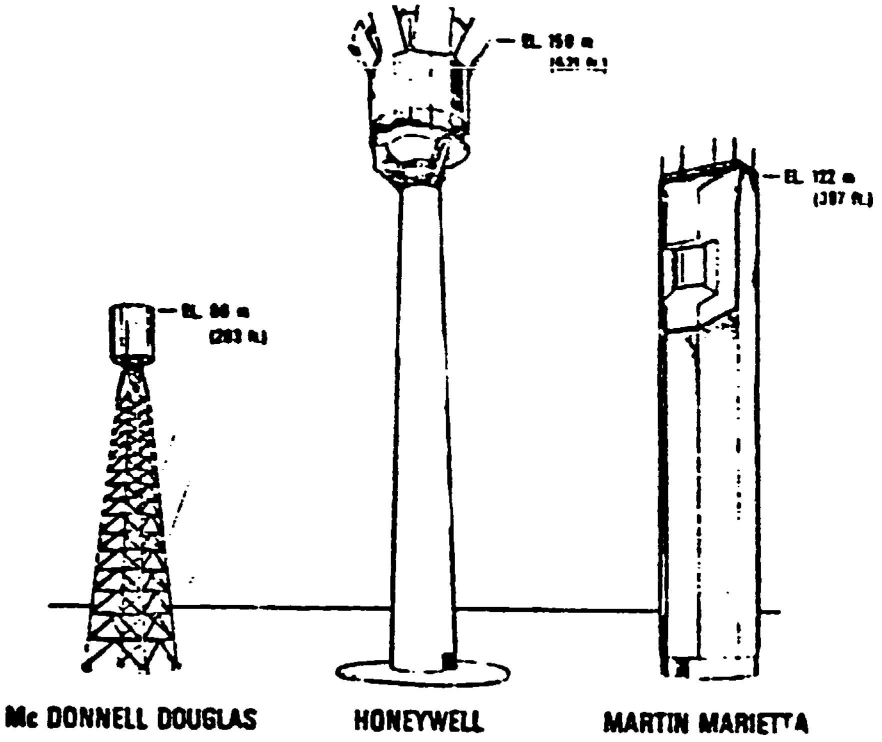


Figure XXIII. Receiver/tower designs.

Source: Ibid.

Regarding Figure XXIV the following remarks are made:

- The Rankine cycle may be used up to 1100°F (593°C) with a maximum Carnot efficiency of about 40 percent.
- The Brayton cycle may be utilized between 1200 and 2500°F (650-1370°C), however there is a limitation on materials, for example 870°C constitutes the upper limit for the Nickel Alloys.
- The advantages of the Brayton Cycle is its high efficiency and its relatively low consumption of cooling water.

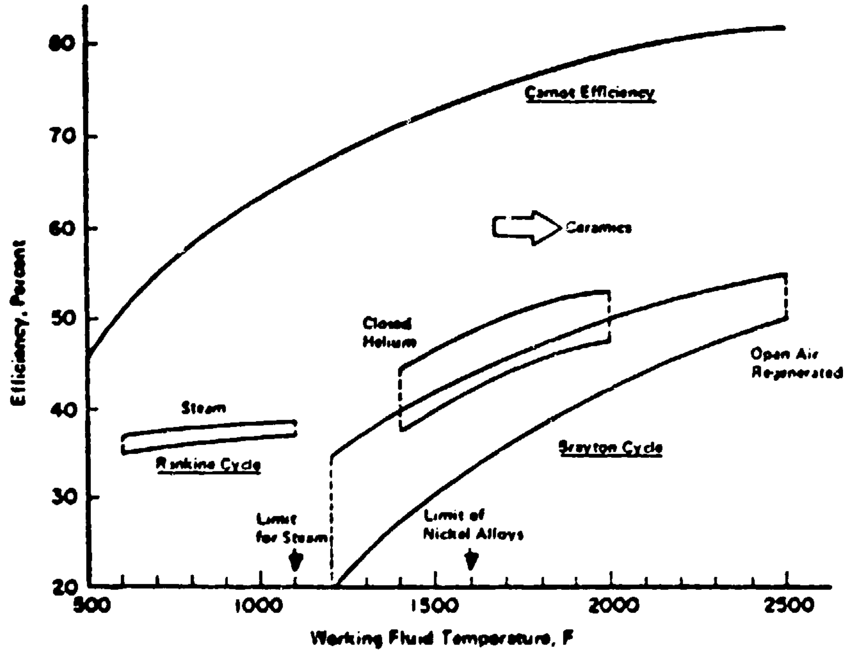
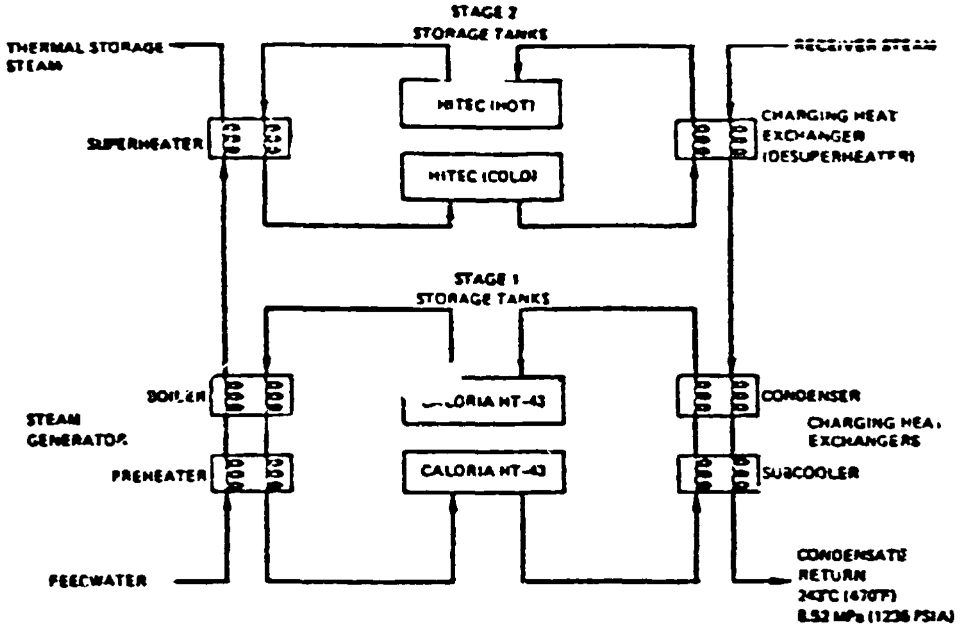
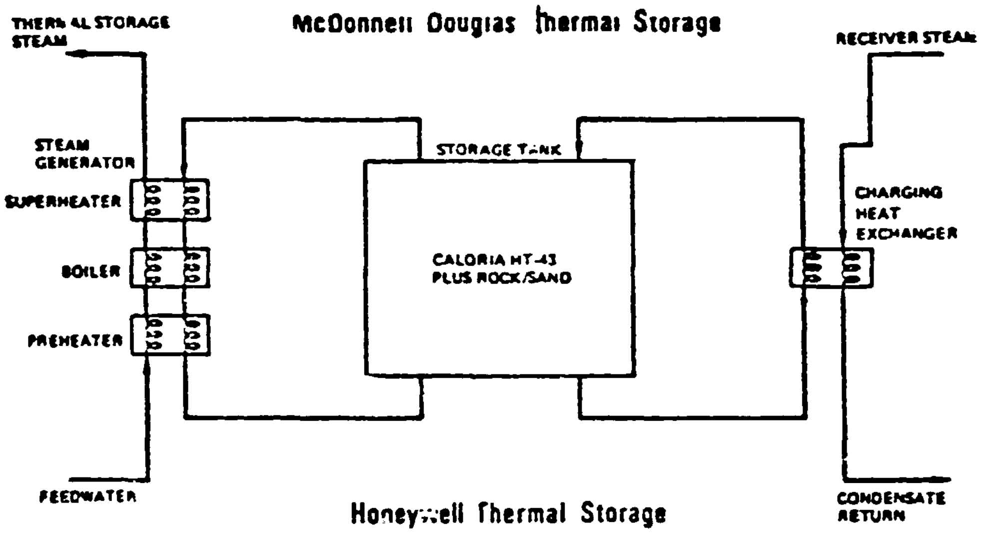


Figure XXIV. Cycle efficiency for Rankine steam and Brayton cycles compared with Carnot efficiency as a function of temperature.

Martin Marietta Thermal Storage



McDonnell Douglas Thermal Storage



Honeywell Thermal Storage

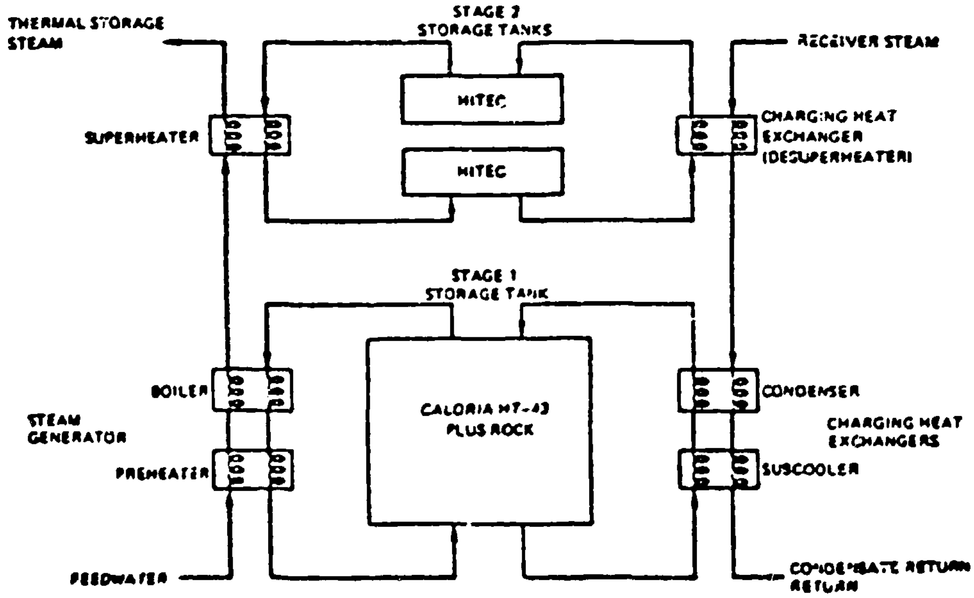


Figure XXV. Energy storage subsystems.

Source: Documents of the International Symposium, April 1978, Cologne, FRG organized by DFVLR on Solar Thermal Power Stations.

Solar Distributed Thermal Power Plants

The solar distributed thermal power plants may utilize plate collectors preferably with selective coating, for temperature of the working fluid in the range of 30-90°C, or concentrating collectors for a temperature of the working fluid in the range of 130-250°C. Higher temperatures may be achieved if the optimization of the project requires such a temperature.

