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SOLAR ENERGY:
ITS TECHNOLOGIES AND APPLICATIONS

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ABSTRACT

Solar heat, as a potential source of clean energy, is available to all of us. Extensive R & D efforts are being made to effectively utilize this renewable energy source. A variety of different technologies for utilizing solar energy have been proven to be technically feasible. Here, some of the most promising technologies and their applications are briefly described. These are: Solar Heating and Cooling of Buildings (SHACOB), Solar Thermal Energy Conversion (STC), Wind Energy Conversion (WECS), Bioconversion to Fuels (BCF), Ocean Thermal Energy Conversion (OTEC), Photovoltaic Electric Power Systems (PEPS). Special emphasis is placed on the discussion of the SHACOB technologies, since the technologies are being expeditiously developed for the near commercialization.

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1. Direct Thermal Conversion and Storage

a) Solar Collectors

This is a mechanical device which captures the radiant solar energy and converts it to useful thermal energy. In general, two types of collectors exist. They are the non-concentrating types such as flat plate collectors, evacuated tube collectors, etc., and the concentrating types which include tracking mirror or lens concentrators, non-tracking mirror or lens concentrators, evacuated tube collectors with reflectors, etc.

Figure 1 shows various designs of solar water and air collectors. The radiant solar energy passes through the cover glasses (usually 1-2) and is absorbed on the surface of the black plate (or absorber plate). Converted thermal energy in the absorber plate is carried away by the coolant, which is either liquid or air. Heat losses from the collector itself are minimized by insulating the bottom and edge of the collector and by proper number of glazings.

In Figure 2 the cross section of a vacuum tube collector is shown. Here, the convection heat loss is minimized by providing a vacuum between the inner surface of the outer glass tube and the outer surface of the inner glass tube (or absorber). Shown schematically in Figure 3 is an example of a parabolic trough concentrator. Here, sunlight is concentrated on the small absorber area by the parabolic trough shaped mirror.

Table 1, below, gives the examples, operating temperature ranges, and efficiency ranges of three categories of collectors.

Table 1

Classification of Solar Collectors[2]

Category	Example	Temperature Range	Efficiency
No Concentration	Flate Plate	150- 300°F	30-50%
Medium Concentration	Parabolic Cylinder	500-1200°F	50-70%
High Concentration	Parabodial	1000-4000°F	60-75%

Some of the important applications of solar collectors are listed here based on the temperature level of the collected energy.

- Low temperature collectors ($60^{\circ}F$ - $140^{\circ}F$)
    - swimming pool heaters
    - solar assisted heat pumps
- Medium temperature collectors ($140^{\circ}F$ - $250^{\circ}F$)
    - space heating and domestic hot water heating
    - absorption chiller
- High temperature collectors (> $250^{\circ}F$)
    - solar thermal electric conversion
    - industrial and agricultural processes
    - photovoltaic cells
    - heat engine/vapor compression chiller

Materials generally used in collector construction[3] are:

- Copper, aluminum, steel, plastics, ceramic, glass, etc. for absorber plate
- Glass, plastic sheets or films (Tedlar, Mylar, Lexan, etc.) for cover glazing
- Fiberglass with or without organic binder, ceramic fiber blanket, mineral fiber blanket, calcium silicate, Urea-formaldehyde foam, urethane foam, etc. for insulation
- Flat black paint, black chrome, nickel black, etc. for absorber coating

The key factors for the selection of good collectors could be:

- Good performance or efficiency for a given application
- Long durability against corrosion, stagnation, thermal expansion, etc.
- Cost-effectiveness in both collector cost and installation cost

Representative collector prices of some manufacturers are shown in Table 2, for your reference.

Table 2

Representative Collector Prices, 1977[4]

Supplier	Type	Unit Selling Price ($/sq. ft.)
Sunworks	Liquid, copper single glazed	
	for commercial sale	\$8.50 to \$10.00
	for retail sale	\$12.00 to \$14.00
Northrup	Liquid, aluminum commercial sale	\$8.00 to \$10.00
Revere	Liquid, copper double glazed for retail sale	\$11.50
Solar Energy Products, Gainesville, Fla.	Liquid, aluminum single glazed	\$10.00 to \$12.00
Solaron (Enersol)	Air, steel for dealers	\$12.05

b) Solar Thermal Energy Storage

Storing of the solar energy is often necessary since the availability is intermittent. The thermal capacity of the storage subsystem is usually designed for 1-3 days. Two types of storage materials have been under consideration: sensible heat type such as water, rocks, etc., and latent heat type or phase changing materials (pcm) such as salts, wax, etc. Table 3 lists the thermal storage of 1 MBtu with 20°F temperature swing.

Table 3

Thermal Storage of One Million BTU with 20°F Temperature Change[2]

	Water	Rocks	Phase Change Material
Specific Heat (BTU/lb°F)	1.0	0.2	0.5
Heat of Fusion (BTU/lb)	-	-	100
Density (lb/ft^3)	62	140	100
Weight (lb)	50,000	250,000	10,000
Volume (ft^3) with 25% passage	1,000	2,150	125

Glauber's salt (sodium sulfate dekahydrate) and its eutectics have been suggested for use as a latent type heat storage material in the space heating and cooling applications.[5] The salt hydrate, however, needs crystallization seeding (Borax) to avoid supercooling and also requires a thickening agent (thixotropic additive) to prevent segregation among the unmelted crystals, the melted crystal, the borax crystal seeds and the anhydrous sodium sulfate.

The container materials for the thermal storage subsystems are usually steel, concrete, reinforced concrete, fiberglass-reinforced plastic, aluminum, etc.

Shown in Table 4 are the cost estimates for several thermal storage subsystems with 35°F temperature swing.

Table 4

Cost Estimates for Several Thermal Storage Systems with 35F Temperature Swing[6] (1976)

	Sodium Thiosulfate Pentahydrate	Paraffin	Water	Rock
Raw Material Cost (1)	\$.11/lb	\$.10/lb	(glycol \$1.25/gal, deionized \$0.02/gal)	\$15/ton
Material Cost (\$/250,000 Btu)	303	277	70	290
Gross Required Volume (ft^3/250,000 Btu)	35	75	125	295
Heat Exchanger Cost (2) (\$/250,000 Btu)	585	1200	90	none required
Tank Cost (3) (\$/250,000 Btu)	200	395	565	980
Total Storage Cost (\$/250,000 Btu)	1090	1870	725	1270

(1) Chemical Marketing and Drug Reporter

(2) Calculated assuming a cost of \$1.85/ft^2 for the installed tubular heat exchanger/containers.

(3) Reference (1).

2. Solar Swimming Pool Heating System

One of the economic and popular applications of solar energy is heating a swimming pool (about 80°F). Since the solar collector operates at low temperatures, simple and inexpensive collectors can be used at a high efficiency of 70-80%. The collector area needed for a pool heating system is approximately from 1/2 to 3/4 of the total surface area of the pool.

In Figure 4, the schematic diagram of a swimming pool solar heating system is shown. Here, when the collector panel temperature is equal to or lower than the water temperature at the pool outlet, the collector is by-passed. Auxiliary heaters may be required to provide heat when the solar energy is not available. The average annual (about a 3 month operation) efficiency of a swimming pool solar heating system is presently about 60%.

An inexpensive and durable solar collector is the key to the cost-effective pool heating system. The installed cost of a typical system may range from $1,500 to $2,500 depending on the pool size, construction requirements and location.

3. Solar Domestic Hot Water Heating System

The technology for the solar hot water heating system is well developed, and various systems are now commercially available. Basic system types are thermosyphon, self-drainable/forced convection, and closed loop/forced convection types.

a) Thermosyphon Type

The thermosyphon system, shown in Figure 5, employs the natural convection of the heat transfer fluid and does not require pumps and controls. However, the storage tank should be located above the solar collectors since sufficinet pressure head is necessary for gravity feeding of heat transfer fluid to the collectors. Cold water from the bottom of the storage tank enters the collector by gravity and is heated as it rises slowly into the storage tank where the heated water replaces cold water with higher density. A conventional water heater is necessary to provide additional thermal energy input when the solar energy is not available in sufficient quantity.

This type of system is adequate for the areas where freezes are infrequent. The collector fluid must be drained manually when the freezing weather is expected.

b) Self-drainable, Forced Convection Type

Forced convection systems with the provision of a drain-down freeze protection is shown in Figure 6. Here, a pump is employed to circulate the collector heat transfer fluid. As a freeze protection, a thermostat is used to sense the fluid temperature at the collector inlet. Collector fluid is automatically drained when the collector inlet temperature approaches the freezing point of the fluid (usually water). This system has high efficiency and may be suitable for most climates. The system was also shown to present the least amount of system problems, although long-term corrosion may still exist due to the frequent air (or O_2) infiltration into the system whenever it drains.

c) Closed-loop, Forced Convection Type

Also shown in Figure 7 is a forced convection type system employing a pump which circulates the heat transfer fluid in a closed collector loop. Here, anti-freeze solution is used in a collector loop. This type of system may have a higher initial cost with some decrease in efficiency due to the heat exchanger approach temperatures, but are suitable for all climates.

A good solar hot water heating system should include proper protection from freezing, long-term corrosion control and reliable system controls. Average annual efficiency of a typical solar domestic hot water heating system is about 40% at the present time.

The average cost of an installed solar domestic hot water system for a typical residential house would be about $1,200 (1977 estimate)[4], which includes about 50 ft^2 of collector, storage, pumps and controls.

4. Active Solar Space Heating and Cooling System

The most publicized application of solar energy so far is the active heating and/or cooling of buildings (SHACOB). A simplified schematic diagram of a typical liquid solar system is presented in Figure 8. In the diagram, the energy flow of the system is conveniently divided into six separate sections of various functions.[9]

Brief descriptions of each section in sequence are made as follows:

- Energy Collection
  Solar energy is captured by a collector
- Energy Transfer (1)
  Collected solar energy is transferred from the collector to the energy storage (by two pumps) via a heat exchanger. The closed collector loop usually contains an anti-freeze solution such as ethylene glycol-water (50/50%).
- Energy Storage
  Solar energy is stored as hot water in the tank, which could be sized to provide thermal energy for 1-3 days of operation. A portion of the stored energy can also be used for preheating the domestic hot water.
- Energy Transfer (2)
  Thermal energy from the storage is transferred either to the cooling device or directly to the heating coil, depending on the kind of applications.
- Energy Conditioning
  A thermally activated cooling device (air conditioner or chiller) is employed during the hot weather. Auxiliary heaters must be installed as a back-up energy source for the cooling device and for the space heating coil. The cooling device usually requires heat rejection to the ambient, and employs either a fan/coil unit or a cooling tower.
- Space Conditioning
  Thermal energy from the storage and/or from the auxiliary heater provides heat for space heating. Space cooling can also be achieved when the cooling device is in operation.

Some of the most frequent problems of the solar space heating and cooling systems are:

- Corrosion

  Provide proper corrosion protection on the solar system (such as analysis of water sample, deionization of water if needed, freezer protection (antifreeze solution), proper level of inhibitors, use of buffering agents, flow velocity control, use of good filter systems, periodic check and replacement of heat transfer fluid, avoidance of direct contact of dissimilar metal, minimization of 0_2 infiltration, proper piping -- avoid sharp bends, etc.)
- Hydraulic Concerns

  A leak-proof piping system, with proper piping size and configuration, matched pump capacity, etc. is essential.
- Control Systems

  Reliable control systems with effective control strategy for both heating and cooling applications, is an important factor since it directly effects the COP of the total system.
- Collector Support Structures

  The design of the collector support structure should be such that it would stand against wind load, snow load and weather corrosion for the design life period.

Average annual efficiency of a solar space heating, cooling and hot water system is about 40%, and that of a combined space heating and hot water system is about 25%.

The average cost of a space heating system for a new residential house of about 1,500 ft^2 would be about $6,000, which includes about 300 ft^2 of collectors.[4] Retrofit installations may cost more than the new installations. However, the cost of a solar space heating, solar cooling and solar domestic hot water system could go up to about $25,000 for a residential application.

a) Solar Assisted Heat Pump

The heat pump is an electrically activated mechanical device which can perform both heating and cooling functions. Shown in Figure 9 are the schematic diagrams of an advanced conventional air-to-air heat pump.

In a heating mode, as shown in Figure 9(a), hot and high-pressure refrigerant gas from the compressor is liquified in the indoor coil (as a condenser), providing heat to the load. Condensed and high-pressure refrigerant from the indoor coil passes through the accumulator heat exchanger and expands across the subcooling control valve (or expansion valve), from which low pressure, liquid/vapor mixture is sent to the outdoor coil. Refrigerant mixture evaporates in the outdoor coil, absorbing heat from the ambient. Cold and low-pressure refrigerant mixture from the outdoor coil separates into vapor and liquid phases in the accumulator. Low-pressure refrigerant vapor from the accumulator returns to the suction side of the compressor.

Figure 9(b) shows the schematic diagram of the same heat pump operating in a cooling mode. With a simple manipulation of a reversing valve, the outdoor coil is now used as a condenser for heat dissipation to the ambient. The indoor coil becomes an evaporator, which absorbs heat from the space to be conditioned.

Solar energy as a heat source to the evaporator component of a heat pump, can improve the heating performance (or heating COP) of a heat pump significantly, thus less electrical energy input is required for the heat pump to meet a given load. In Figure 10, the heating COP of a heat pump as a function of the evaporator temperature is plotted at the condenser temperature of 135°F.[10] Solar contribution to the evaporator temperature may, perhaps, lead to about 100°F, and the improvement in COP is quite large (compared with the COP at 50°F evaporator temperature) as shown in the figure.

The COP (the ratio of heat output over the equivalent heat input) of a solar assisted heat pump is expected to be about 7-10, compared with about 3-4 of the conventional heat pump.

A simplified schematic diagram of a solar assisted heat pump system is represented in Figure 11. In order to develop a cost-effective solar assisted heat pump system, the following tasks should be performed.

- Development of a new heat pump whose COP would be higher at increased evaporator temperature. Operation of the presently available heat pumps is limited by the evaporator temperature at about 50°F.
- Development of a low-cost, low temperature solar collector, and an inexpensive energy storage subsystem.

b) Absorption Chiller

The absorption chiller is a mechanical device built on the principles of one of the thermodynamic absorption cooling cycles. The absorption chillers can be directly activated by the solar thermal energy at 170°F - 400°F.

Two types of absorption chillers have been commercially available, i.e., ammonia-water and water-lithium bromide units. Ammonia-water chillers were originally developed as gas fired, requiring a generator input temperature of over 350°F. The condenser/absorber components are air-cooled, and the typical COP value is about 0.4-0.5. Water-lithium bromide units have also been available as gas-fired or steam-fired, requiring a generator input temperature of about 245°F. Water-cooling of the condenser/absorber components is a must due to the crystallization problem of lithium bromide. The typical COP value of these units is about 0.5-0.6.

Shown in Figure 12 is a simplified schematic diagram of a standard H_2O-LiBr absorption cycle. Here, water is the refrigerant and the solution contains lithium bromide dissolved in water.

Referring to the diagram, heat is applied to the generator to vaporize water (refrigerant) from the mixture of H_2O-LiBr solution. Water vapor from the generator then passes to the condenser, where it condenses to liquid water, liberating the heat of condensation. Cooling tower water is generally used for the dissipation of condenser heat. Liquid water from the condenser passes through the expansion valve and it immediately vaporizes in the evaporator due to the sudden pressure drop across the expansion valve. The required evaporation heat of water in the evaporator thus produces the cooling effect.

At the absorber, water vapor from the evaporator is absorbed in the water-poor solution coming from the generator via the solution heat exchanger (SHX). Here, heat of absorption is also dissipated to the cooling tower water. Resulting water-rich solution from the absorber is then pumped back to the generator via the solution heat exchanger. The solution heat exchanger (SHX) is employed to reduce the generator heat input and to decrease the amount of absorber heat dissipation, thus improving the cycle COP. The pressure reducing valve is also necessary between the solution heat exchanger and the absorber to maintain the high and low pressure sides of the absorption cycle.

For the adaptation of conventional units for solar applications, the generator temperature must be decreased as practically as possible to accommodate the low temperature input available from solar collectors. Modification of the absorption unit requires changes in the generator heat exchanger, refrigerant-absorbent concentration, heat exchanger surface areas (condenser, absorber and/or evaporator) and solution pump capacity.

At the generator temperature of 200-250°F, ammonia-water chillers should be water-cooled. Air-cooling is also possible at the generator temperature of 250-350°F. A COP of about 0.5-0.7 is attainable and the need for concentrating-type solar collectors is evident. For water-lithium bromide units, the generator temperature could be anywhere between 180 and 245°F, and the condenser/absorber components should always be water-cooled. The attainable COP value of about 0.6-0.8 could be expected. Flat plate solar collectors and cooling towers are usually employed.

Direct use of large industrial H_2O-LiBr units for solar application is possible without any hardware modification or only slight modification in the generator heat transfer surface. The consequence is a decrease in unit capacity.

The maximum performance of a single-effect absorption unit can be estimated for realistic operating conditions in solar applications. As an ideal cycle, or Carnot cycle, the COP value may range anywhere from 0.5-3.0. The maximum theoretical COP of the absorption unit using presently available working fluid could not exceed 1.0 and the practical COP of the commercially available single-effect units could range from 0.5 to 0.8, depending mainly on the type of absorption cycle employed, air-cooling or water cooling of absorber/condenser components, and the kind of working fluids used.

Absorption chillers, optimized for solar applications, are now commercially available in limited quantities. These are the water-cooled H_2O-LiBr units by Arkla Industries, Incorporated. For the residential application, a 3 ton - Solaire 36 (Model WF 36) is available, whose rated COP is 0.72 at the generator input temperature of 195°F, and the condenser input temperature of 85°F.

The schematic diagram of the Arkla Solaire 36 is shown in Figure 13. In addition, Figures 14 and 15 show, respectively, the capacity and the COP of the chiller as a function of generator inlet hot water temperature with the condenser inlet cooling water temperatures as parameter. The trade price of the unit is $2880 (5/1/77) and the cooling tower cost of $400-500 is additional. Also introduced was the 25 ton - Solaire 300 (Model WFB 300) for commercial applications. The rated COP is 0.69 at the same conditions as above, and the trade price of the unit is $15,200 (5/1/77) with the extra cooling tower cost of about $3100.

Other absorption chillers are also available for solar cooling experiments or demonstrations. These may include Trane's single effect H_2O-LiBr units (101-1660 nominal tons) with minor modification of the generator, and York's H_2O-LiBr units (110-1377 nominal tons) with no hardware modification.

c) Heat Engine/Vapor Compression Chiller

The heat engine is a mechanical device which can convert thermal energy into shaft-driven mechanical power. This energy can be eventually utilized to drive the generator for electricity production, pumps for various purposes, and vapor compression cycles for heating and cooling. For the solar applications, the Rankine heat engine is believed to perform at higher attainable cycle efficiency at low temperatures ($< 300^\circ F$) than other heat engine cycles such as Brayton, Stirling, etc.

The choice of a working fluid for the Rankine heat engine depends on many factors such as input temperature, reliability (stability), first cost, operating cost (pumping power) and acceptance (toxicity). The best suggested working fluids in the different temperature ranges are:

- Water for $700 < T < 1{,}100^\circ F$
- Toluene for $500 < T < 700^\circ F$
- Fluorocarbon refrigerants for $T < 300^\circ F$
  (R-11 and R-113 are preferred to others)

Figure 16 represents the schematic diagram of a fuel-superheated Rankine heat engine/vapor compression chiller. Without a superheater it also represents a standard Rankine heat engine/vapor compression chiller.

In the heat engine cycle, the refrigerant is vaporized in the boiler by the heat input from solar heated water. The hot, high pressure refrigerant vapor from the boiler drives the turbine which powers the vapor compression chiller.

Exhausted, low pressure refrigerant vapor from the turbine is liquified in the condenser, dissipating heat to the ambient. Liquid refrigerant from the condenser is pumped back to the boiler via a regenerator. The regenerator is a heat recovery device used to increase the cycle efficiency.

The other half of the chiller or the vapor compression cycle works just the same as the electrically driven heat pump in a cooling mode, which was mentioned earlier. Conventional vapor compression chillers in small capacities usually employ piston compressors with R-12 refrigerant.

Cycle shaft efficiencies of various small heat engines are plotted in Figure 17 as a function of the maximum cycle temperature (i.e., boiler temperature). For most solar cooling applications, the cycle shaft efficiency is limited by about 17% at 400°F, as shown in the figure.

The Rankine cycle shaft efficiency of a fuel-superheated heat engine, as shown in Figure 16, is superior (approximately double) to that of a standard Rankine heat engine. Figure 18 gives the performance comparison between the two.

The COP of a cooling unit may be defined[13] as follows.

$$\left\{\text{Cooling Unit COP}\right\} = \left\{\text{Heat Engine Cycle Shaft Efficiency (CSE)}\right\} \text{X} \left\{\text{Vapor Compression Cycle Energy Efficiency Ratio (EER)}\right\}$$

or

$$\left\{\frac{\text{Cooling Output}}{\text{Thermal Energy Input}}\right\} = \left\{\frac{\text{Shaft Energy Output}}{\text{Thermal Energy Input}}\right\} \text{X} \left\{\frac{\text{Cooling Output}}{\text{Shaft Energy Input}}\right\}$$

For example, assuming a water-cooled system at 300°F heat input,

$\text{CSE} \doteqdot 0.14$ from Figure 16

$\text{EER} \doteqdot 5 - 6$ (typical value)

Therefore, $\text{COP} = (\text{CSE}) \text{ X } (\text{EER}) = 0.7 - 0.8$

As a summary, the performance (COP) of various solar powered, water-cooled chillers as a function of generator input temperature is plotted in Figure 19.

Shown in Figure 20 is an artist's conception of a solar powered Rankine heat engine/Vapor Compression Chiller (or heat pump) system.

The costs of small capacity Rankine heat engine/vapor compression chillers are not known, but were roughly estimated, and are compared with those of other chillers in Table 5 below.

Table 5

Cost Comparisons of Small Capacity Chillers

Cooling Unit	$/ton (1977) 3 ton unit	 25 ton unit
Conventional Electric Air Conditioner	300	250
Solar-Powered LiBr Absorption Chiller	1,000	500
Solar-Powered Rankine H.E./V.C. Chiller	3,000	2,000

d) Others

Other active cooling concepts may include desiccant chillers, chemical absorption cycle (zeolite and salt hydrate systems), metal hydride chemical heat pump, Nitinol heat engine cycle, vapor jet cooling cycle, etc.

The basic principles of the desiccant chiller are as follows. Air from the room is dehumidified (and also heated) with a solid or liquid desiccant, then it is sensibly and evaporatively cooled. The resulting low-temperature air returns to the room. The desiccant is regenerated by the solar thermal energy for the subsequent cycle. Solid desiccants include silica gel and molecular sieves; liquid desiccants are triethylene glycol and lithium chloride.

The projected COP of the desiccant chiller system (either a rotating drum type or stationary bed type) is about 0.5-0.7. The major problem of all desiccant systems is the high parasitic power loss in addition to the high initial cost. The above mentioned cooling concepts, except perhaps desiccant chillers, are either in a conceptual stage or not practical for solar application at the present time.

5. Passive Solar Space Heating and Cooling Systems

Passive solar systems are ones in which either the heating or cooling function can be achieved by the naturally induced heat transfer mode(s) with no need of (or the least amount of) external energy for its operation. A large variety of different passive designs are possible, and any number of design combinations may be incorporated into the passive systems of new constructions.

The passive solar systems can be broadly classified as[14]:

- Direct Gain Systems

  The building structure itself is utilized to collect and store the solar energy as shown in Figure 21.

- Indirect Gain Systems

  Incorporated in this type of system can be the extra interior structural mass such as concrete wall[15] or the phase changing materials such as Glauber salts[16] for the collection and/or storage of the solar energy.

  Figure 22 shows the concept of indirect gain systems. Here, the solar heated wall heats the air and also induces the natural convection of the room air. During the night, a damper is used at the top of the wall to prevent heat loss by reverse thermosyphoning. For the cooling operation during the hot weather, a solar heated wall can also be utilized to induce warm room air to the outside and cool outside air into the room.

  The indirect gain system with a roof pond, shown in Figure 23, is an interesting passive system concept, which may have a great potential for the practical applications in the Southwest, United States.

  For the winter heating, the roof pond collects the solar energy during the day and provides heat for the room. Proper insulation of the roof pond can prevent heat loss during the night. In a cooling mode, the roof pond collects heat from the living space during the day and dissipates it into the sky during the night.

- Isolated Gain System
  This system employs either attached greenhouses or passive-type collectors with no circulation pump. Solar energy captured in the greenhouse can be easily regulated and also be stored according to the needs of the living space. For the system with a passive-type collector, an energy storage or a pebble bed should be located above the collector so that the heated air from the collector can circulate naturally through the system by the air density difference.

Like any other solar system, the passive system needs an auxiliary energy back-up. Other limitations of the passive systems may include:

- Geographical limitations, for example, not applicable in humid areas
- Difficult retrofit applications
- Less controllable than active systems

However, the prospects for the reliability and the cost (both initial and operating) of the passive system seems very bright. It was reported[14] that the cost of a residential passive solar heating and cooling system may range from $500 to about $5,000 depending on the kind of system employed, the system design capacity (usually anywhere between 25 and 75% of the total heating or cooling load), geographical location, etc.

6. Agricultural and Industrial Applications

a) Agricultural Applications

Direct solar thermal applications for agricultural purposes may be classified into the following categories.[17]

- Space heating of greenhouses
- Space heating of animal shelters (such as poultry houses, swine farrowing and growing houses, and other farm buildings). An example of a passive type space heating system for an animal shelter is schematically shown in Figure 24.

- Drying and curing of a variety of grains and crops (such as rice, soybean, potato, corn, tobacco, forage, wheat, peanuts, and coffee beans).

  Shown in Figure 25 is a block diagram of the 3-stage agricultural process for the dehydration of diced potatoes. Here, solar energy is utilized in intermediate and final stages where the moisture content of the diced potatoes reduces from 30% to 7%.