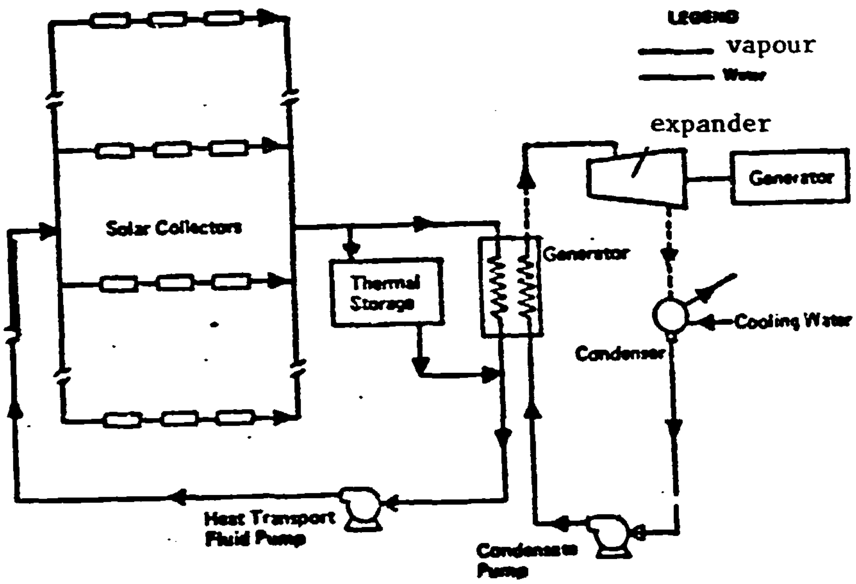


Figure XXVI Distributed solar thermal power system.

This system may be used efficiently in the range of power of 1-50 KW, however higher power range may be obtained. The system utilizes solar concentrator collectors of different shapes, materials, coating, arrangement of collectors-absorbers and tracking systems. (See Figure XXVI).

Figures XXVII-XXXII represent the major types of collectors (see pages 116 and 118)[14].

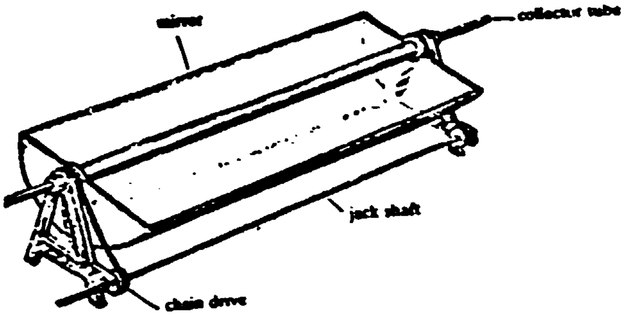


Figure XXVII. Parabolic mirror collector.

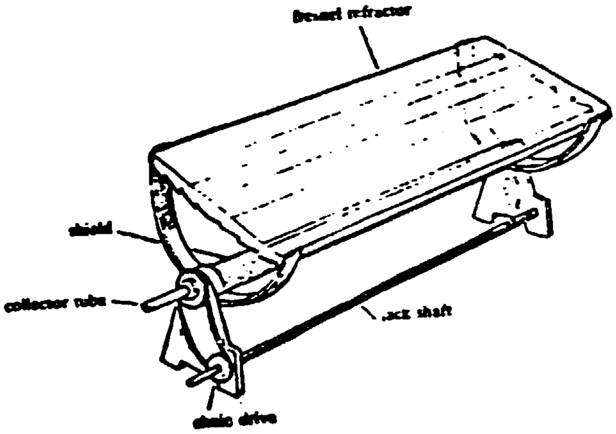


Figure XXVIII. Fresnel lens collector.

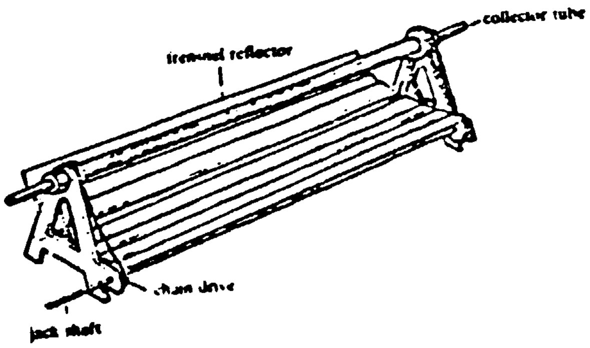


Figure XXIX. Collector with mirror strips, fixed in a moving frame.

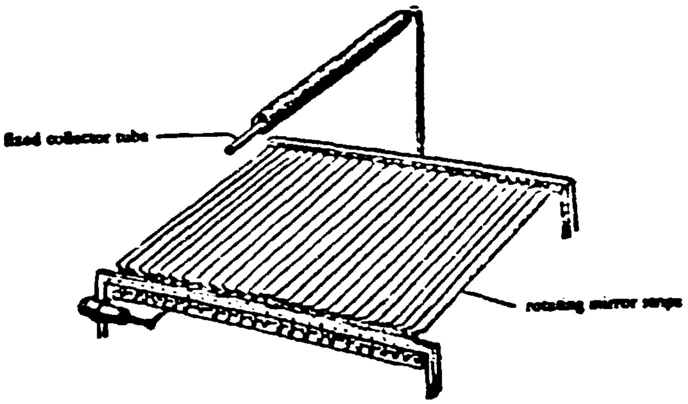


Figure XXX. Strip mirror collector. Moving strips in fixed frame.

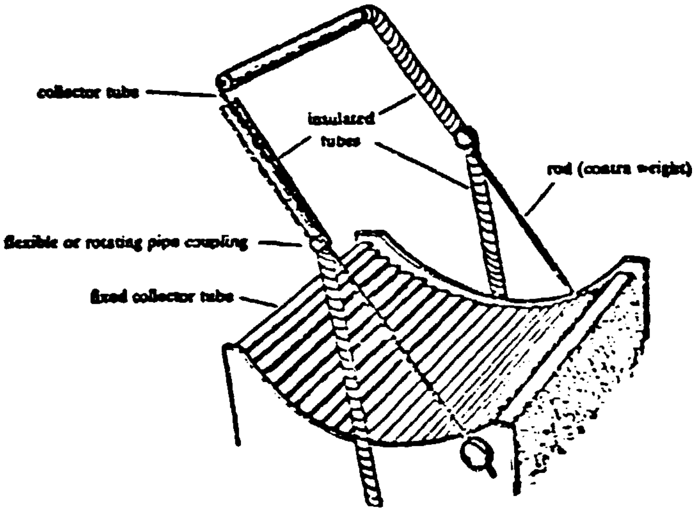


Figure XXXI. Collector with fixed strips and movable absorber tube.

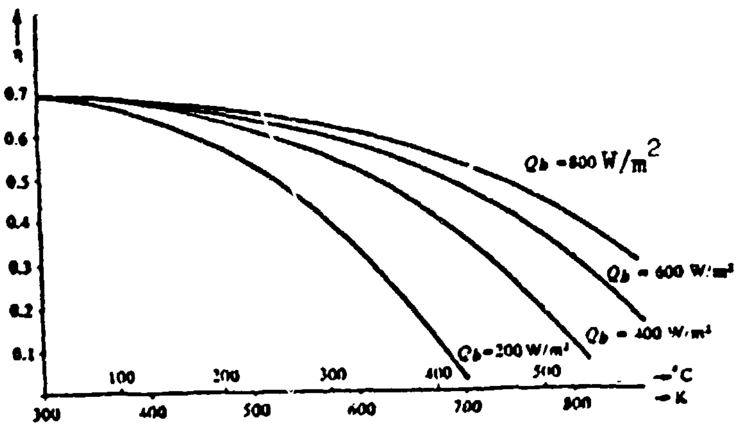


Figure XXXII. Calculated efficiency curves of a strip mirror collector with a concentration ratio of 30.

The overall system efficiency may go up to 10 percent when the temperature of the working fluid is around 300°C. in a Rankine Cycle.

The efficiency of the system for a given concentration ratio increases with power output until a certain value. It then starts to drop due to increasing losses in the heat collecting network. This happens only when power output exceeds some hundreds of kW.

The efficiency of the system can also be increased with selective coating on the absorber tubes which allow higher temperatures with a given concentrating factor or smaller concentrating factor at the same temperature with the same fluid.

The intercept factor comprising losses due to dispersion of the solar picture, positioning inaccuracy of the absorber and inaccuracies of the reflectors, has a large influence on the total efficiency of the system.

The tracking system also has an important influence. Intershading of the collectors should therefore be carefully examined when designing a solar farm system.

Feustal et al[15] (Figure XXXIII) give a numerical example of optimal efficiency for a system comprising a multistage steam turbine, $800 W/m^2$ insulation; 20°C ambient temperature, and a sun concentration of 40°C. The optimal efficiency--the product of the collector field efficiency and the power conversion efficiency--in this case occurs at a temperature of about 280°C.

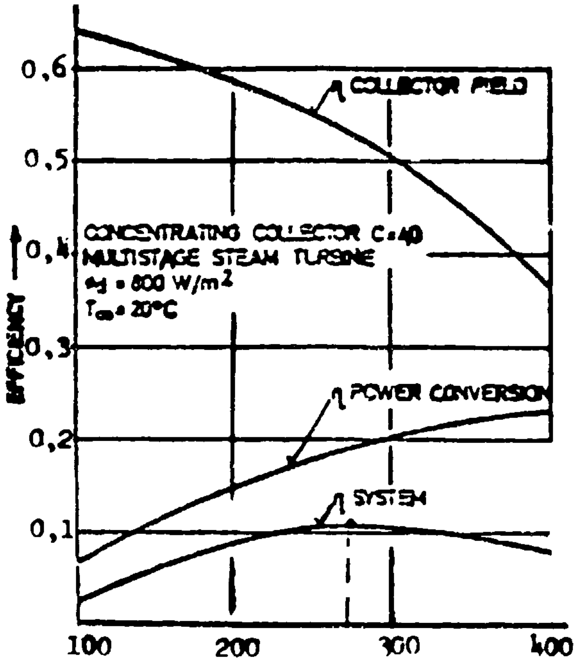


Figure XXXIII. Optimal efficiency for a System Comprising a Multistage Steam Turbine.
Source: (15).

Feustal et al[15] also give a tentative table showing the range of applicable expanders, in the short-term, for different ranges of power:

"Piston type steam engine	10 - 500 kW
Stirling engine	50 - 100 kW
Screw type steam engine	50 - 5000 kW
Closed cycle gas turbine	50 - 50,000 kW."

Other types of expanders with expected results in the range of 10-50 kW may be included in the above. In particular the two following prototypes may be mentioned:

- A screw vapour expander similar to the MBB expanders utilized in a 10 kW joint project India - Federal Republic of Germany.