One of the popular applications of solar energy is to employ active solar devices for the agricultural processes. For example, Rankine heat engine, teamed with the concentrating collectors can provide mechanical energy for irrigation pumps[19] and for feedmills. Figure 26 shows the schematic diagram of a solar-powered Rankine heat engine system mechanically coupled with an irrigation pump.

b) Industrial Process Heat

Solar energy for industrial process heat can be, in general, provided in the form[20] of:

- Hot water up to 212°F
- Steam between 212°F and 350°F
- Hot air up to 350°F

According to U. S. Department of Energy classification, solar energy application for industrial process heat is classified by three different temperature ranges. Listed below are the three temperature ranges and their corresponding applications.

- Low temperature (< 212°F)

  Low temperature applications are in the areas of food products processing such as dehydration of food on an industrial scale.
- Intermediate temperature (212 - 350°F)

  Intermediate temperature applications may include the generation of low pressure steam for various processes, and of hot air for a variety of drying processes in the food, textile, and paper and pulp industries. As an example, a simplified schematic diagram for the production of industrial process steam in textile drying is included as Figure 27.

- High temperature (> 350°F)

  High temperature applications may include the production of high pressure steam and heat for a number of chemical processes.

Solar energy can provide a large fraction (i.e., up to about 35% in the U.S.[20]) of the total industrial process heat requirements. However, the success of an industrial solar energy system strongly depends on its economics. Roughly, a 3-5 year payback period could be adequate.

7. Solar Thermal Electric Conversion (STC)

Sunlight can be concentrated to yield a high grade energy, and this high temperature energy can be used to activate a heat engine/turbogenerator for the generation of electricity.

A simplified schematic diagram of a solar thermal electric conversion system is shown in Figure 28. Here, a solar ray is focused by a field of tracking heliostats to an elevated receiver on top of the tower. Figure 29 is an example of such an arrangement actually being used in France. In the diagram, the solar ray is reflected toward the parabolic concentrator by a bank of heliostats. A concentrated solar ray from the parabolic concentrator enters the cavity of the tower receiver. Another method is to use a field of distributed collectors (such as parabolic trough types) and receiver pipes containing the working fluid.

Collected high-grade solar energy in the absorber can be transported by a working fluid to a thermal storage or can be directly used to drive the turbogenerator for the production of electricity. The low-pressure working fluid, expanded from the turbine, is liquified in the condenser (or cooling tower) and is pumped back to either the receiver (or absorber) directly or to the thermal storage, depending on the energy availability.

As discussed in Section 4(c), the efficiency of a Rankine heat engine is only limited by the maximum permissible cycle temperature of the working fluid. Using water as a working fluid, the cycle shaft efficiencies of about 21-25% could be obtained at the boiler heat input temperature of about 800 - 1200°F (see Figure 17, Water-cooled Condenser). Combined efficiency of the Rankine heat engine and the turbogenerator is, then, about 19-23% based on the generator efficiency of about 92% at full load.

The state-of-the-art is in developing a pilot plant of small capacity (about 10 MW). Before an extensive demonstration of the large capacity systems, extensive R & D work needs to proceed to solve many potential problems, some of which may include:

- High capital costs for system components
- Waste heat disposable problem
- Wind load problem on heliostats
- Fouling and control problems of heliostats ($\pm 0.2^{\circ}$)
- Thermal cycle fatigue of boiler surfaces
- Need of large land area
- Need of effective energy storage (pcm or sensible-rocks)

The estimated cost of electricity of a solar thermal electric conversion system would be about $4,000/KW in 1981[22] based on the plant capacity of about 10 MW.

For comparison purposes, the estimated solar electric costs (1977 - 2020), by various solar technologies, are shown in Table 6 below.

Table 6

Estimated Solar Electric Costs by Various Solar Technologies (1977 - 2020)[22]

SYSTEMS DESCRIPTION	CURRENT OR PILOT SYSTEM			EARLY COMMERCIAL SYSTEM			ULTIMATE SYSTEM	
	Size	Year	Cost	Size	Year	Cost	Size	Cost
Solar Thermal Central Receiver c.f. = 0.5[2]	10 MW	1981	4000$/kW	100 MW	1986	2300$/kW	100 MW	1400$/kW
Solar Thermal Central Receiver c.f. = 0.36, Fuel Saver	5 MW	1978	N - A	100 MW	1990	2300$/kW	100 MW	860$/kW
Solar Thermal Combined Cycle Hybrid, c.f. = 0.5, Intermediate				100 MW	1990	1200$/kW	100 MW	690$/kW
WECS-MOD I 18 mph Average Wind Speeds, Hydro-electric Hybrid, c.f. = 0.48, Intermediate				100 MW	1981	960$/kW	100 MW	760$/kW
WECS—Advanced Design 14 mph Average Wind Speed, c.f. = 0.48, Fuel Saver	1.5 MW[3]	1979	1870$/kW	1.5 MW	1983	1500$/kW	1.5 MW	800$/kW
Photovoltaics, 250 MWhe Storage, c.f. = 0.3, Semi-Peak, Thin Film Cells				100 MW	1990	1630$/kW	100 MW	920$/kW
Photovoltaics, 250 MWhe Storage, c.f. = 0.3, Semi-Peak, Silicon Cells	100 MW	1978	18,000$/kW	100 MW	1990	1400$/kW	100 MW	1190$/kW
Photovoltaics, c.f. = 0.26, Fuel Saver, Thin Film Cells				100 MW	1990	2400$/kW	100 MW	580$/kW
Biomass Electric, c.f. = .80, Base				46 MW	1980	1190$/kW	46 MW	1190$/kW
OTEC, c.f. = 0.6, Base				250 MW	1993	2200$/kW	250 MW	1290$/kW

Sources: *Solar Energy—A Comparative Analysis to the Year 2020*, MITRE Technical Report, MTR-7579, March 1978, The MITRE Corp., METREK Division, McLean, Va. *Systems Descriptions and Engineering Costs for Solar-Related Technologies, Volume 1, Summary*, MTR-7485, June 1977, The MITRE Corp., METREK Division, McLean, Va.

8. Photovoltaic Energy Conversion (PEPS)

a) Photovoltaic Cells

Direct conversion of the solar energy into electricity can be obtained by the internal photoelectric effect of the solar cells, made of various semiconductors. The semiconductor materials may include single crystal silicon (Si), Cadmium sulfide (CdS)/Copper sulfide (Cu_2S), gallium arsenide (GaAs)/ gallium aluminum arsenide (GaAlAs), etc.

Figure 30 represents a schematic diagram of a silicon solar cell. It consists of two types of semiconductor silicon; P type silicon (positively doped with boron atoms) and N type silicon (negatively doped with arsenic or phosphorus atoms). An electric field is created by forming a P-N junction between the two different types of silicon materials. When the silicon atoms absorb photons from the solar ray near the P-N junction, electron-hole pairs are created. These liberated electrons move toward the positively charged N type silicon and produce spontaneous photocurrent when an external circuit is attached to the two sides of the P-N junction.

Silicon solar cells produce about 0.45 volts per cell regardless of their size with the maximum power output of about 40 watts per m^2 on a 24 hour basis The efficiencies of the current commercial silicon solar cells fall within about 10-12%, which is about half of the theoretical maximum efficiency of 22-23%.

The average conversion efficiencies of the cadmium sulfide/copper sulfide photovoltaic cells are low, and are about 3-5% at the present time, but can be improved to over 10%. Cadmium cells can be fabricated inexpensively using the thin-film technique. At the present time, cadmium sulfide cells are available at about \$1 per ft^2, compared with about \$150 per ft^2 silicon cells. The main problems of the cadmium cells are the degradation in the presence of water vapor, and low tolerances for high temperature operation.

Gallium arsenide cells could be improved to convert solar rays to electricity at 17-22% efficiency. Combinations of gallium arsenide and other metals may even double the above efficiency.

Applications of the solar cells are wide-open. Some of the present applications may include the power sources for:

- Satellites in space program
- Water pumps in agricultural irrigation[25]
- Fan motors in grain drying[25]
- Television, buoys, railroad/road signals, emergency telephones, refrigerators, lights, radios, etc.[23]
- Water pumps for solar space and hot water heating system
- Remote location usages

The primary raw materials for the solar silicon cells are abundantly available from sands, and is inexpensive. However, the costs of the present solar cells are extremely high, mainly due to the complicated manufacturing processes. Various advanced techniques are under development to reduce the manufacturing costs.

The cost of the silicon cell power plant (about 100 MW(e) in 1978) is compared with other typical values as follows:

- Photovoltaic cell power plant -- \$15,000 - 18,000/KW(e) (ultimate goal -- \$1,200/KW(e))
- Coal power plant -- \$400-500/KW(e)
- Oil power plant -- \$300-400/KW(e)
- Nuclear power plant -- \$450-500/KW(e)

Solar cell power is about 50 times more expensive than conventional power. If solar cells are to be competitive with other conventional power systems, a solar cell system cost of less than about \$200 per peak KW is required.

b) Hybrid Photovoltaic Concept

Recently proposed is a hybrid photovoltaic system, which can provide electric energy as well as thermal energy. The hybrid photovoltaic system is a combination of photovoltaic cells and solar thermal collectors. The photovoltaic cell portion yields both electricity and thermal energy (i.e., excess photon energy that converts to thermal energy in the cell). The other portion is a normal solar thermal collector.

The hybrid system may be ideal for the applications requiring both types of energy sources, for example, electricity for the home appliances, lights, etc. and thermal energy for the space and hot water heating system in residential dwellings. The hybrid systems are to be operated above the optimum operating temperature of the photovoltaic cells so that proper grade thermal energy can be collected for the thermal applications. This may reduce the efficiency of the photovoltaic cells below its optimum value.

9. Wind Energy Conversion (WECS)

Wind energy is considered one form of solar energy since it is primarily generated by the difference in thermal gradient of the earth's surface created by the solar energy.

Among many types of wind energy collectors, machines using rotors are common and can be classified in terms of the orientation of their axis of rotation with respect to the wind direction:[17]

- Horizontal-Axis Rotors
  The axis of rotation is parallel to the wind direction, or is both horizontal to the earth surface and perdendicular to the wind direction.
- Vertical-Axis Rotors
  The axis of rotation is perpendicular to both the earth surface and the wind direction. Some examples of the wind energy collectors are shown schematically in Figure 31.

Kinetic energy, captured by wind collectors, could be used to produce either useful mechanical energy or electricity.

The mechanical energy, usually that of a rotating shaft, is produced by the kinetic energy of the moving air via the rotational motion of the fan-blades or turbine. The maximum theoretical efficiency of a wind turbine is about 59 %, where the efficiency is defined as the ratio of the extractable power output over the kinetic energy flux of a wind stream. Average efficiency of a well-designed windmill falls between 50 % and 75 % of the theoretical maximum.[24]

Figure 32 shows the relationship between the power output of a wind turbine and the wind speed. Note that the system is designed for full output at the wind speed of Vm. Below the speed, Vm, the power output decreases very rapidly since it is a strong function of the wind speed to the 3rd power.

Electrical energy from the windmills can be obtained by using a DC generator attached to the rotating shaft via a gear train.

A picture of a typical, two-bladed wind turbine system is shown in Figure 33. Also schematically shown in Figure 34 is a newly proposed Vortex Tower wind turbine system.[27] A large turbulence can be developed inside the cylindrical structure, and a turbine can be placed in the center where a vortex exists. Due to the low pressure within the vortex the turbine rotor is no longer susceptible to the stress created by the wind. Capacity of the Vortex Tower wind system could be on the order of about 10 MW(e).

The wind turbine systems usually need some type of energy storage devices, which should be inexpensive and reliable for the long life-time of the system. A bank of batteries are normally employed as an energy storage system. Other methods of storing the produced energy may include motor-generator/flywheel, elevated water reservoir, compressed air, etc.

The wind energy system needs a great number of large wind turbines for a power output comparable to the conventional systems. For example, an average 1 GW wind energy system would require over 5,000 wind turbines of 60 m-diameter.[24]

Some of the present applications of the wind energy are to:

- pump water mechanically or electrically for irrigation and for hydro-storage
- produce electricity for power networks or direct applications such as residential use
- produce electricity in isolated rural regions such as islands and off-shores.

The cost of the wind energy system (in 1979) is estimated to be about \$ 1,870 per KW for a power plant capacity of 1.5 MW.[22] Small (≑ 1 KW) or medium (≑ 15 KW) wind machines are presently available at the price of \$ 2,300 and \$ 20,000 respectively.

10. Ocean Thermal Energy Conversion (OTEC)

Utilizing the temperature gradient of the ocean between the surface and the depths, a heat engine can be employed to produce electric power. Two different types of power cycles are possible, and are shown in Figures 35 and 36.

In an open cycle, the sea water serves as the working fluid. In the boiler, steam is generated by the heat input from the warm surface water under a vacuum. A vacuum pump is used to expel dissolved gases and to maintain subatmospheric conditions in the boiler. This low-pressure, high volume steam is, then, expanded across the turbine to produce useful work for the generation of electric power. Expanded steam is liquified in the condenser by dissipating heat to the cold water from the ocean depth.

An advantage of an open cycle is in that the heat exchanger approach temperature differentials are no longer necessary. The major disadvantage is the requirement of a very large turbine due to the low efficiency and large specific volume of the working fluid.

In a closed cycle, as shown in Figure 36, a separate working fluid (such as ammonia, propane or freon) could be used. The working fluid, now vaporizes in the boiler, expands across the turbine, liquifies in the condenser, and is pumped back to the boiler in a closed loop.

The advantages of the closed cycles are:

- smaller turbine size than that of an open cycle
- higher operating pressure & smaller specific volume of working fluid than that of an open cycle

However, large heat transfer areas of the boiler and condenser heat exchangers are required to minimize the heat exchanger approach temperature differentials.

A closed, Rankine heat engine system with ammonia as a working fluid, seems the most promising on the basis of its higher cycle efficiency than others. The efficiencies of the OTEC power plant (i.e., closed, Rankine cycle) is about 2-3% at the typical operating conditions (i.e., source temperature of 77°F, and sink temperature of 59°F), compared with the Carnot efficiency of about 3.4% at the same conditions. A substantial fraction of the total power output must be consumed to operate the circulation pumps for the condenser and boiler heat exchangers.

The major advantage of the OTEC system is in that the virtually unlimited amount of energy is available with no intermittency. Some of the disadvantages or problem areas may include:

- high initial cost
- geographical limitation (probably only adequate between the latitudes; Tropic of Cancer and Tropic of Capricorn)
- need of sophisticated and new heat exchanger design
- corrosion and biofouling problems
- environmental effect on ocean
- power transmission problem

An artist's conceptual view of an OTEC system is shown in Figure 37.[17]

The projected cost of the OTEC system was estimated to be about $2,100 per installed KW(e).[28]

Although totally different from the OTEC principles, a new concept of power generation, utilizing the kinetic energy of the ocean current, has been suggested. A huge turbine, rotated by the moving ocean current, drives the motor/generator assembly for the power generation.

11. Extraterrestrial Solar Energy Collection

Solar energy can be collected most effectively in space since the terrestrial environmental effects (such as clouds, wind, rain, snow, etc.) do not exist, and the solar collection time could be unlimited in a synchronous orbit.

Two different types of systems using earth-orbiting satellites have been considered. One system uses photovoltaic cells to convert solar rays directly into electricity. The other system employs a heat engine/turbogenerator assembly. Highly concentrated solar energy, produced by the field of heliostats, activates the Rankine heat engine/turbogenerator to produce electricity.

The electrical energy, thus produced, powers the microwave generator. Microwaves are then transmitted via a microwave antenna on the satellite through the space to the receiving microwave antenna on Earth. Captured microwave energy at the receiving station on Earth can be reconverted to electricity for the end uses. The schematic diagram of such a scheme is illustrated in Figure 38.

Although the microwave technology is already well developed, some potential problems should be addressed, such as:

- high cost of space transportation
- environmental effects on Earth (i.e., microwave radiation, eventual thermal pollution, etc.)

The total cost of a satellite solar power plant was reported to be in the range of $1,500-3,000 per KW(e) (estimated in 1972 and 1973).[2] The cost of the system, using the photovoltaic cells, was estimated to be slightly higher than that of the system employing a heat engine/turbogenerator.[2]

12. Bioconversion to Foods and Fuels (BCF)

a) Terrestrial and Marine Biomass Production and Conversion

Photosynthesis is an energy conversion process in which solar energy is utilized to synthesize organic compounds from carbon dioxide and water. Elementary chemical reaction of photosynthesis can be expressed as,

$$CO_2 + H_2O \xrightarrow[\text{Chlorophyll}]{\text{Solar Energy (photons)}} CH_2O + O_2$$

where CH_2O is an elementary molecule from which various carbohydrates are formed. Chlorophyll, here, acts as a catalyst.

The average conversion efficiency of the light quanta to biomass is low, and is about 1-2%, which can be compared with the theoretical maximum of about 5-8%. Several methods of improving the efficiency of the photosynthetic processes have been applied as follows.[29]

- application of carbon dioxide
- biologic and genetic modification
- nitrogen fixation
- optimization of plant nutrients

Biomass or organic matter can be produced by cultivating terrestrial and/or marine crops via the natural photosynthesis processes. Terrestrial crops include agricultural products (such as corn, grass, spinach, kenaf, sugar beets, sugar cane, sunflower, etc.) and silviculture products (such as alder, poplar, eucalyptus, cottonwood, sycamore, etc.) Marine crops are algae, kelp, water hyacinth and so on).

Fresh water algae is one of the most promising crops, which grows fast, and is also rich in protein. It can yield up to 70 tons per acre per year, and can be used either for feeding livestock or for producing methane.[29]

For ocean farming, seaweeds such as kelp can be cultivated in the open ocean. The products can be converted to foods for animals and humans, and to a variety of fuels (such as methane or liquid fuels), chemicals, and related products. It was predicted that the annual crop of seaweeds could yield about 400 million Btu per acre per year.[30]

Shown in Figure 39 is a process diagram of the kelp culturing technique before being sent to an ocean farm, and Figure 40 illustrates the conceptual design of a 1000 acre ocean food and energy farm unit. Here, nutrient-rich sea water can be provided to the kelp by constant upwelling of the fresh sea water from the ocean depths.

b) Agricultural and Forestry Residue Conversion

Organic matter can also be obtained from agricultural wastes (such as animal residue, crop residue, etc.), forest residue, and Urban wastes(such as solid refuse, sewage, industrial wastes, etc.).

Production of these biomass resources and conversion to useful fuels involve a variety of physical, chemical or biological processes. Shown in Figure 41 is the representation of the biomass resources and various options of the conversion processes. As an example, a process chart for the production of methane and other products from raw kelp is shown in Figure 42.

CONCLUDING REMARKS

Energy from non-renewable resources such as coal, natural gas, oil and uranium ores, is fast depleting; for instance, gas/oil within decades and coal within centuries. The remedies to prevent a forthcoming energy crisis all over the world may be suggested as follows.

a) Conservation

Every effort should be made to reduce the consumption of non-renewable energy resources for fuel in all residential, commercial, agricultural and industrial sectors.

Figure 43 is a comparison of total energy consumption of the U.S.A. from 1960 to 2000 (provided by the U.S. House Science and Technology Committee).[31] Without conservation efforts, the projected total energy consumption would be 84 million barrels of oil per day equivalent in 2000. With strong conservation efforts, however, the projected consumption is shown to be 56 million barrels of oil per day equivalent in 2000, which is a substantial reduction by 1/3 from the previous total energy consumption.

b) Use of Renewable Energy Resources

The renewable energy resources for fuel should be expeditiously exploited and the use should be increased. Solar energy, among all other candidates, appears to be most attractive since it is available in large quantity (although dilute and intermittent), and is non-polluting.

Most of the solar-related technologies and applications have been briefly described in this paper. Again, these are:

- Solar Collectors
- Solar Thermal Energy Storages
- Solar Swimming Pool Heating Systems
- Solar Domestic Hot Water Heating Systems
- Active Solar Space Heating and Cooling Systems
- Solar Assisted Heat Pumps
- Solar Powered Absorption Chillers
- Solar Activated Heat Engine/Vapor Compression Chillers and Others
- Passive Solar Space Heating and Cooling Systems
- Agricultural and Industrial Applications of Solar Thermal Energy
- Solar Thermal Electric Conversion

- Photovoltaic Energy Conversion
- Wind Energy Conversion
- Ocean Thermal Energy Conversion
- Extraterrestrial Solar Energy Collection
- Bioconversion to Foods and Fuels

In the U.S.A., intensive R&D efforts are being performed on all the above areas except the solar swimming pool heating systems whose technology has been well developed and has resulted in commercialization.

In Europe, R&D efforts cover all listed areas with less emphasis or none on[32] swimming pool heating systems, wind energy conversion, ocean thermal energy conversion, and extraterrestrial solar energy collection. However, the solar still has been added to the R&D list. A solar still is a simple device which can be used to obtain fresh drinking water by evaporation from salty or polluted water.

For Korea, new R&D efforts may be initiated to cover all the listed areas except, perhaps, swimming pool heating systems, ocean thermal energy conversion, and extraterrestrial solar energy collection. Careful studies are needed for the planning of effective R&D programs including the prioritization of the listed areas and for the appropriation of the proper level of funding according to the program needs.

c) Active Government Role

Some of the solar technologies are in the stage of, or near to, commercialization. For example, the SHACOB (solar heating and cooling of buildings) technologies are in the early stages of commercialization.

The success of the accelerated commercialization, or wide spread use of solar energy, depends strongly on its economics against other alternatives. In order for the economics of the solar systems to be competitive with other options, strong governmental support is needed, initially, to remove or ease economic, institutional, and legal barriers, and to provide financial incentives for the consumers.

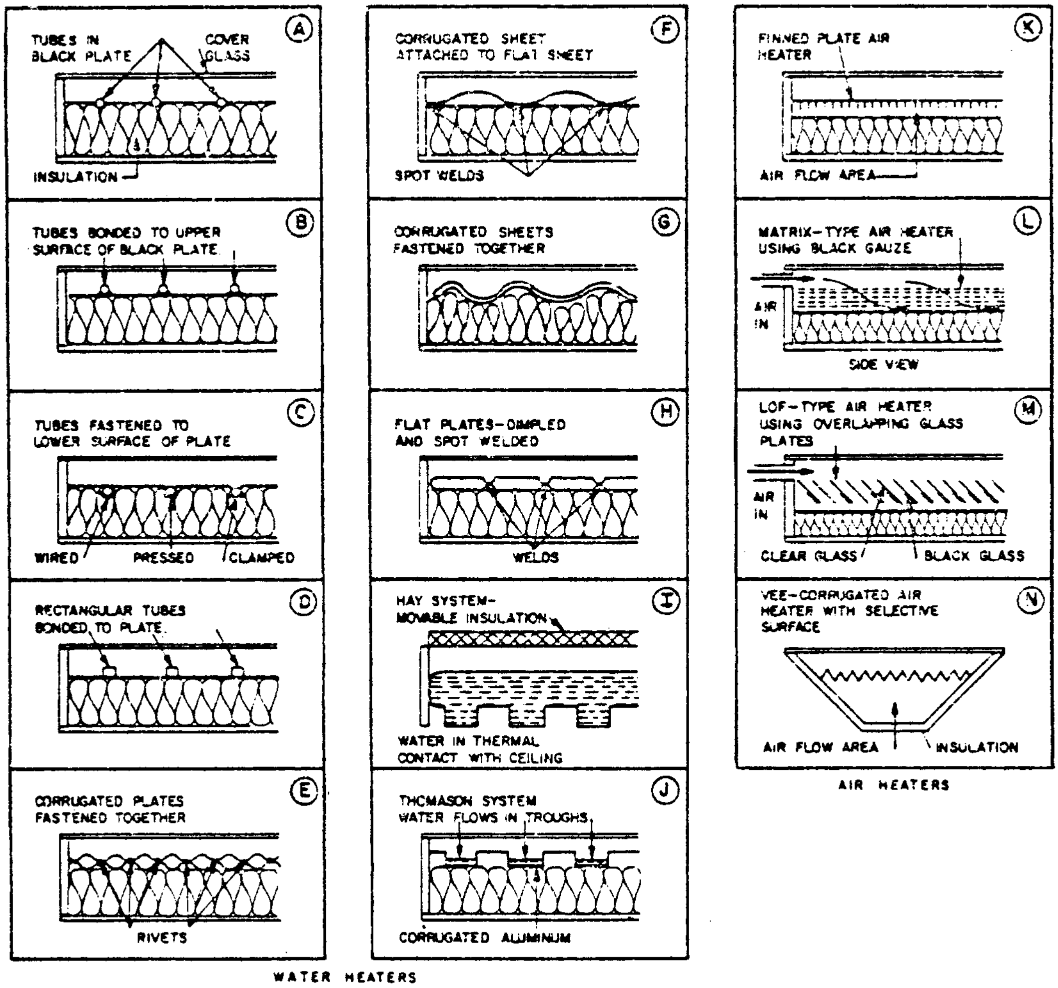


Fig.1 Various Designs of Solar Water and Air Collectors (1)

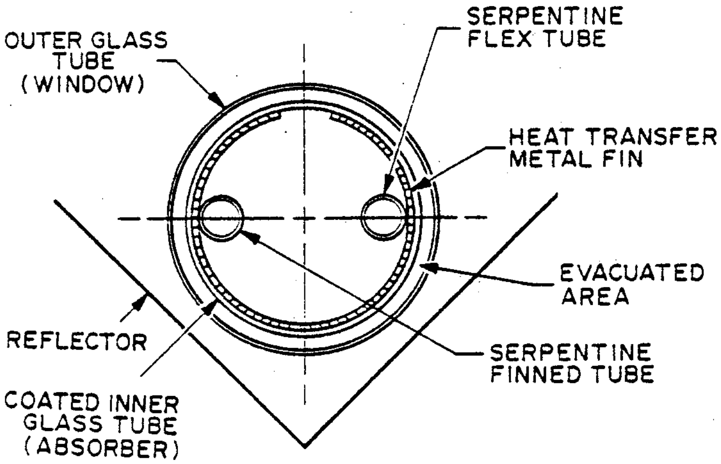


Fig.2 Cross-sectional View of GE Vacuum Tube Solar Collector

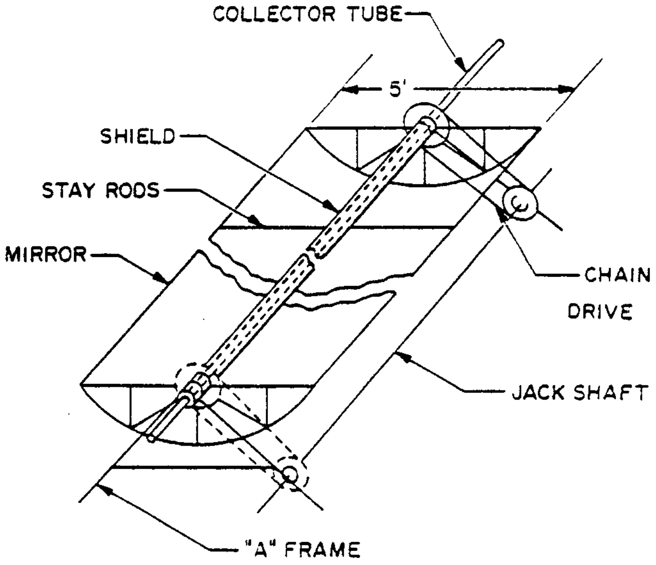


Fig.3 Schematic Diagram of Parabolic Trough Concentrator (2)