- A rotating expander developed by sun power systems in the USA, see page 10 of the UNIDO document[31].

The selection of the working fluid is of great importance when designing the expander. Each working fluid has its own merits and inconveniences. This influences the efficiency of the adopted cycle, the dimensions of the expander, its materials, speed and control system. Steam still represents a reliable medium and conventional steam engines may be profitably utilized.

Techno-economic Evaluation

Central receivers

Existing plants are of recent construction. They are still being developed and the limited available information does not set down an established technology in this field.

The relatively low efficiency of the Rankine Cycle, which may use mainly conventional equipment, has to be compared with the higher efficiency of the Brayton Cycle which requires the development of new materials and equipment.

The technical feasibility of the central receivers solar power plants is not yet fully demonstrated and economic feasibility is not expected within the near future.

Distributed systems

The global efficiency is relatively low. It is still in the range of 4-8 percent.

Technical feasibility is demonstrated, but no established technology exists at present.

Economic feasibility is not yet demonstrated.

The solar collectors need periodic cleaning and they are, when glass is used, subject to breakage.

The short period of operation of the existing plants does not suffice to make a well founded judgement of the economic feasibility of small solar thermal power plants which are, in the short and medium terms, more promising for developing countries. A specific example of a 10 KWe plant is considered.

The following favourable assumptions are made regarding solar plants:

> The solar plant will run at full load 4000 hours per year. This pre-supposes utilization of a large thermal storage system to store excess energy created by the difference between rated and peak output. It also pre-supposes an important excess area of solar collectors.

The electricity produced is utilized directly without any electrical storage (this is a very optimistic assumption).

The labour cost is the same for the solar and the conventional plant.

Two sets of diesel generators, 10 kW each is used for comparison.

The life of the solar system is eight years (about five years for the solar engine and twelve years for the subsystems). The life of each diesel generator is 10,000 hours. This short lifetime is considered because it appears more economical to replace a diesel engine in a remote area rather than to make major repairs. The assumption is very pessimistic, at least for the electrical generator.

The theoretical consumption of gas oil in a well designed diesel engine is in the range of 160g/horse power or 217g/kWh, we assume that the actual consumption will be higher by about 25 percent and we assume also that the lube oil cost is equivalent to 4 percent of the consumed fuel. The equivalent fuel is then 285g/kWh say 0.3 kg/kWh. The annual energy saving for the 40,000 kWh is 12,000 kg of gas oil or 1200 kg/kWe.

The repair and maintenance cost is 8 percent for the diesel generator and 3 percent for the solar plant.

The annual rate of interest is 10 percent (actually it can be much higher depending on the country and currency), and it is assumed that the annual cost of the loans made to finance the installation is equal to half the rate of interest multiplied by the amount of the loan. This simplification will not effect the accuracy of comparison because it applies on the two sides of the equation and is relatively unimportant as against the other terms.

The comparison omits the effect of inflation. The following equation may be written:

$$(a_s + b_s + \frac{i}{2}) \; K_s = (a_d + b_d + \frac{i}{2}) \; K_d + q_f \; c_f$$

Where the symbols have the following meanings:

Variables

a - annual rate of depreciation.

b - ratio of the annual cost of maintenance and repair to the cost of the installed plant.

i - rate of interest on the loan used to finance the cost of the installed plant.

K - Cost of plant per unit of installed power.

q - Annual rate of consumption of diesel fuel, per unit of installed power in Kg.

c_f - Unit cost of diesel fuel.

Subscripts

s solar, d diesel.

When substituting the numerical values, the equivalent is:

$$(0.125 + 0.03 + 0.05)K_s = (0.20 + 0.08 + 0.05)2K_d + 1200 \; C_f$$

$$K_s = 3.22 \; K_d + 5853.66 \; C_f, \text{ we adopt}$$

$$\boxed{K_s = 3 \; K_d + 6000 \; C_f} \qquad (1)$$

This means that when the cost of installed kWe solar plant, including its heat storage subsystem is less or equal to three times the cost of installed kW diesel generator, added to the cost of six tons of gas oil, the solar thermal power plant becomes commercially feasible.

Numerical application:

$US200/kW of diesel generator;

$US300/ton of gas oil.

$$K_s \leq 2400 \$$$

From the above discussion the following conclusions are made.

- A solar thermal power plant within the range of 2-10 kW begins tobe feasible in the present condition when its unit cost does not exceed $2500/kW. The present cost on the market is 3-10 times higher (1981).

- Calculations of the cost per unit of energy (kWh for example) is not useful because the variables change too much from country to country. A general equation, such as equation (1) above, seems more useful.

- Economy of scale cannot be fully applied in the case of solar thermal plants, since the required surface area of the solar collector is approximately proportional to the power of the engine. (The improvement of the efficiency of larger engines can be neglected in a first approximation). The solar collectors represent an important part of the total cost of the installation. However, the cost per unit power of other components, transport and installation will be greatly reduced when the power increases.

- The investment is higher for solar plants.

- The solar power installation will occupy a ground surface of 20-50m^2 for each kilowatt of installed capacity; this extra land cost should be taken into consideration. However, if solar collectors are used as roofs for buildings, the cost per unit of installed capacity will decrease slightly.

- It is difficult to obtain a constant speed on the shaft of a solar engine unless a costly and possibly sophisticated system of control is provided. A constant speed may be necessary for some applications such as electricity generation.

- When working continuously, the machine that is coupled to a diesel or gasoline engine giving the same energy may have half the power of that coupled to the solar engine, so its cost, transport and installation will be cheaper and easier.

III. SOLAR REFRIGERATION AND AIR-CONDITIONING SYSTEMS

General Information

Refrigeration may be defined as the technique of removing the heat or "producing cold" of a product in order to lower its temperature and to keep this temperature artificially below a given temperature.

Air-conditioning means the treatment and handling of air to obtain well-defined values of temperature, humidity velocity and purity of the air in a confined space.

Refrigeration may involve very low temperatures which is not the case in the current applications of aid-conditioning where the temperature at the outlet of the air handling units is always higher than 0°C.

Different equipment and systems may be utilized for "producing the cold": vapour compressors, absorption machines and ejectors. However, only absorption machines will be discussed in this document as they represent the most convenient equipment to be associated with solar energy. Absorption machines may use a large variety of refrigerants, but only ammonia-water and water-lithium bromide will be discussed. These two aqueous solutions are the only ones which have been systematically and extensively studied for solar applications during a sufficient period of time and which represent a good potential for wide solar energy utilization.

Absorption machines can function either continuously or intermittently, however, in the intermittent machines only very small units may be envisaged and their flexibility is very poor.

It is now accepted that absorption machines heated by the sun may be inserted in existing heating and cooling systems without the need for major modifications.

Similar equipment such as: absorption machines, vapour compression chillers, evaporators, condensers, cooling towers, fans, pumps, etc., are utilized both in refrigeration and in air-conditioning. Both of these applications are studied in this chapter.

The comfort conditions accepted in residential and commercial premises depend mainly on the external conditions (temperature and humidity) and the activity, clothing, age, sex and duration of occupation of the area.

The external conditions vary with the time of the year, time of the day, pollution conditions, etc. No international standard yet exists for defining these conditions. They should therefore be defined very carefully. Selecting high external temperatures and low internal temperatures will lead to a very high cooling load which may be reached only during a few hours per year, for example this happens frequently in the Gulf area, and leads to:

- Very high installation cost;
- thermal shock; persons entering from the outside when temperatures are high, coming into a building where low temperatures prevail.

Reasonable internal and external factors should therefore be selected. It is well known that high temperatures and relative humidities are obtained during very few hours per day. In addition, the thermal inertia of the building may play a regulating role. Also, occupants may accept less comfortable conditions during some hours per day for a few number of days per year.

First Case Study: Cooling Load

In order to demonstrate that the designed cooling load in the current conventional air-conditioning practice may be largely reduced, if accepting certain reasonable restraints, we will consider the following typical example.

Basic systems and classification of air conditioning systems:

As an example, the following Figure XXXIV is given from a YAZAKI catalogue.

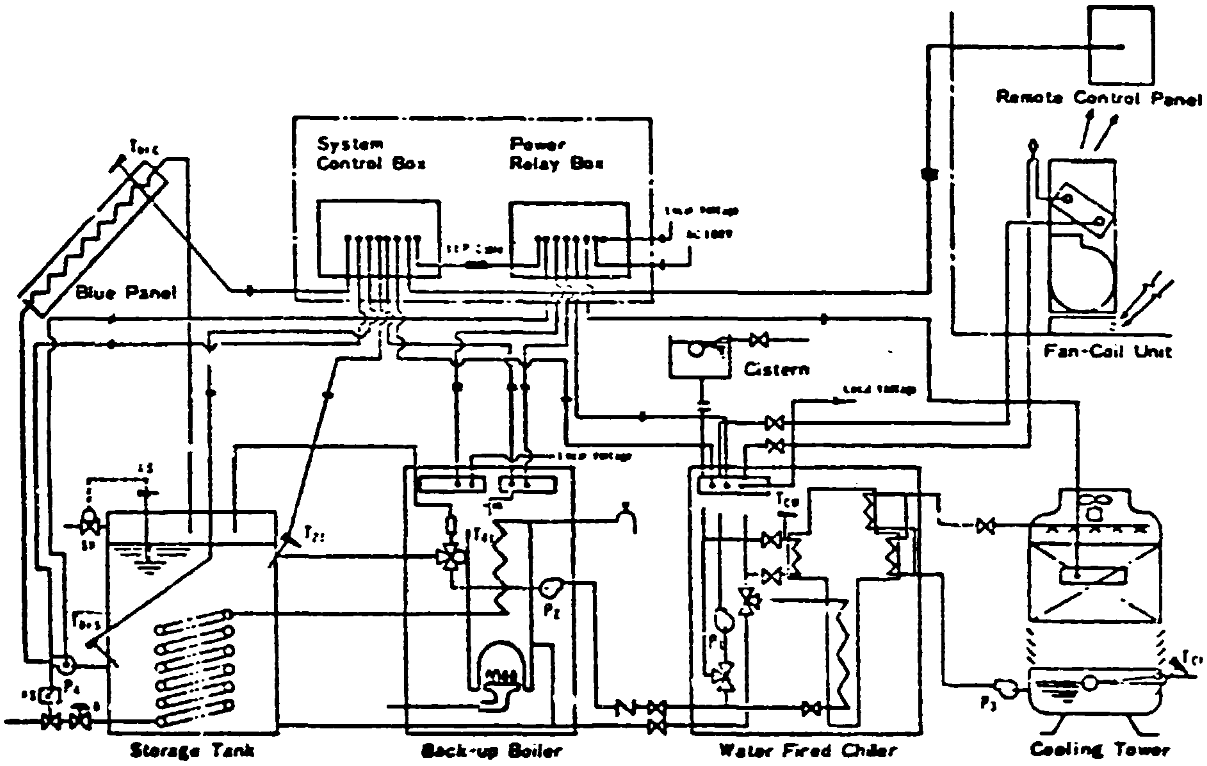


Figure XXXIV. Yazaki Basic Solar Air Conditioning System.

Air conditioning systems may be classified in various ways, the following classifications may be mentioned:

- By arrangement of equipment: centralized, semi-centralized and decentralized;
- By nature of fluids: a chilled water-air, freons-air;
- By utilized system: induction units, fan coils units, dual ducts;
- By kind of utilization: residential, commercial, industrial;
- By level of pressure: low, medium or high pressure;
- By number of pipes connected to the terminal units: 2 pipes (one supply and one return pipe), 3 pipes (one supply hot water, one supply chilled water and one common return), 4 pipes (one supply and one return hot water, one supply and one return chilled water).

The example No.11, chapter 28, ASHRAE Handbook of fundamentals, edition 1977, cooling load calculation will be discussed. Correction to outdoor design conditions for time of day and time of year will be based on Carrier system design manual, part 1, pages 1-18 and 1-19, ninth printing 1972 - Carrier Airconditioning CY-Syracus, New York.

- A one storey building of 80 x 50 feet is located in an Eastern state near 40 degree latitude, the summary of the cooling load calculation is:

"Outdoor conditions	94 DB	78 WB	0.0161 humidity ratio
Space conditions	75 DB	62.5 WB	0.0093 humidity ratio
Difference	19		0.0068

SENSIBLE LOAD		
Transmission	Btu/Hr	
Roof = ...	30,840	
S. wall = ...	3,060	
E. wall = ...	8,000	
N. wall exposed =..........................	910	
N. and W. party wall = ...	3,680	
Floor none		
Doors N. and E. = ...	780	
Doors S. = ...	920	
Transmitted Solar Radiation and Transmission		
S. glass (Table 35) =......................	3,480	
N. glass (Table 35) =......................	900	
Internal Load		
Infiltration 67 cfm x 1.08 x 19	1,400	
Lights (17500 x 1.20 + 4000) 3.41	85,100	
People 85 x 250	21,250	
	160,320	
TOTAL SENSIBLE SPACE LOAD		160,320
LATENT LOAD		
Infiltration 67 cfm x 4840 x 0.0068 = ...	2,210	
People 85 x 200 = ...	17,000	
TOTAL LATENT SPACE LOAD		19,210
Ventilation 1275 x 4.5 (40.30 - 28.25)= ...		69,140
GRAND TOTAL LOAD		248,670"

Comments: Roof Load

The global heat exchange coefficient U is equal to 0.12 Btu/ft^2.h.^{o}F which represents a good level of thermal isolation. However, if solar collectors were installed on the roof, the resulting shading will reduce the load.

The difference between the equivalent external temperature in the unshaded area and the internal dry bulb temperature is:

$\frac{30\ 840}{0.12\ (80 \times 50)} = 64.25^{o}F$ where the difference is

(94 - 75) = 19^{o}F in the shaded area. Indeed this latter difference is slightly higher.

Assuming that 65 - 80 percent of the roof area will be shaded by the solar collectors, a reduction of the load by about 15000 Btu/h may be estimated.

External walls load

The calculated load is 15650 Btu/h which represents about 6 percent of the total load. The U of the walls varies from 0.39 to 0.48 which is relatively high and may be easily reduced by a good isolation, however the saving will not affect the total cooling load very much.

Infiltration

It seems difficult to reduce the considered value of 67 cubic feet per minute.

Lighting

The installed 17500 W flourescent and 4000 W incandescent will give a high level of illumination, in the range of 500-600 Lux. The level of lighting depends on the characteristics of the illuminated premises (form, dimensions, colour) and the characteristics of the lighting devices and their arrangements.

However, 500 Lux is a relatively high level and this yields about 48 percent of the external cooling load (not including the fresh air load).

It may be reasonable to restudy the lighting system: it seems possible to reduce the resulting load by about 25 percent without affecting personal comfort conditions too much.

Ventilation:

Fifteen cu.ft.min. of fresh air per person is assumed in the example for ventilation purposes, this figure may be halved on the following assumptions:

- not all persons are smokers;
- all persons will not be present in the office at the same time;
- fresh air for ventilation is necessary to provide oxygen, extract CO_2 and dilute odours given off by occupants, smoking and other internal air-contaminants. Five cu.ft.min. per person is considered as the minimum for satisfactory dilution.

Assuming that the rate of ventilation is about seven cu.ft.min. and that all persons are not present at the same time, the load will be reduced by about 35000 Btu/h.

Occupancy

If a rate of occupancy of 80 percent is assumed, the heat load resulting from the occupancy (sensible and latent) may be reduced by:

$$85 \times 0.2(250 + 200) = 7650 \text{ Btu/h.}$$

Correction for outdoor design conditions:

Assuming that the daily range of temperature is 25°F and that the system will operate from 8 am to 8 pm, the average external dry bulb design temperature will be reduced by 3°F according to the above estimation. This represents $\frac{3}{19}$ = 15.8 percent, the difference between the designed external and internal dry bulb temperatures. The difference on designed wet bulb temperature will be reduced by 0.75°F. The percentage of reduction of the cooling load resulting from this correction will be less than 15.8 percent due to the equivalent temperature considerations.

Correction for time of year:

Assuming that the yearly range temperature is 60°F, the difference between the designed maximum external and internal dry bulb temperatures will pass from 19°F in July and August to:

April	May	June	July	August	September	October
12	17	18	19	19	17	14°F.

The maximum calculated cooling load capacity of 248670 Btu/h may be then reduced by:

15 000 Btu/h	Shading the roof.
20 000	Redesigning the lighting system.
35 000	Reducing the fresh air flow.
7 000	Reducing the number of occupants
77 000	Total

Concluding remarks:

Minimizing the cooling load is possible by more accurate calculations, insulation of roof and walls, optimizing the lighting system, minimizing the fresh air but keeping within the health requirements, accepting a small degree of comfort during a short period of the day during a few days per year, and relying on the thermal inertia (fly wheel effect) of the building. The estimated cooling load within the assumed conditions will be decreased from 248670 Btu/h (20.7 TR) to 172 000 Btu/h (14.33 TR) or about 30 percent.

Second Case Study: Kindergarten in Kuwait.

The Kuwait Institute for Scientific Research (KISR) has in 1980, in co-operation with the Ministry of Education, installed a solar absorption cooling system with the following objectives:

- Serve as a demonstrative plant.
- Study the durability and the weatherability.
- Get further experience in the design installation, operation and maintenance.

The conditioned space is a one floor building consisting of six class rooms with a total area of $550m^2$. The calculated peak cooling load is 30 TR (90 000 kcal/h). Four YAZAKI water LiBr (Lithium-Bromide) absorption chillers of 10 TR nominal capacity each are installed. 180 solar flat plate collectors of $1.9m^2$ each installed on the roof in saw-tooth arrangement are connected to a 25 cubic meter hot water storage tank at 85°C. A chilled water storage tank of $10m^3$ at 10°C is also provided.

The piping network is designed as an open (drain down) system to eliminate the possibility of water boiling in the collectors and reduce thermal losses during the night.

The condenser is water cooled and an electrical boiler constitutes the back-up energy supply.

In the absence of sufficient data on the design of the building, the lighting system and the occupants, it is not possible to discuss the load and the design of the air-conditioning system. However, the description of this project shows, in the light of the discussion of the first case study, that the designers of conventional air-conditioning systems in Kuwait are rather "generous" in terms of the cooling load. It shows also the importance of local conditions such as the dusty weather and the urgency of defining a reliable system for cleaning collectors. The back-up heating system is an electrical boiler, this solution is acceptable at the laboratory level, but absolutely unacceptable when designing a commercial system as it is not feasible to convert electrical energy into heat,and it is more economical in this case to shift to vapour compression chillers.

It is regrettable that we do not at present have the results of this research which will be very useful for a wide range of countries with similar climates.

Techno-economic Evaluation

Comparison between an ammonia-water and a water LiBr (Lithium-Bromide) absorption machine:

Both types of machines have been on the market for a long time and they are used for conventional applications in refrigeration and air-conditioning. The United States firm Carrier, for example, markets a large number of models of water-LiBr absorption chillers with cooling capacity going from 100 to 1000 TR. However, the systematic study for using absorption machines in solar refrigeration and air-conditioning is quite recent.

Among the advantages of the water LiBr machines when compared with the NH_3/H_2O machines, the following advantages may be mentioned:

- Non-inflammable and non-toxic fluid which permits the direct expansion of refrigerant;
- No need for rectifying equipment; only the water vapour is driven off;
- A higher coefficient of performance COP (ratio between output and the input energy) in the range of 0.7-0.8 versus 0.5-0.6 in case of NH_3/H_2O machines;
- Smaller pressure drop in the system;

- Commercially available at an acceptable price.

Among the disadvantages of water-LiBr machines, the following may be mentioned:

- Need for a relatively high temperature, 75°C. constitutes practically the minimum temperature at the outlet of solar collectors to have an acceptable efficiency of the system. Selective surfaces are needed to have temperatures in the range of 75-95°C. which allow an acceptable efficiency of the system;
- Crystallization may occur if the temperature of the solution reaches the temperature of crystallization;
- Ice manufacturing is not possible with the LiBr machines as practically the temperature of the chilled water does not go under 4 to 5°C. (evaporators cannot operate at a temperature much below 4°C. since the refrigerant is water vapour);
- Need of a source of water for cooling the condenser, which represents an inconvenience in areas with limited sources of water .

The solar ammonia-water systems are in a less advanced stage of development, they are bulky and they need more external electrical/ mechanical energy for operating the pumps. A rectifying colon is needed to assure that no water vapour mixed with NH_3 enters the evaporator where it could freeze.

Ammonia is not recommended to be used in air-conditioning applications as there is a hazard of leakage. Also, ammonia should not be stored or used in dwelling areas.

Energy Saving by Utilizing Solar Absorption Machines

When considering a solar absorption machine it is very important to define the cooling capacity to be considered. Indeed the nominal capacity of the machine which is given generally at:

t_1 : 195°F (90.55°C) hot water inlet temperature.

t_2 : 85°F (29.44°C) condensing cool water inlet temperature

t_3 : 55°F (12.78°C) chilled water inlet temperature.

t_4 : 45°F (7.22°C) chilled water outlet temperature.