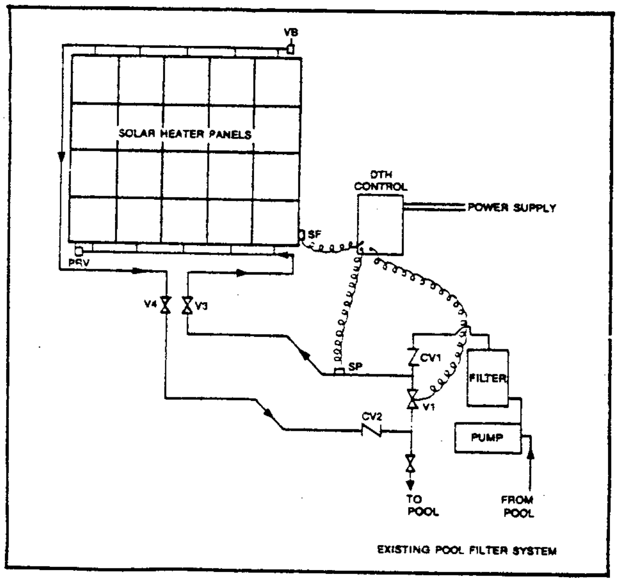


Fig.4 Schematic Diagram of Swimming Pool Solar Heating System (7)

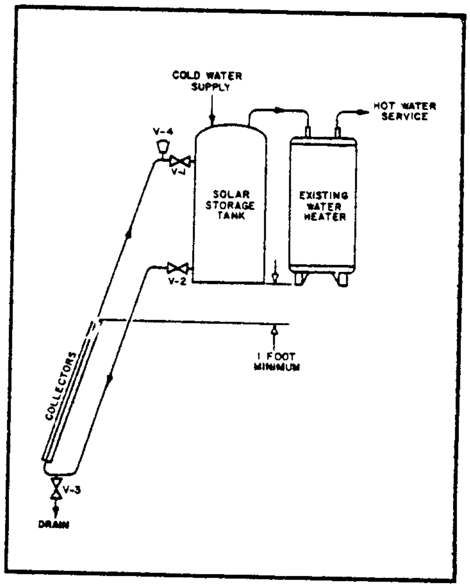


Fig.5 Schematic Diagram of Thermosyphon Type Solar Domestic Hot Water Heating System (8)

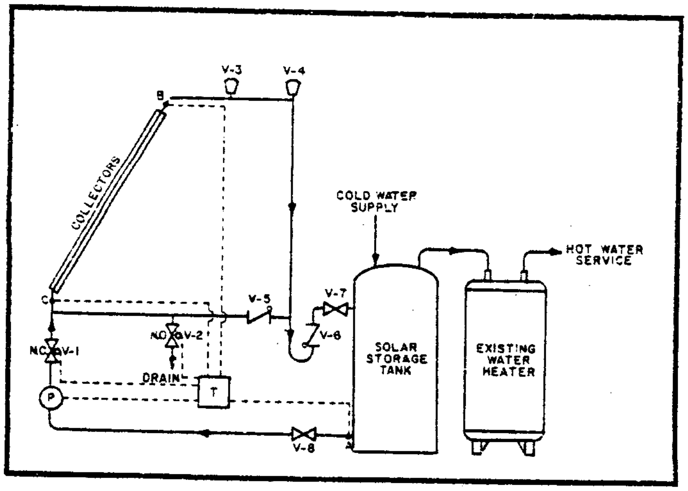


Fig.6 Schematic Diagram of Self-drainable, Forced Convection Type Solar Domestic Hot Water Heating System (8)

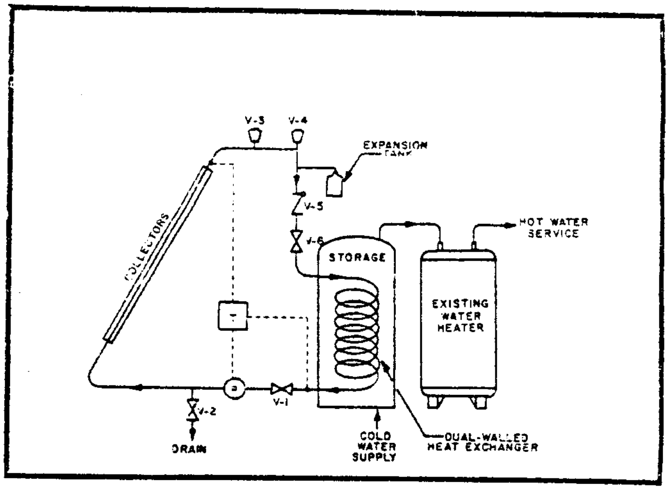


Fig.7 Schematic Diagram of Closed-loop, Forced Convection Type Solar Domestic Hot Water Heating System (8)

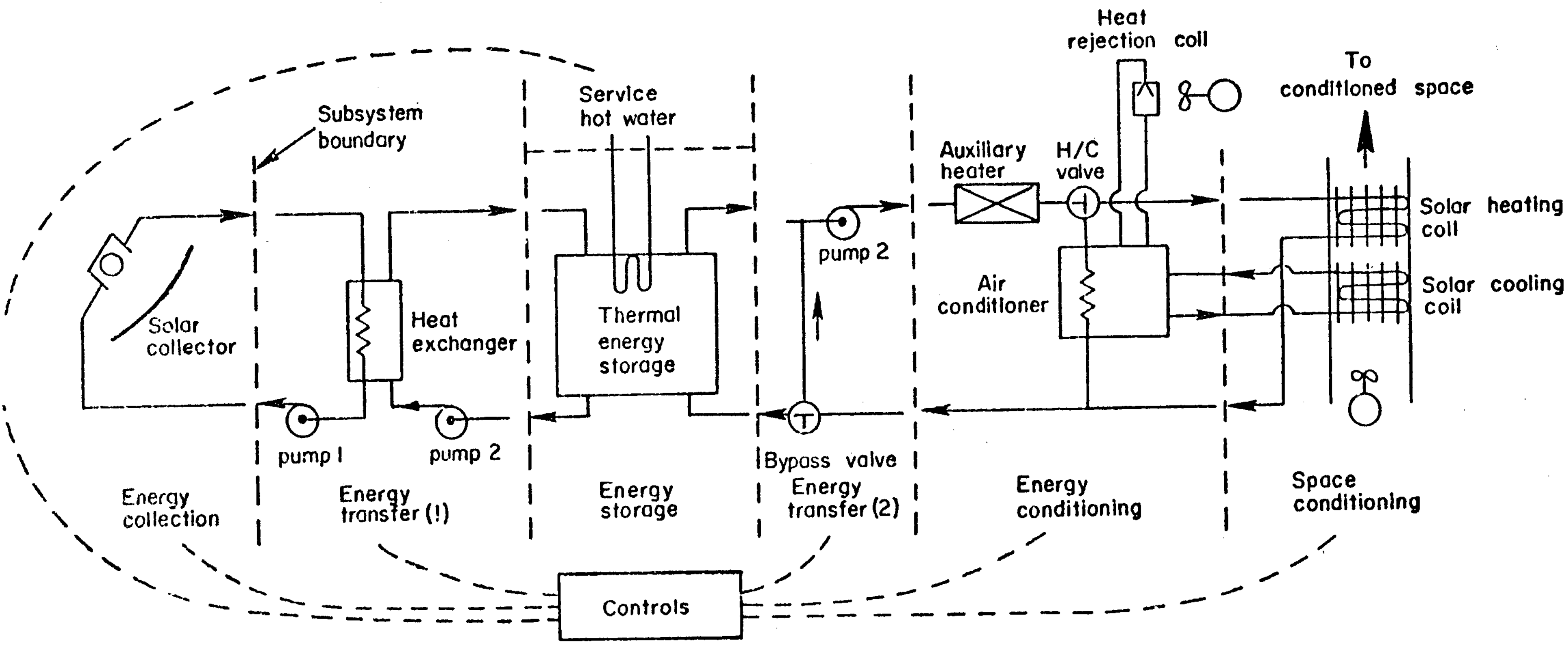


Fig.8 Simplified Schematic Diagram of Typical Liquid Solar Heating and Cooling System (9)

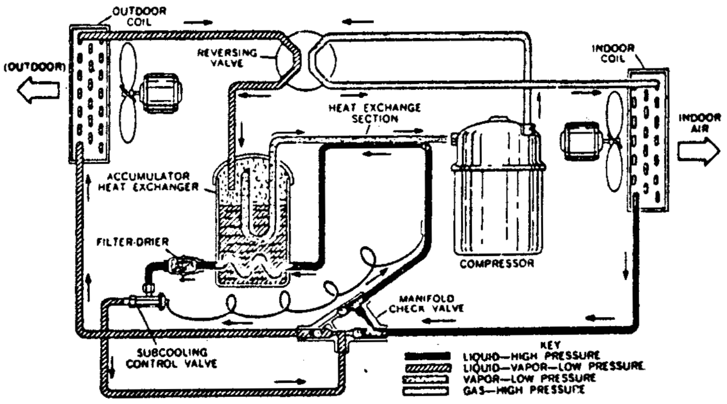


Fig.9a Schematic Diagram of an Advanced, Conventional Air-to-Air Heat Pump in a Heating Mode (Westinghouse)

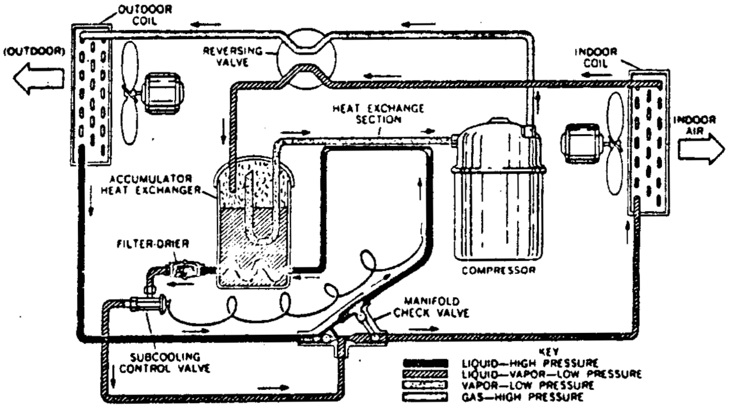


Fig.9b Schematic Diagram of an Advanced, Conventional Air-to-Air Heat Pump in a Cooling Mode (Westinghouse)

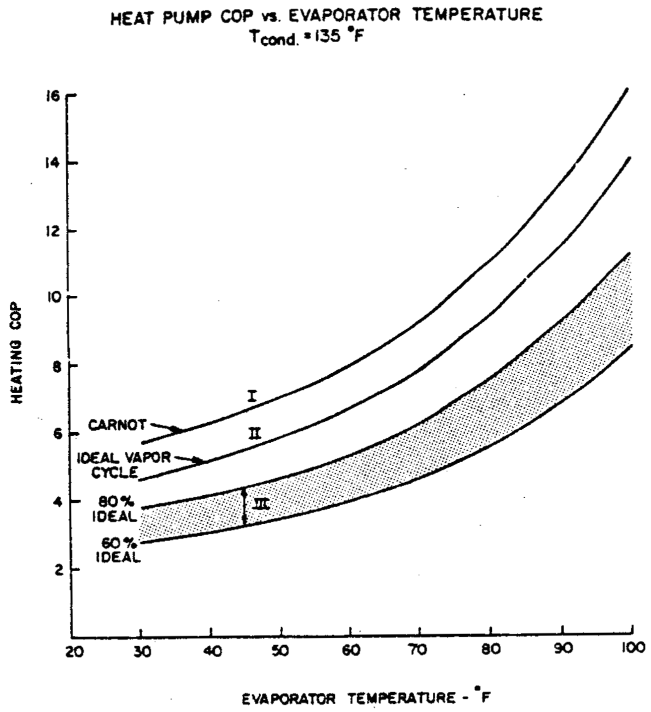


Fig.10 Heating COP of Heat Pump vs Evaporator Temperature at T_{cond} = 135°F (10)

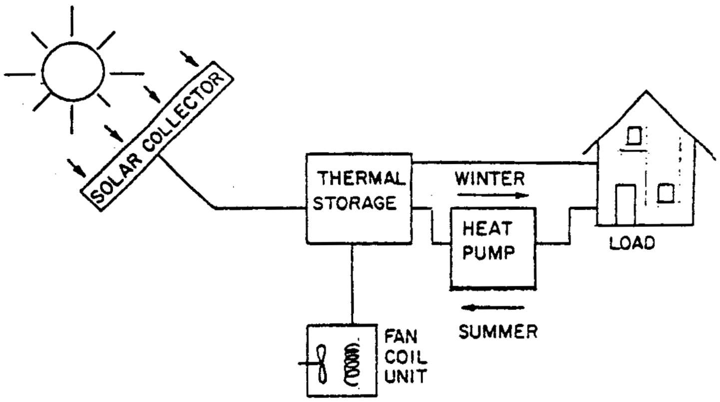


Fig.11 Simplified Schematic Diagram of Solar Assisted Heat Pump System

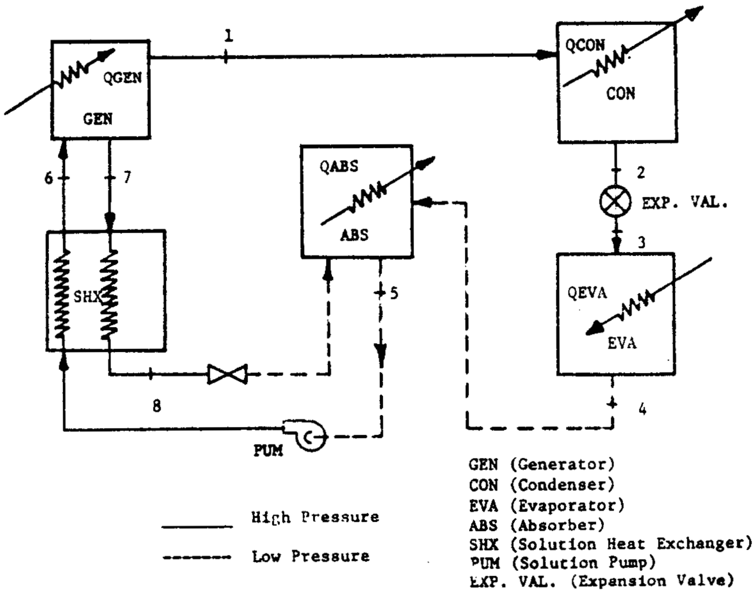


Fig.12 Simplified Schematic Diagram of Standard H_2O-LiBr Absorption Cycle(11)

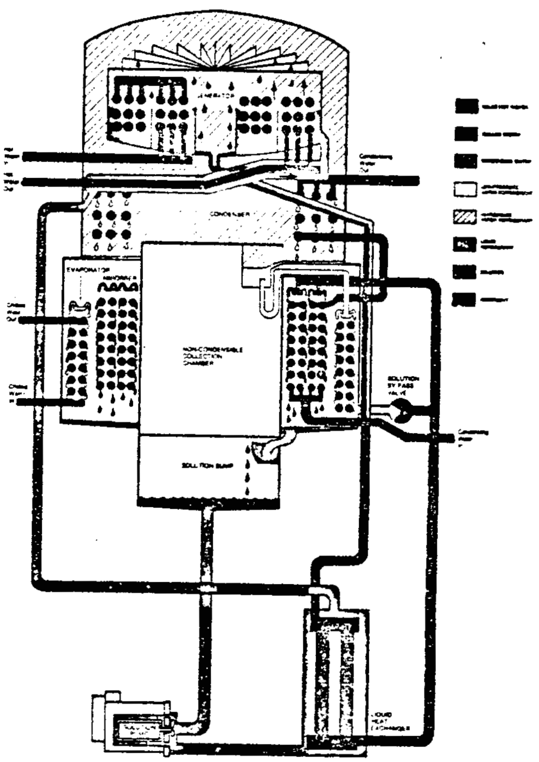


Fig.13 Schematic Diagram of Arkla Solaire 36 Unit (3 ton cooling capacity)

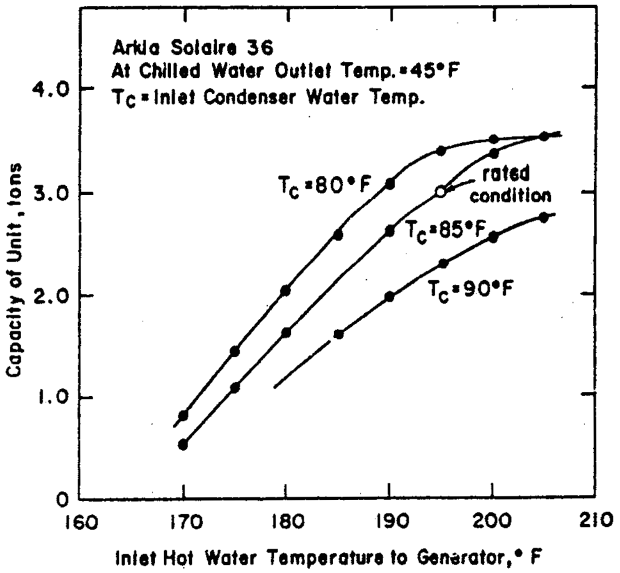


Fig.14 Capacity of Arkla Solaire 36 as a Function of Generator Inlet Water Temperature (11)

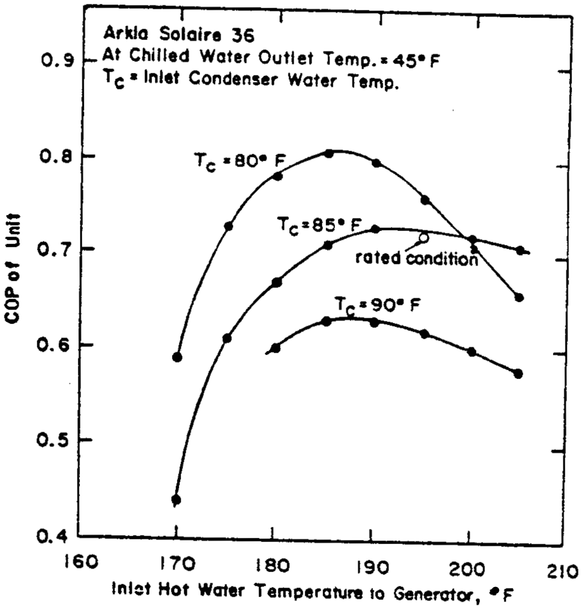


Fig.15 COP of Arkla Solaire 36 as a Function of Generator Inlet Water Temperature(11)

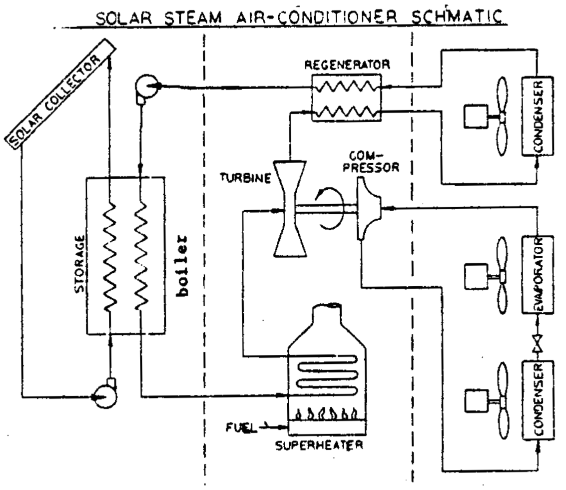


Fig.16 Schematic Diagram of Fuel-superheated Rankine Heat Engine/Vapor Compression Chiller (ETI)

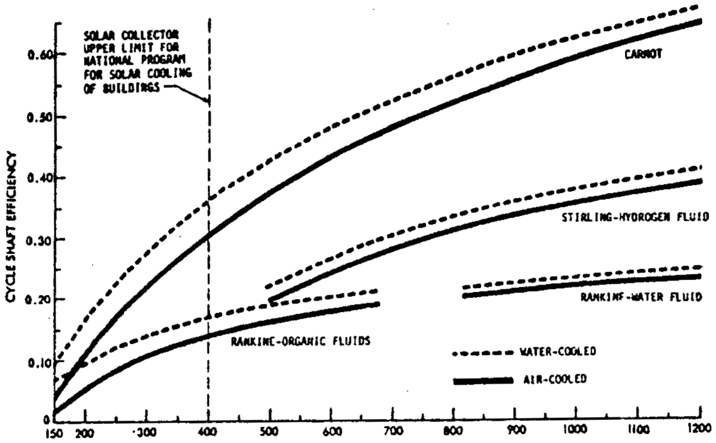


Fig.17 Cycle Shaft Efficiencies of Various Small Heat Engines vs Maximum Cycle Temperature (or Boiler Temperature)(12)

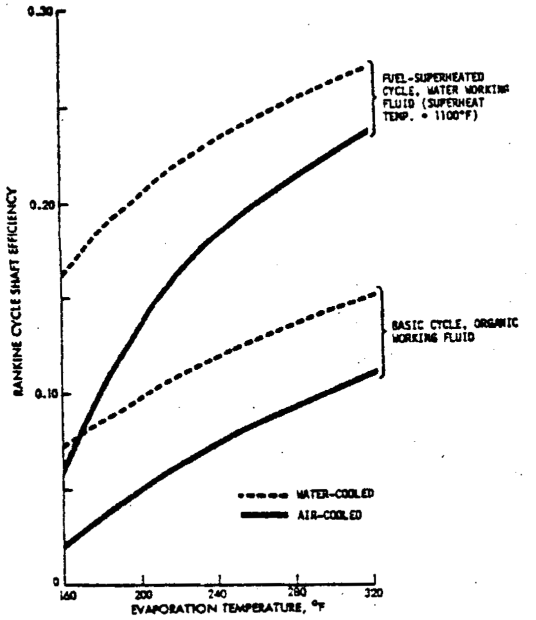


Fig.18 Cycle Shaft Efficiencies for Solar Powered Fuel-superheated Rankine Heat Engine and Basic Solar-Powered Rankine Heat Engine vs Evap. Temp. (12)

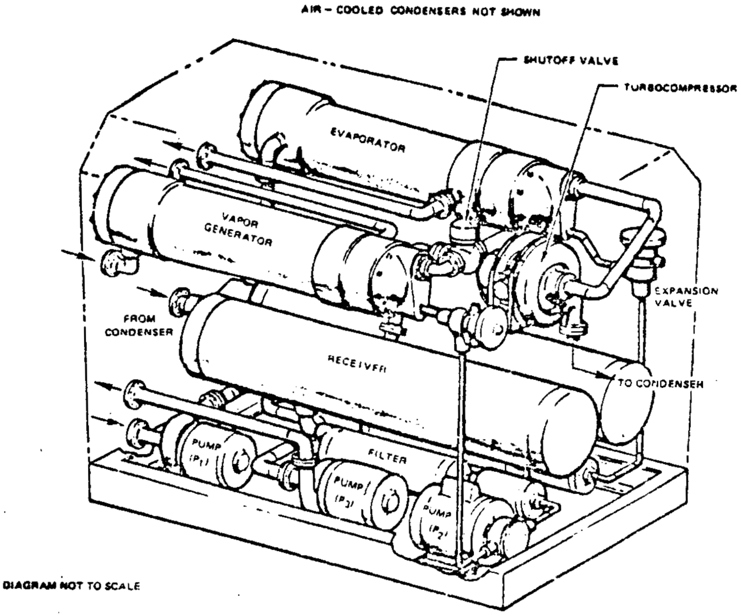


Fig.20 Artist Concept of Solar-Powered Rankine Heat Engine/Vapor Compression Chiller System (United Technologies)