These temperatures are not often reached. To illustrate the difference between the actual and the nominal capacity, the following is extracted from a 25.5 TR ARKLA catalogue.

t_1	t_2	t_4	TR
195	80	45	28.7
195	85	50	27.4
195	85	45	25.5(nominal)
195	90	45	19.8
180	85	50	20.5
180	85	45	18.7
180	90	45	16.3

The above-mentioned figures permit, in this specific example, the following remarks:

If accepting a chilled water outlet temperature of 50°F instead of 45°F, the cooling capacity will increase by about 7 percent over the nominal capacity The increase of the chilled water temperature will require the increase of the air flow, which means a higher pressure drop in the air ducting system.

If a lower condensing water inlet temperature is available, the cooling capacity will increase by about 12.5 percent when passing from 85 to 90°F.

If a higher condensing water inlet temperature is available the cooling capacity will decrease by about 12.5 percent when passing from 85 to 90°F.

If keeping constant the inlet condensing temperature 85°F and the chilled water temperature 45°F, but decreasing the feeding hot water temperature to 180 instead of 195°F, the cooling capacity will decrease by about 20 percent. If in addition to decreasing the inlet hot water temperature the cooling temperature is increased to 90°F instead of 85°F, the cooling capacity becomes about 64 percent of the nominal capacity.

From the above discussion the importance emerges of having high water temperature to feed the machine and low water temperature to cool the condenser (Carnot efficiency).

To have an approximate idea about the energy saving, a fictive example with the following assumptions is considered:

A 20 TR vapour compression chiller and a 20 TR water-LiBr absorption will be compared.

The installed electrical energy is about 30 kW in case of the reciprocating compressor chiller and 4.5 kW in the case of the LiBr machine.

The cooling tower will require about 1.5 kW more for the LiBr machine than the vapour compressor chiller.

It is assumed that the air-conditioning system will operate continuously 180 days/year and that the energy consumption will be on average 50 percent of the maximum cooling load of 20 TR then: the electrical energy savings will be about:

$$180 \times 24 \times (30 - 6) \times 0.5 = 51840$$ or about 50 000 kWh/year or 2500 kWh/TR.year.

This result supposes that the system is working continuously with solar energy and without any back-up conventional energy.

Some Guidelines for Designing Solar Air-Conditioning Systems

Designing a solar air-conditioning system requires the adaptation of the system to the daily pattern of sun radiation temperature and humidity, also the means of heat rejection bearing in mind the specific conditions of the building, the occupants and the type of utilization. However, it seems reasonable to take into consideration a certain number of important factors of which the following may be mentioned:

- Adaptation of "reasonable" design conditions for external and internal dry bulb and wet bulb temperatures;
- Acceptance of a "reasonable" degree of discomfort during short periods;
- Careful examination of the storage factors, space temperature swing and diversity factors;
- Use of the shading factors;
- Careful design of the lighting system;
- Maximizing the solar collection by the increase of the solar collectors area and/or by improving the efficiency of collection and optimizing the inclination degree of the flat plate collector according to the location and to the utilization in the summer time;
- Considering carefully the storage of hot water and eventually chilled water, or other storage media (pebble bed for example)
- Minimizing the electrical energy required to operate the pumps and the fans by a judicious selection of the equipment and the arrangement of this equipment;
- Combining solar heating and sanitary water heating with the air-conditioning when this is possible;
- Location of hot water storage tanks out of the air-conditioned area. It is more economical to loose heat during the heating period than to "produce cold" during the cooling period.

The chilled water inlet temperature should be studied taking into consideration that the sum of energy consumed by the pump(s) and the fan(s) for the air handling unit(s) will be optimal. Indeed the air flow may be continuous where the chilled water flow may be intermittent. Another factor to be considered is the rated capacities of the chiller absorption machine which depends on the chilled water outlet temperature as already mentioned.

- The control system should be designed very carefully as it greatly influences consumption.

- Sophistication should be avoided when this does not greatly influence the electrical energy consumption.

Comments

Solar refrigeration and air-conditioning systems are presently technically feasible and they are for certain applications, commercially available. They utilize, to a large extent, conventional equipment and they need external energy, mechanical or electrical, for operating the fans and pumps.

In case of absorption water-LiBr machines, an external source of cold water is needed for cooling the condenser, and if the water is to be recirculated (which happens in the majority of cases) a cooling tower is required.

Except in particular cases where a large heat storage system is provided and intermittent utilization is accepted, a back-up system of conventional energy is required.

The system becomes more economical when it is combined with space heating and domestic water heating.

The energy saving may attain some 2500 kWh/TR per year.

The cost of a solar absorption machine is presently about 1.5-2 times the cost of equivalent vapour compression chillers.

The high cost of the system is mainly due to the solar collectors and heat storage. For example, the cost in the gulf area is in the range of $1600/TR for a conventional chilled water system and may raise to $7000/TR for a solar system.

Solar air-conditioning may be provided only for one floor, and in particular cases, for two floor buildings if the solar collectors are installed on the roof.

The commercial feasibility of solar refrigeration and air-conditioning system is not expected in the short-term.

IV. SOLAR SPACE HEATING AND DOMESTIC WATER HEATING SYSTEMS

General Information

Solar space heating and domestic water heating systems are presently being developed in industrialized countries. The consumption of energy for these two applications is an important part of the total consumed energy, it goes from a few percent in Spain, 20 percent in the USA, up to about 60 percent in Scandinavian countries. In France, for example, the number of solar water heaters was about 20,000 units in 1979 and the prediction of the Commissariat Energie Solaire is 600,000 units in 1985.

Solar space heating and water heating equipment belong now to a well established technology and, excepting the solar collectors, it utilizes mainly conventional equipment. The heat storage still represents a problem when utilizing the latent heat.

Heating capacity for heated spaces depends on a large number of factors including: location, climatic conditions, orientation, dimensions, materials and specifications of the building, type of utilization, intermittent or continuous operation, degree of comfort, etc.

When designing a space heating system, the designer should first of all take the maximum advantages of passive heating. Thermal insulation is now widely used in industrialized countries and some of them have already issued regulations for improving the insulation of new buildings with a total heat exchange factor U not exceeding 0.6 Kcal/m^2.h.°C. for the walls and 0.4 for the roofs. In some countries the degree of comfort has been regulated in public and commercial buildings with a maximum internal temperature of 18°C. These measures are promoting the insulation industry (fiber glass, polyurethane, polystyrene...) and influencing the construction of prefabricated buildings. Double glazing and air filtration already constitute a real concern for architects and space heating designers.

Although passive heating is of prime importance, it will not be discussed further in this chapter, as it does not involve solar equipment manufacturing.

Solar space heating may be obtained with air or water by natural or forced convection (fans/pumps) and this requires the utilization of solar collectors and heat storage through sensible (water, pebble beds) or latent heat (chemical).

The technology of solar collectors is now well established and production is slowly starting. The technology of heat storage chemicals is not yet technically feasible, however, the R and D in this field is promising.

The economic feasibility of solar space heating and domestic water heating depends on the local and specific problems and the definition of economics. When considered at the socio-economic level, solar space and water heating is often feasible, but this is not often the case when speaking about the commercial feasibility. However, it is necessary to make feasibility studies case by case or at least by type of building in a given area.

Third Case Study: Solar House I in Colorado State University

This case study is extracted from Phil. Trans. R. Soc.Lond.A 295, 349-345 (1980), solar space heating with air and liquid systems, by G.O.G. Lof. Solar Energy Applications Laboratory, Colorado State University, Fort Collins, Colarado 80523, U.S.A.

"Solar House I in the Solar Village at Colorado State University has about 130 m2 of floor space on the first floor and an equal area in the basement. Both floors are heated and cooled. The south wall of the basement is above grade while the north wall is below grade. Collectors are mounted on the roof and tilted at 45° from horizontal and face southward; the storage and mechanical equipment for heating and air conditioning are located in the basements. The building is used as offices for the staff and graduate students of the Solar Energy Applications Laboratory and is occupied nearly every day. The heat demand, at an outdoor temperature of -23°C is 17.5 kW.

System Characteristics - Liquid system: Solar House I

The solar heating and cooling system in C.S.U. Solar House I has been in operation since August 1974. The solar heating and cooling system, shown schematically in figure 1, consists of flat-plate, liquid-heating collectors, water storage, lithium bromide absorption chiller, and gasfired auxiliary water boiler. The double glazed, site built, non-selective collectors occupy an overall roof area of 71.3 m2 with an absorber area of 67.0 m2. Solar heat is stored in an insulated steel water tank of 4275 l capacity. Figure 1 shows a domestic water heating system consisting of 364 l preheater tank and a 150 l conventional gas-fired hot water tank. A 50 per cent solution of ethylene glycol and water flows through the collectors and is spread from the storage tank fluid with a counterflow heat exchanger.

The cooling unit is an Arkla Solaire WF-30 absorption water chiller with a charge modified from 52 to 50 % lithium bromide to match cooling water temperatures usually prevailing at this location. In the commerical version, the chiller has a design point of 38 MJ/h at typical cooling water temperatures of 29°C. The C.S.U. chiller has a capacity of 50 MJ/h at a coefficient of performance (c.o.p.) of almost 0.8, and it can be operated at generator temperatures as low as 66°C with a corresponding capacity of 20 MJ/h.

During November and December 1976, an additional set of evacuated tube collectors (made by Corning Glass Works) was mounted on a test bed adjacent to Solar House I. The set of collectors on the test bed consists of 36 modules and each module has six evacuated tubes, with a total absorber area of 1.11 m2, that covers a mounting area of 1.92 m2. When mounted on the test bed, the gross area required for collectors and manifolds is 75.2 m2 although the total absorber area is 39.9 m2. There is a separate storage tank with 4275 l capacity for the evacuated tube collector system.

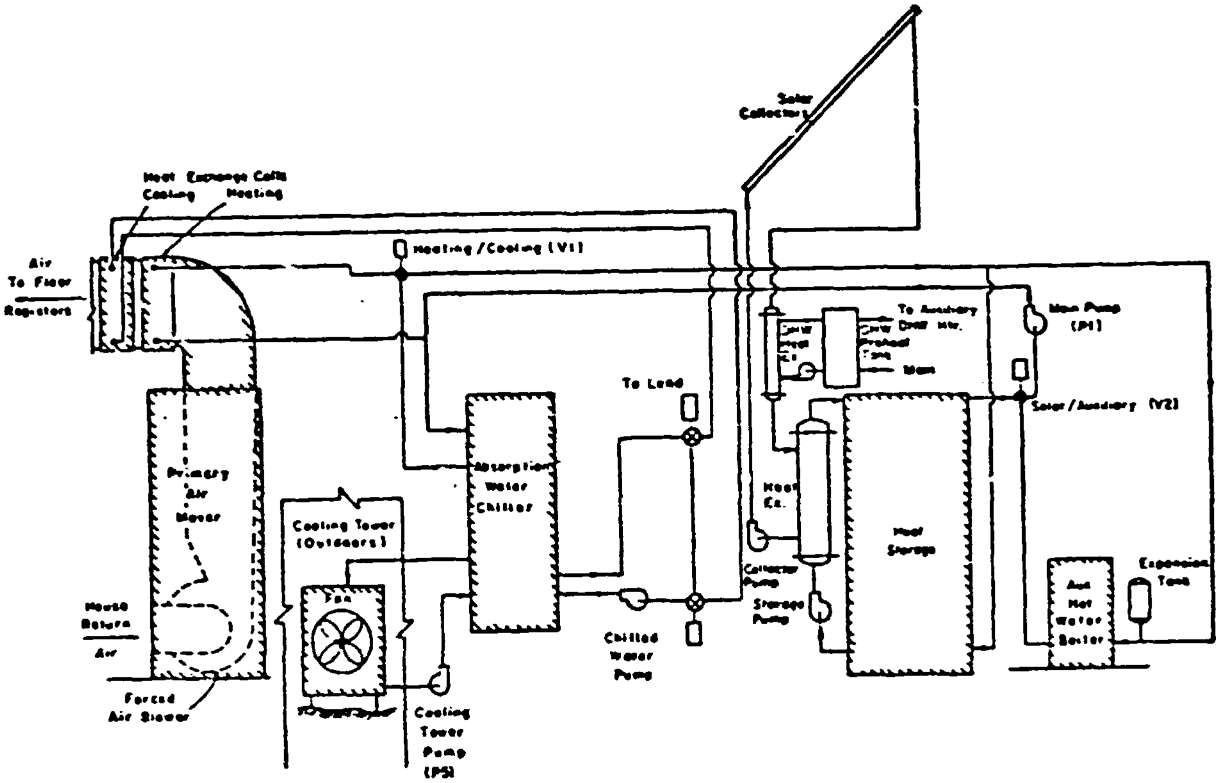


FIGURE 1. Solar House I heating, air conditioning and hot water equipment.

The piping and accessories are arranged so that either the flat-plate collectors on the building roof or the evacuated tube system can deliver heat to the same space and domestic hot water loads in House I. In October and November 1976, the flat-plate collector on the house roof was used, and in the following months, the Corning evacuated tube collector was used.

The house is heated by air from a heat exchanger supplied with solar heated water from the thermal storage tank or from an auxiliary boiler. Cooling requirements are met by use of cold water circulated from the Arkla chiller or from cool storage. The use of cool storage was found to be a negligible advantage, so was discontinued. Heat energy is supplied to the chiller by hot water either from thermal storage or the auxiliary boiler. Heat rejection from the chiller is to water circulated through a cooling tower outside the building. Service hot water is heated by exchange with the hot collector fluid and stored in a 364 l (80 gallon) tank followed by a conventional gas-fired water heater. Heat is transferred to the main storage by circulating a non-freezing solution of ethylene glycol through the collector and through an exchanger in which water from storage is heated.

TABLE 1. MONTHLY AND ANNUAL AVERAGES OF DAILY ENERGY QUANTITIES (MJ/DAY) AND FRACTIONS, SOLAR HOUSE I

month and year	total solar†	solar to storage‡	solar to load	solar to heating	auxiliary to heating	solar to hot water	auxiliary to hot water
Oct. 1976	1404	191	183	65	0	47	61
Nov. 1976	1086	139	174	124	113	43	60
Dec. 1976							
Jan. 1977	1087	415	396	360	110	36	52
Feb. 1977	1149	360	379	338	37	41	60
Mar. 1977	1394	566	285	229	12	57	41
Apr. 1977	852	297	227	108	20	119	84
May 1977	—	—	—	—	—	—	—
June 1977	—	—	—	—	—	—	—
July 1977	—	—	—	—	—	—	—
Aug. 1977	1287	439	417	0	0	73	47
Sept. 1977	1584	537	452	0	0	50	38
f.p.c.	1248	175	179	94	56	47	61
e.t.c.	1227	436	359	259§	45§	63	54

month and year	solar to cooling	auxiliary to cooling	solar fraction heating	solar fraction cooling	solar fraction heat and cool	data base days	solar fraction hot water
Oct. 1976	71	64	1.00	0.53	0.68	28	0.44
Nov. 1976	4	0	0.52	1.00	0.53	19	0.43
Dec. 1976							
Jan. 1977	0	0	0.77	—	0.77	20	0.40
Feb. 1977	0	0	0.90	—	0.90	12	0.41
Mar. 1977	0	0	0.95	—	0.95	29	0.58
Apr. 1977	0	0	0.86	—	0.86	21	0.63
May 1977	—	—	—	—	—	—	—
June 1977	—	—	—	—	—	—	—
July 1977	—	—	—	—	—	—	—
Aug. 1977	344	459	—	0.43	0.43	13	0.61
Sept. 1977	402	236	—	0.63	0.63	17	0.57
f.p.c.	38	32	0.63	0.54	0.60	24	0.43
e.t.c.	373‖	348‖	0.85	0.52	0.67	19	0.54

f.p.c. = flat plate collector average, Oct.–Nov. 1976.
e.t.c. = evacuated tubular collector average, Jan.–Sept. 1977.

† Based on 75.2 m^2 gross collector area Jan.–Mar. and Aug.–Sept.; 25.1 m^2 8 days, 50.1 m^2 4 days, and 75.2 m^2 9 days, all in April; and 71.3 m^2 gross collector area for Oct.–Nov.

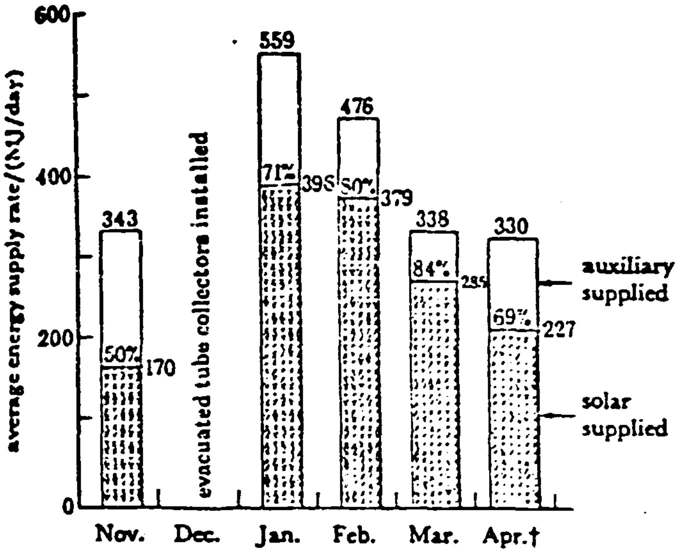
‡ Solar to storage includes solar to hot water.

§ Averages for four winter months only.

‖ Averages for two summer months only.

Performance of Systems - Liquid systems thermal performance: Solar House I

A summary of monthly and annual energy use for space heating, domestic hot water (d.h.w.) heating, and space cooling is presented in table 1 and figures 3 and 4. The collector performance is presented in figure 5. The first two months of data were obtained with the system employing flat-plate collectors, whereas heating and cooling during the following ten months were supplied by the evacuated tube collector system.



† Note reduced collector area for part of April as defined in table 1.

FIGURE 3. Solar and auxiliary contribution to total space heating and d.h.w. heating in Solar House I, 1976–7 heating season.

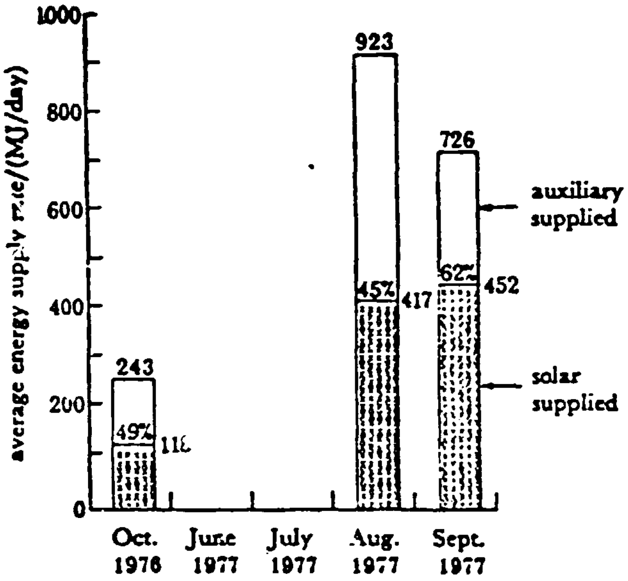


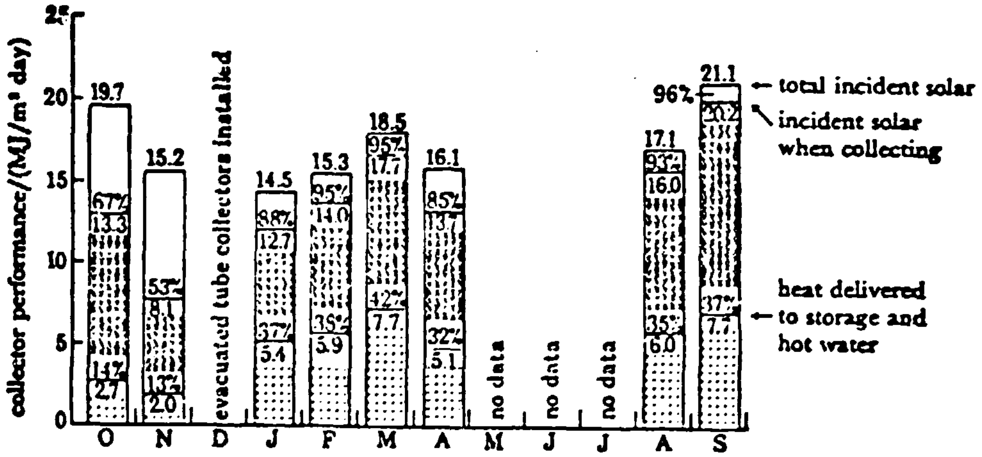
FIGURE 4. Solar and auxiliary contribution to space cooling and hot water heating in Solar House I, 1976–7 cooling season.

Solar collection and solar space heating were usually low in November. In previous years, a similar (but not identical) system with the same collector provided more than 90 % of the space heating in November, rather than about 50 % supplied in 1976. This difference is largely accounted for by unusually severe weather conditions on 12-15 November and 27-30 November 1976.

Following the installation of the evacuated tube collector. the performance of the system increased by a sizeable amount. Figure 3 shows that over 70 % of the heat required for hot water and space heating were supplied by solar. Of the 51034 MJ required for these uses in the January-April period, solar provided 75.5 %.