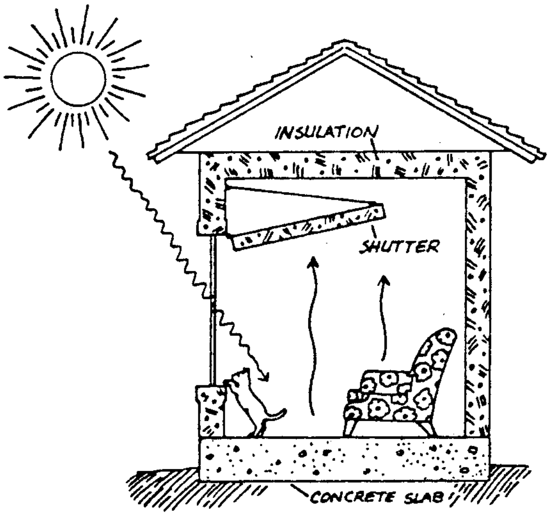
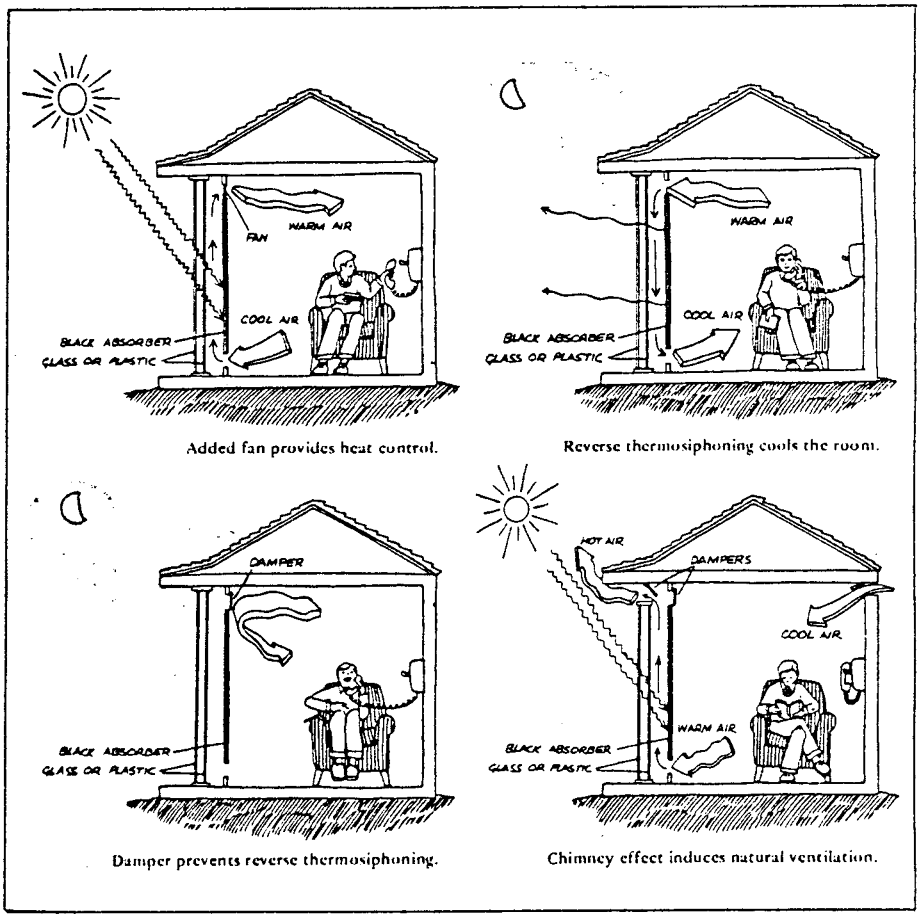


Fig.21 Schematic Diagram of Direct Gain Passive Solar System (14)



Added fan provides heat control.

Reverse thermosiphoning cools the room.

Damper prevents reverse thermosiphoning.

Chimney effect induces natural ventilation.

Fig.22 Schematic Diagram of Indirect Gain Passive Solar System: Mass Wall (14)

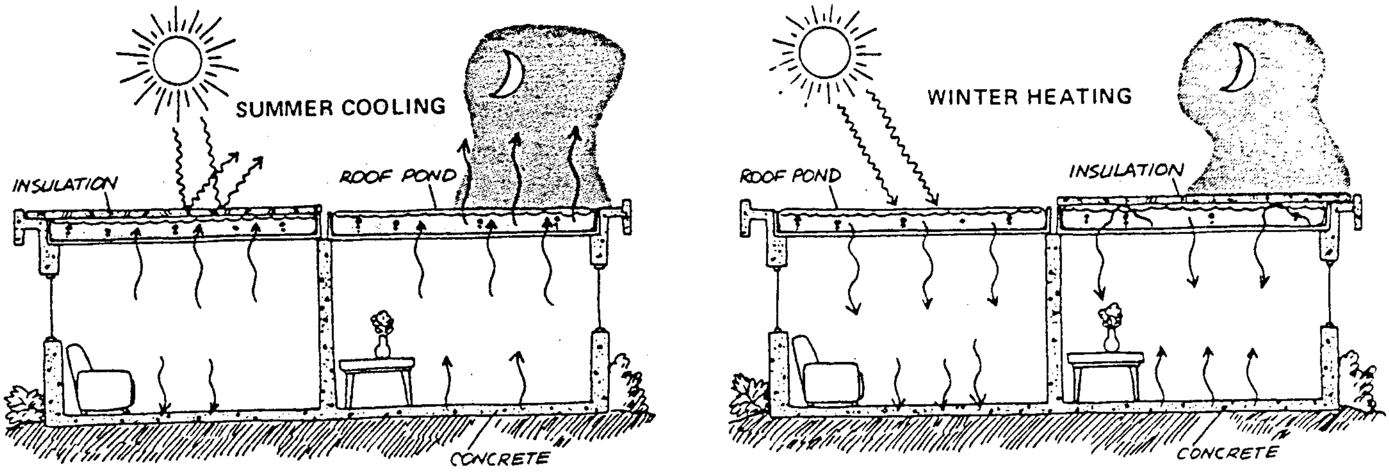


Fig.23 Schemtaic Diagram of Indirect Gain Passive Solar System: Roof Pond (14)

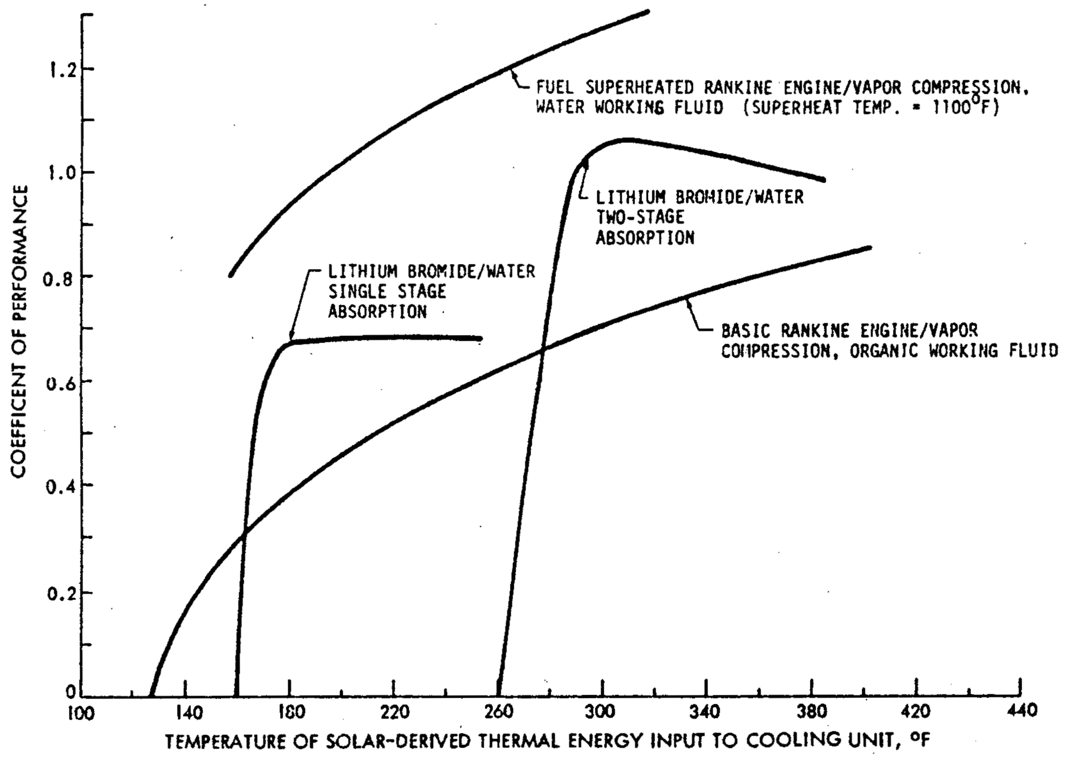


Fig.19 Coefficient of Performance Comparison for Water-cooled Rankine Engine/Vapor Compression Chillers and Absorption Chillers (13)

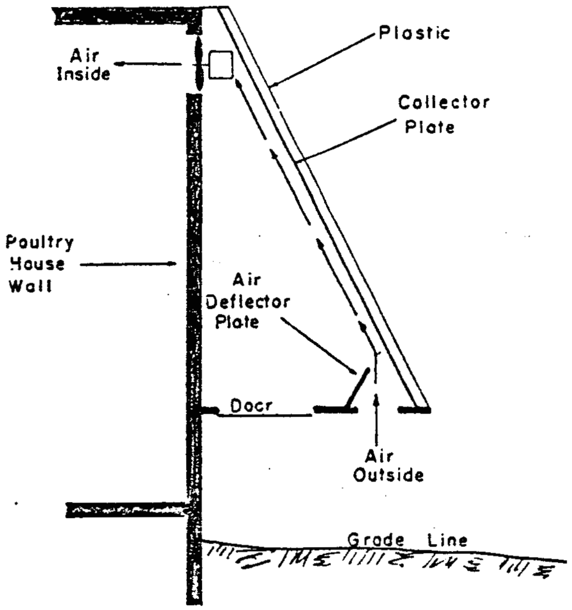


Fig.24 Schematic Diagram of Space Heating System for Poultry House (17)

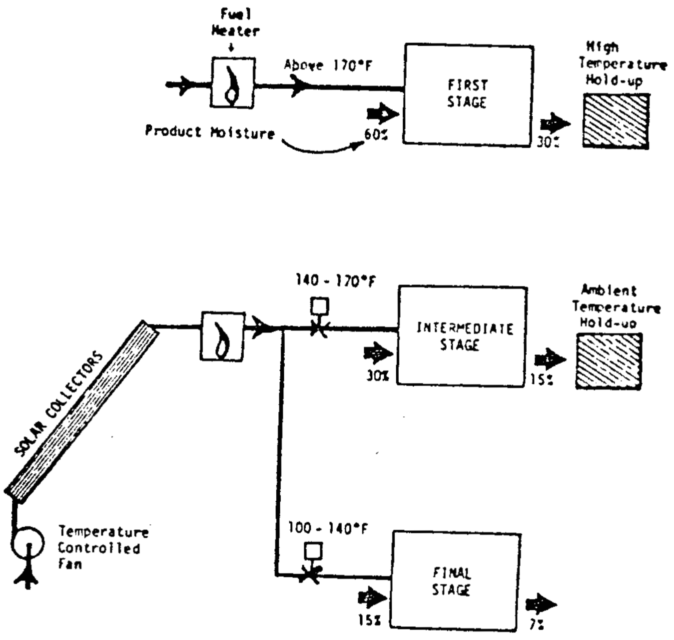


Fig.25 Block Diagram of 3-stage Agricultural Process for Dehydration of Diced Potatoes(18)

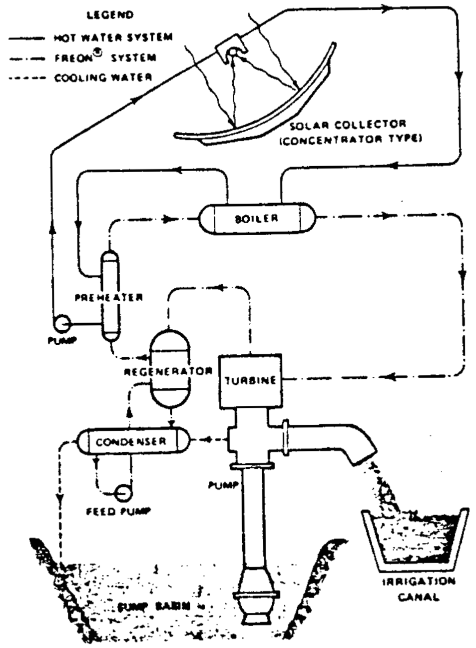


Fig.26 Schematic Diagram of Solar-Powered Rankine Heat Engine System Coupled with Irrigation Pump (19)

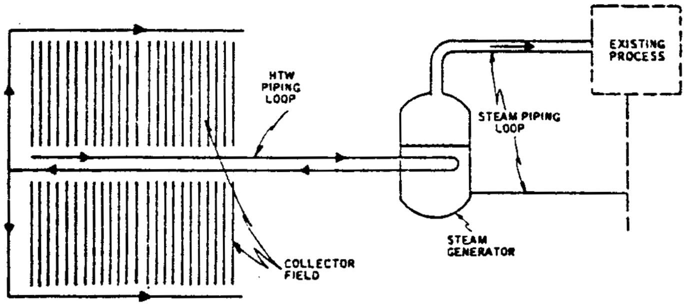


Fig.27 Simplified Schematic Diagram for Production of Industrial Process Steam in Textile Drying (21)

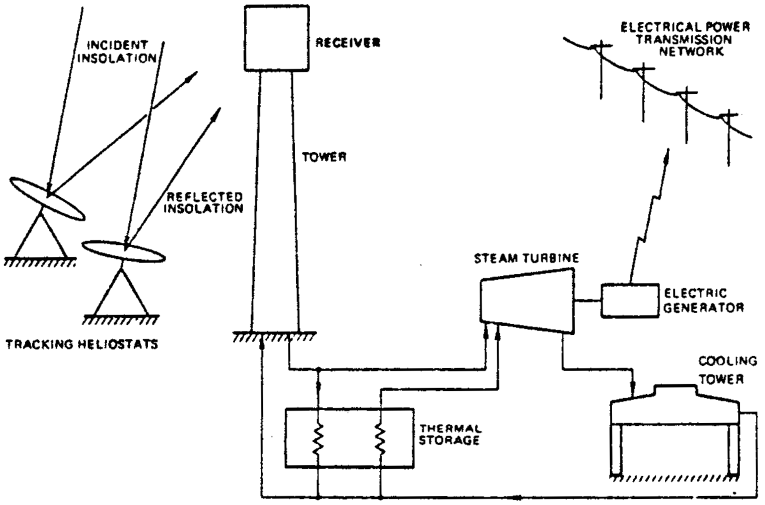


Fig.28 Simplified Schematic Diagram of Solar Thermal Electric Conversion System(17)

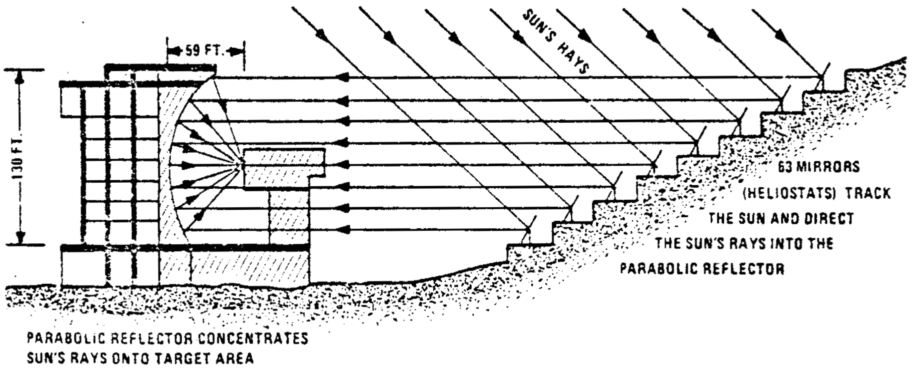


Fig.29 Schematic Diagram of Solar Energy Concentrator for Solar Thermal Electric Conversion System (in France), Solar Eng., p.22,(7/77).