Hot water heating

The solar contribution to hot water supply in October and November was roughly half its share in previous years. As indicated below, similar results were obtained with the evacuated tube collector. The decreased solar heat delivery to hot water is due to moving the hot water exchanger to the collector loop. Formerly, water was solar heated whenever main storage temperature was sufficient. The new design provides solar heated water only when collection is possible and when collection temperature is below main storage temperature. The frequency and duration of this dual occurrence are insufficient for the heating of a large fraction of the water supply. Although this design prevents depletion of needed temperatures in main storage, important for cooling operations, the loss of water heating capability (particularly when heat in storage is not needed for other uses in spring and fall), is greater than the gains from increased solar heating and cooling. Return of the hot water exchanger to storage heat supply has therefore been decided.



Data based on 71.3 m^2 flat-plate collector area and 75.2 m^2 evacuated tube collector area, both equal to total occupied area, including space for manifolds.

† Collector area reduced during April, 4 days at 50.1 m^2, 8 days at 25.1 m^2, 9 days at 75.2 m^2.

FIGURE 5. Collector performance of the liquid system in Solar House I.

Liquid collector comparison

Comparison of the data on the system employing evacuated tube collectors with the flat-plate results shows, in figure 5 and table 1, (a) high solar collector efficiency, and high fraction of space heating load carried by solar energy from the evacuated tube collector; (b) higher solar hot water delivery, but less than can be obtained by relocating the hot water exchanger; and (c) over half of the large cooling requirements met by solar.

Radiation data are based on total area occupied by the evacuated tubular array, about half of which is effective absorber area. Based on this total area, the fraction collected is about double the flat-plate figure. Per unit absorber area, the improvement is nearly fourfold.

Cooling comparison

Although very limited cooling data were obtained with the flat-plate system in October, it is evident that major improvements resulted from the change to evacuated tube operation. The portion of the cooling load carried by solar was about 50 % (compared with 45 % and 62 % in August and September 1977), but the August and September cooling loads were over five times as great as in the previous October. The solar supplied to cooling, 417 and 452 MJ/day in August and September, at an averate c.o.p. of 0.6, provided about 63 kWh per day, which would normally be sufficient for a comparable residence in the Fort Collins summer climate. The much higher cooling demand in C.S.U. Solar House I is due to heat losses from the storage tank and other hardware in the equipment room, high electricity use for instruments, motors, and lighting at office intensities, and to heat generation by two or three times the normal residential human occupancy."

Comments

Combining solar space heating and cooling with domestic hot water improves the feasibility of the project.

Installing evacuated tubular collectors gives a better efficiency of solar collecting, however manufacturing this type of collector for this kind of application may not be feasible in the near future. Also manufacturing evacuated tubular collectors requires special and costly equipment. When a higher temperature is really needed, selective coating may constitute at present a more economical solution.

The feasibility of this solar application is, as is the case for other solar applications dependent mainly on the availability, storage, distribution and cost of conventional energy at the individual and national level.

In this case we will only discuss the economics of solar heating by making some assumptions to show in a simple and approximative way its value in energy savings.

Based on table 1 and considering the period October 1976-September 1977, we assume that the contributions of solar energy in December 1976 and January 1977 were equal, we also assume that the solar contribution to the domestic hot water was on average 120 Mj/day during May, June and July 1977.

Annual solar energy to space heating:

30(65 + 124 + 360 + 360 + 338 + 229 + 108) = 47520 Mj/year.
(heating season is 7 months).

Annual solar energy to domestic hot water:

30(47 + 46 + 46 + 36 + 41 + 57 + 119 + 3   120   73 + 50) = 26250 Mj/year.

The total energy saving is then 73770 Mj/year, assuming that the calorific value of the fuel is 10,000 Kcal/Kg and that the global efficiency of the boiler is 75 percent, the quantity of fuel saved annually will be:

$$\frac{73770 \times 1000}{4.18 \times 10{,}000 \times 0.75} = 2353.1 \text{ Kg.}$$

(Say 2.5 tons of fuel/year).

In this example it seems possible to increase the area of solar collectors or their efficiency in order to minimize the quantity of conventional energy needed, it is also possible to enlarge the heat storage system. A seasonal storage (underground storage) may be envisaged when no conventional back-up heating is desired. If the air-conditioning system is not required, the hot water can be circulated directly in radiators or in fan coils. However, air heating should be compared with water heating before selecting the last one.

In order to show the merits of solar heating, the following preliminary comparison is made.

If we consider, for example, that the cost of solar collectors is $100 per installed square meter and that the cost of storage system, extra piping, pumps and control equipment is about 30 percent of the cost of solar collectors, the additional investment for the solar system is about $10,000.

If we consider that the present cost of fuel is $0.3/Kg or about $7.5 per million Btu (the present cost in USA is $\$2\text{-}3/10^6$ Btu) and that the escalation in the cost of fuel is equal to the discount rate (12 percent for example), the net presaat value of the saved oil during 15 years (the expected life time of the solar system) will be approximately equal to the additional investment and maintenance cost of the solar system.

This result is rather promising, in the light of the expected decrease in the cost of solar collectors by mass production and the expected increase in fuel cost by more than 12 percent annually.

Economics of Solar Hot Water Heating:

Regarding the solar hot water heating, it seems appropriate to give some extracts from M. Stuart's paper as follows:
"An assessment of solar hot water heating in the Washington D.C. area, application for local utilities", Solar Energy Vol.5. pp. 331-342, 1980, we give the table below representing the payback analysis in the Boston area:

"Economic measures for solar hot water systems in single family homes; source of data: USDOE/CS-0023, 1978, p.11, Table 2

	Electricity is the Alternative		Fuel Oil is the Alternative		Natural Gas is the Alternative	
	Without Tax Credit	With Tax Credit	Without Tax Credit	With Tax Credit	Without Tax Credit	With Tax Credit
Boston						
Payback	15	13	23	21	21	20
Yrs to cover downpayment	8	1	18	12	18	14
Yrs.to + cash flow	1	1	8	8	9	9

"

From the Building Research Establishment Information paper, August 1981: cost and performance of solar water heating systems in the UK, by Wozniak - we extract the passage regarding the system costs: -

" (a) Installed costs of 4.5 m2 solar collector systems in the field trial at Basingstoke, Lincoln and York

(b) Possible future costs

	£ (a)	£ (b)
Installation work	390	190
Solar collector	270	190
Steelwork for roof	82	50
Lead flashing for roof	70	
Copper cylinder (227 l)	67	50
Control system	39	20
Pump	20	20
Pipe	12	10
Incidentals	20	20
Total (1979 prices)	970	540
	= £215/m2	= £120/m2

"

V. SOLAR LABORATORIES IN DEVELOPING COUNTRIES

Solar Radiation and its Measurements

Solar constant

The sun may be considered as a continuous fusion reactor with an effective surface temperature of 3762 K. Radiation can be considered as a vehicle of energy by electromagnetic waves or as a vehicle of heat by photon or quanta of energy.

The quantity of solar radiation received at the earth's surface is a function of the time of the year, the time of the date, the location expressed by the latitude, the meteorological and the pollution conditions. Solar energy approaches the earth by electromagnetic radiation ranging from 0.1 to 100 microns, however, in the current applications of solar energy, only the range 0.3 to 50 microns is taken into consideration and about 99 percent of this energy is contained between 0.28 and 4.96 microns.

The solar constant, defined as the solar radiation on a surface normal to the sun's rays beyond the earth's atmosphere at the earth's mean distance from the sun. The most probable value based on rockets and satellite measurements is 1353 $w.m^{-2}$. Due to the elliptical form of the orbit, this constant varies slightly from 1399 $w.m^{-2}$ on 1 January to 1309 $w.m.^{-2}$ on 5 July.

Solar radiation components

The total solar radiation Q is composed of three components:

Q_n direct normal incident radiation on a normal surface to the sun, θ angle between a normal to the receiving surface and the incoming solar ray
Q_d diffuse radiation
Q_r direct solar radiation reflected (from adjacent surfaces).

$$Q = Q_n \cos \theta + Q_d + Q_r$$

Short-wave radiation:

This radiation consists of three components:

direct components of sunlight;
diffuse components of skylight;
reflected components from natural surfaces.

The short-wave radiation is usually in the range of 0.3 to 5 microns, practically from 0.3 to 3 microns.

When measuring direct and diffuse components of solar radiation on a horizontal surface, the result is the global radiation.

The short-wave radiation is measured with a pyronometer which may measure:

- global radiation,
- diffuse radiation (with the incorporation of a shading arrangement to screen off the sun),
- reflected radiation (albedo).

With a special arrangement, the above mentioned components may be measured in defined wavelength bands. The direct short-wave is attenuated by absorption, of oxygen, ozone, water vapour, carbon dioxide and by reflection from dust, emission particles and water droplets and by *scattering of air molecules.*

Long-wave terrestrial radiation

The long-wave terrestrial radiation is usually in the 3 to 100 micron range, practically from 4 to 50 microns. Its consists of:

- Incoming atmospheric components (downward emission by the gas of the atmosphere: water vapour, carbon dioxide...);
- Outgoing components (upward emission and reflection by natural surfaces and atmospheric gases). It is impracticable to separate long-wave emission and reflection.

The long-wave radiation is measured with a pyrogeometer. It measures fundamentally the balance of radiation between a horizontal blackened surface (detector) and the target viewed (sky or ground).

With a special arrangement the device can eliminate the radiation emitted by the detector.

A special pyrogeometer, called a radiometer, is a device for measuring radiation (infrared).

Classification of solar measurement instruments

The World Meteorological Organization (WMO) has defined four class instruments: reference standard, first class, second class and third class. Refer to page 135 of ref.23. In table 2 below the following terminology is used:

- Pyranometer: for measuring global solar radiation.
- Pyrheliometer: for measuring direct solar radation at normal incidence.
- Pyrradiometer: for measuring both solar and terrestrial radiation.

Characteristics of some commercially available solar measuring instruments : Terminology.

Pyranometer

It measures global (total sun and sky) radiation.

Spectral pyranometer

It measures the sun and sky radiation totally or in defined wavelength bands.

It can also measure reflected shortwave radiation (albedo).

With the incorporation of a shading arrangement to screen off the sun, the diffuse sky component may be measured.

Normal incidence pyrheliometer

It measures total or spectral direct solar intensity.

For periodic readings, the pyrheliometer should be attached to a mount with provision for varying the elevation and the azimuth settings.

Table 2. Classification of accuracy of solar radiometers.

	Sensitivity (mW cm^{-2})	Stability (%)	Temperature (%)	Selectivity (%)	Linearity (%)	Time constant Max.	Cosine response (%)	Azimuth (%)	Errors in auxiliary equip. Milliameter Galvonometer	(%)	Coronometer
Reference standard pyrheliometer	± 0.2	± 0.2	± 0.2	± 1	± 0.5	25s	---	---	0.1 unit	0.1	0.1s
Secondary instruments											
1st class pyrheliometer	± 0.4	± 1	± 1	± 1	± 1	25s	---	---	0.1 unit	0.2	0.3s
2nd class pyrheliometer	± 0.5	± 2	± 2	± 2	± 2	1 min	---	---	0.1 unit	±1.0	---
									Errors in recording apparatus		
1st class pyranometer	± 0.1	± 1	± 1	± 1	± 1	25s	± 3	± 3		± 0.3	
2nd class pyranometer	± 0.5	± 2	± 2	± 2	± 2	1 min	±5-7	±5-7		± 1	
3rd class pyranometer	± 1.0	± 5	± 5	± 5	± 3	4 min	±10	±10		± 3	
									Errors due to wind %		%
1st class pyrradiometer	± 0.1	± 1	± 1	± 3	± 1	1/2 min	± 5	± 5	± 0.3		± 3
2nd class net pyrradiometer	± 0.3	± 2	± 2	± 5	± 2	1 min	±10	±10	± 0.5		± 5
3rd class net pyrradiometer	± 0.5	± 5	± 5	±10	± 3	2 min	±10	±10	+ 1		±10

Source: "Guide to Meteorological Instruments and Observing Practices", WMO Publ. No. 8 TP.3, 4th ed., Geneva, 1971.

For continuous record, the pyrheliometer must be on a power driven equatorial mount.

Infrared radiometers or pyrgeometer or longwave radiometers:

It measures unidirectional terrestrial longwave radiation.

Ultraviolet radiometer (photometer):

It measures sun and sky ultraviolet radiation.

Absolute radiometer:

It measures the thermal radiation in a given spectral range.

Albedometer:

It measures the shortwave radiation balance or albedo over surfaces of different natures. It consists of two identical solarimeters, one measures the incident solar radiation, and the other measures the radiation reflected by the surface.

Total values of the net energy received over given periods of time can be obtained by means of a solarimeter integrator or a printing electronic integrator.

Pyrheliometer:

It measures accurately the direct solar radiation. It also enables the calibration of secondary pyrheliometer and pyranometers.

Actionometer:

It measures the direct solar radiation and also the effective temperature radiation.

Solar Laboratory Equipment and Materials

Equipment and materials necessary for a solar laboratory depends mainly on the objectives assigned to such a laboratory. Among the large number of factors to be taken into consideration when equipping a solar laboratory, the following are the main factors to be considered:

(1) Scope of activities of the laboratory;
(2) Local meteorological conditions;
(3) Size and features of the country;
(4) Existing facilities in the field of meteorological activities;
(5) Existing R and D institutions;
(6) Scientific and technical personnel;
(7) Level of industrial development;
(8) Available investment for the installation and operation.

Based on the reports of several UNIDO assignments undertaken by the author in various developing countries and in particular on one mission to Jordan and one joint mission to Mali with Mr. C. Mustacchi (3) the following preliminary list of equipment and materials is proposed. This list may be reduced or increased according to the scope of solar activities to be carried out.

The proposed equipment and materials will enable the laboratory to:

- Measure and in certain cases calibrate and record temperature, pressure, velocity, flow, viscosity, density, electrical intensity, voltage power and resistance, heating and refrigerating capacities, solar radiation, wind direction and speed;
- Manufacture elementary/rudimentary components or solar equipment;
- Test solar equipment;
- Undertake a certain level of activity in solar R and D.

A budget estimate for the proposed equipment and materials is in the range of $US 70,000 (1981 dollars).

Quantity	Measuring instruments and laboratory equipment and materials
1	Spectral pyranometer, precision, with hemispheres
1	Pyranometer, black and white
1	Shadow band stand
1	Pyrheliometer, normal incidence
1	Solar tracker
1	"Montage equatorial"
1	Pyrheliometer, Angstrom Electrical Compensation, with control unit

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(3) Consultant, Analysis and Development of Energy Systems, Rome, Italy.

2	Recorder, single point, continuous line Speedomax, Leeds and Northrup, model H or W, or equivalent for use with pyranometers and radiometers
10	Thermocouples, chromel-alumel, stainless steel shielding, 3 mm external diameter, 20 cm length
2	Sets of temperature-sensitive pencils
1	Ultraviolet Radiometer.
1	Precision Infrared Radiometer.
1	Contact thermometer with thermistor, probes and indicator instrument 2 or 3 scale bases, for temperatures of -10°C to 200°C - 8502 - 20, Cole-Palmer, or equivalent
60m	Chromel-alumel wire, insulated with teflon, asbestos or glass fibre, 24 B and S gauge
20	Male/female connectors for thermocouples
1	Accessory kit for thermocouples
2	Kits for cementing thermocouples, Thermocoat kit
4	Reference compensators for chromel-alumel thermocouples, 0°C or 60°C. Precision, approximately ± 1/2°C.
2	Digital-display meters for chromel-alumel thermocouples, resolution to four figures, error + 3°C., with 0.1 percent internal compensation
1	Salinity measuring instrument (brakish water)
1	Salinity measuring instrument (brine)

1	Salinity measuring instrument (potable)
3	Sets of different solar photovoltaic panels about 1 m^2 each
2	Digital multimeters accurate to ± 1 percent, with accessories
1	Set of flow meters with float for water and gas (Water, maximum 2 l/min.; gas, maximum 50 l/min.)
1	Thermistor psychrometer, precision to 1 percent
2	Recorder of temperature and relative humidity, with paper and ink
2	Laboratory chronometers
2	Viscosimeter: one up to 15 cp and one 5 - 300 cp
lot	Laboratory glassware (beakers, pipettes, etc.)
1	Anemometer (protable)
1	Universal potentiometer for thermometry, Type K-5, Leeds and Northrup, or equivalent
1	Anemometer with recorder
1	Micrometric manometers, scale base 20 mm water, Set of Pitot probes, for total pressure and static pressure, sensitivity - 0.02 mm
10	Set of mercury thermometers accurate to ± 0.1°C., with various scale bases
10	Bourdon manometers, with various scale bases
2	Wet-and-dry-bulb thermometers

2	Maximum-minimum atomospheric thermometers
1	Tektronix double trace oscilloscope, low frequency, with accesscries
1	x-y recorder, variable scale base, 1-100 mV input resistance > 100 k 52 Ω with paper, ink and spare pens
2	Vernier sliding calibers, Precision, 1/20 mm
1	Micrometer - - - - - - - } 1/100 mm precision, 25 mm spindle travel
1	Electronic tachometer 0-12000 RPM
10	Two-meter metal measuring bands
4	Ten-meter metal measuring bands
3	Hot water circulators ($90^{\circ}C$), minimum 3 m^3/hour, 3 m manometric head
1	Steam generator electrically heated, 7 bars, 10 Kg/h
2	Rotary mechanical pumps (50 Hz, 220V) for vacuum better than 100 microns Hg, with ballast Flow: 150 l/min. With 20 litres of oil With Pirani head and meter (measurement range: 500-0.1 microns)
2	Manual volumetric pumps, in carbon steel or cast iron for ammonia, butane or other charge, 10 l/min., at 30 atm
6 m^2	A selection of 6 metal collector elements, 1 m^2 each, including: 2 carbon steel sheet (central heating radiator elements) 2 roll-bonded aluminium 2 copper (tubes and sheet)

1	Drying cabinet (stove) With glass window: volume approximately 20 l; maximum temperature, 120°C.; electric heating with thermostat; measurement of relative humidity
1	Manual slicing machine (of the type used for ham, meat and fruits), with thickness adjustment
1	Balance, capacity: 300 g Sensibility: 0.01 g
300 kg	Polyester monomer, with required accelerator and hardener
20 kg	Gel-coat, five colours
100 m^2	Glass-mat for resin glazing, 200 g/m^2
15 m^2	Sheet, 18/8 - 0.5 mm, steel
15 m^2	Sheet, 18/8 - 1 mm, steel
15 m^2	Sheet, electrolytic copper - 0.3 mm
15 m^2	Sheet, electrolytic copper - 0.6 mm
60 m^2	Sheet, aluminium, 99.5 - 0.5 mm
60 m^2	Sheet, aluminium, 99.5 - 1 mm
60 m^2	Sheet, aluminium, 99.5 - 2 mm
20 m^2	Sheet, plexiglass
150 m^2	Aluminium foil (a few hundreths)
60 m	Copper tubing, 3/8 inch
60 m	Copper tubing, 1/2 inch

60 m	Copper tubing, 3/4 inch		
150 tubes	Silicon cement, 100 g-tubes (15 kg)		
150 tubes	Polysulphide 100 g-tubes (15 kg)		
10 kg	Tar tape for expansion joints		
20 kg	Flat black paint with a good level of stability at 120°C., in a selection of three makes		
5 kg	Liquid rubber or neoprene cement		
10 m^2	Neoprene		for joints
2 m^2	Graphited asbestos		
2 m^2	Teflon		
10 kg	Liquid for cold spray galvanizing, 1/2 kg packaging		
5 litres each	Solvents:	Trichloroethylene	Industrial grade
		Chloroform	
		Acetic acid	
		Methyl alcohol	
		Acetone	
2 standard bottles each	Liquid gases:	Acetylene	
		Oxygen	
		Hydrogen	
		Freons	
		Ammonia	
		Argon	
		Hg	
50 kg	Transparent polyethylene tubes and clips (collar-type clamps)		

lot	Fittings and valves	bronze and carbon steel
5 kg each	NaSCN, LiCl 3, LiBr	
lot	Insulating materials: fibreglass, polyurethane, polystyrene	
6	Safety goggles	
6	Welders' goggles	
3	Protective helmets for workshop use	
2	Soldering irons for electronics (one 50 W, one 200 W)	
2 kg	Tin-lead alloy for soldering electronic components with resin core	
	Welding and oxyacetylene cutting torches With pressure-reduction valves: - Oxygen - Hydrogen - Acetylene - Liquid gas - For cutting up to 10 mm thick	
1	Universal shear for notching, ribbing, swaging, grooving, external and internal curved and cornered cutting, flanging, etc.	For sheet metal, up to 3-5 mm Cutting of discs, 1,200 mm Cutting of strips, 600 mm Swaging, 1,000 mm
1	Portable electric drill	For bits ≯ 12 mm in diameter, with sets of bits with bench support and accessories
	Squarring shear for metal sheets up to 2 mm thick and 2 m width.	

1	Electric sharpening and polishing machine	Set of steel tools Approximately 250 W for polishing, dressing, sharpening
1	Riveting machine	Portable, pneumatic for rivets - 4 mm ø 2 kg aluminium and carbon steel rivets
1	Universal bending machine for sections and tubes	
	Pipe threader	Taps and dies, up to 2 1/2 in. With complete set of tools Accessory: support tripod
	Tube cutters	Manual, up to 2 1/2 inches.
1	Sheet metal	Machine for beading and crimping; up to 2 mm
2	Mechanics' tool boxes	Wrenches, pliers, screw drivers, hammer, etc.
1	Bending machine for metal sheets up to 2 mm thick, 2 m width.	
1	Spot electric welding machine.	

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