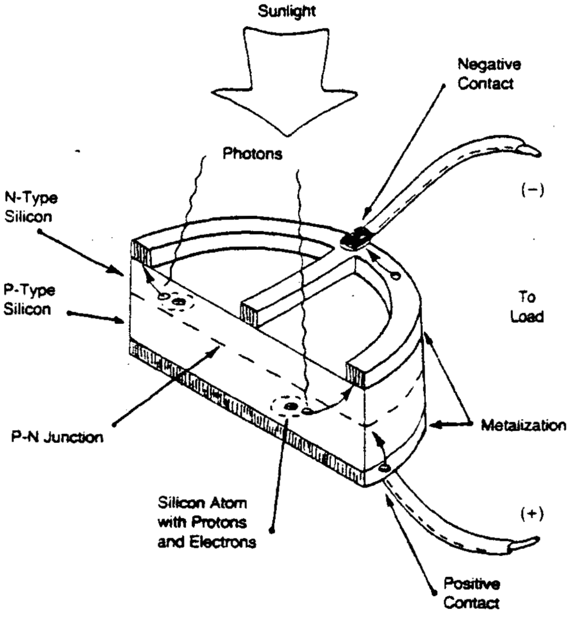


Fig.30 Schematic Diagram of Silicon Solar Cell (23)

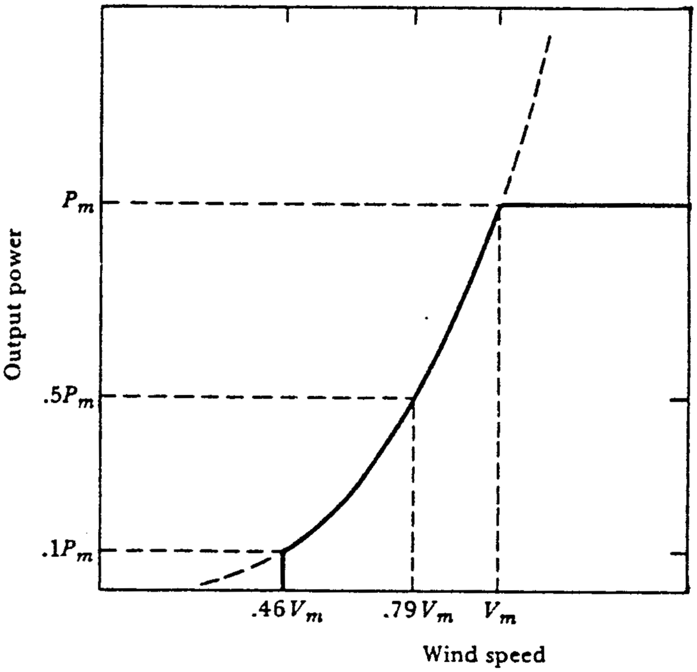


Fig.32 Power Output of a Typical Wind Turbine as a Function of Wind Speed (24)

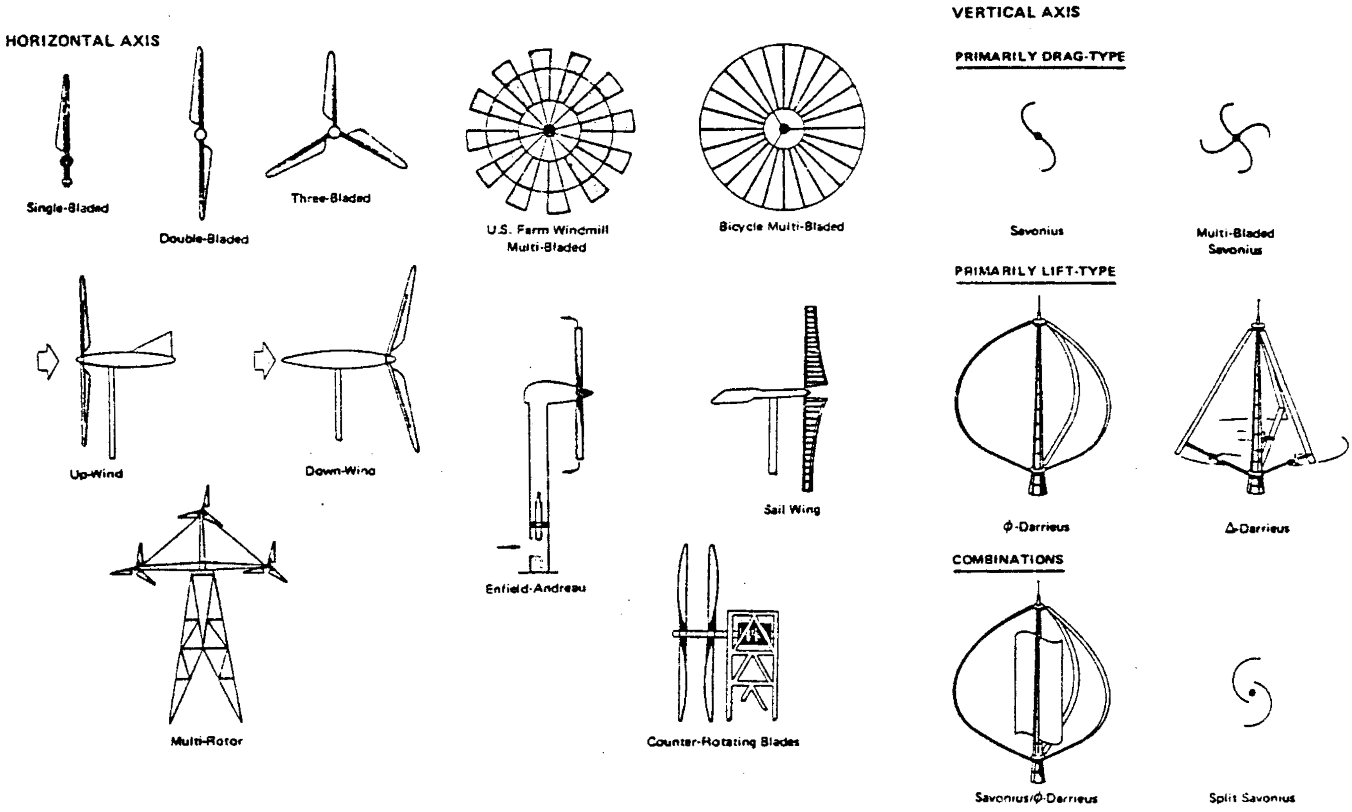


Fig.31 Some Examples of Wind Energy Collectors (17)

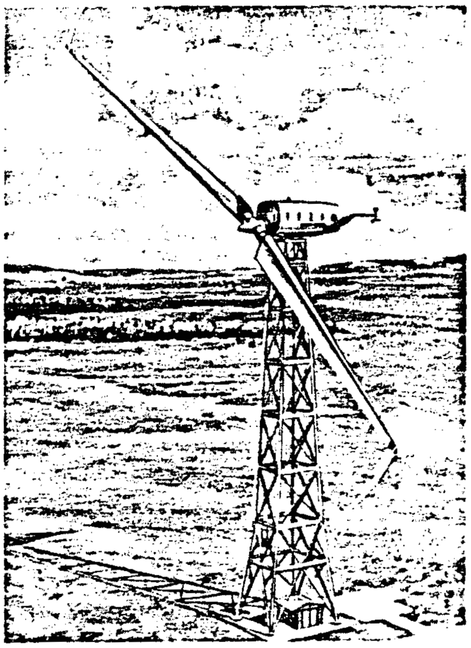


Fig.33 A 200' Diameter Two-bladed Wind Turbine System (U.S.A.) ,(26)

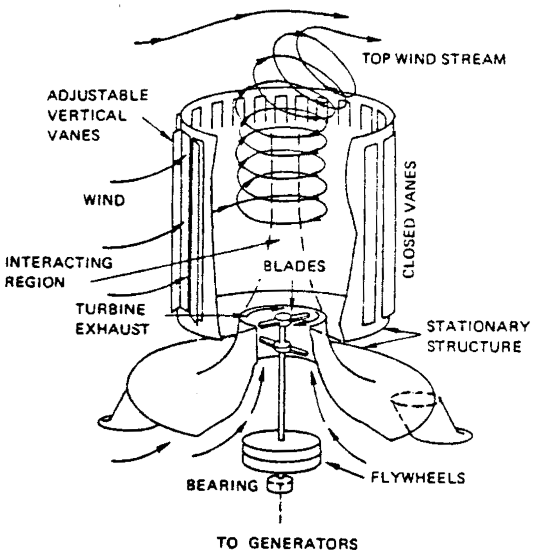


Fig.34 Schematic Diagram of Vortex Tower for Omnidirectional Winds (Grumman Corp.) ,(27)

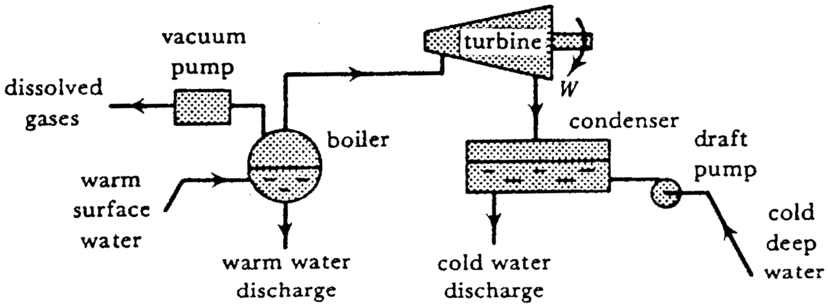


Fig.35 Simplified Schematic Diagram of Open Cycle Ocean Thermal Energy Conversion System(24)

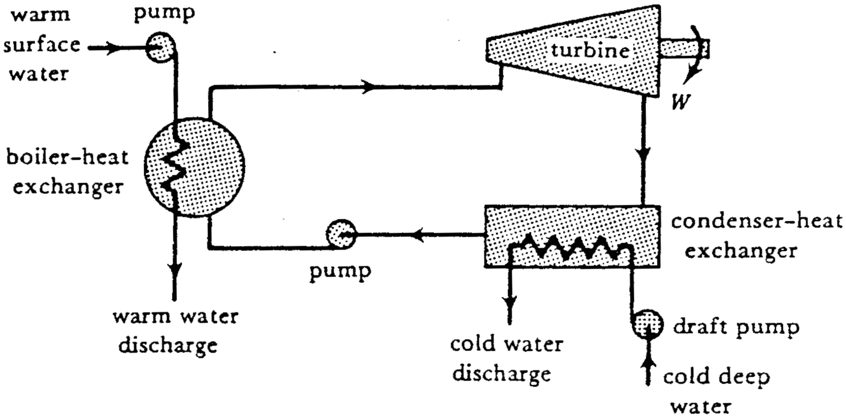


Fig.36 Simplified Schematic Diagram of Closed Cycle Ocean Thermal Energy Conversion System(24)

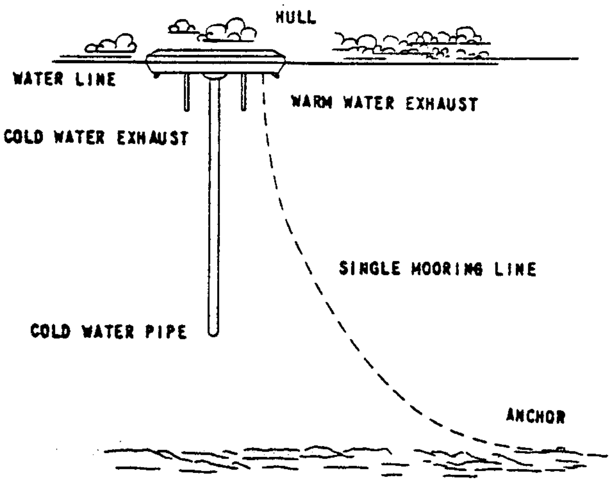


Fig.37 Artist's Conceptual View of OTEC System (17)

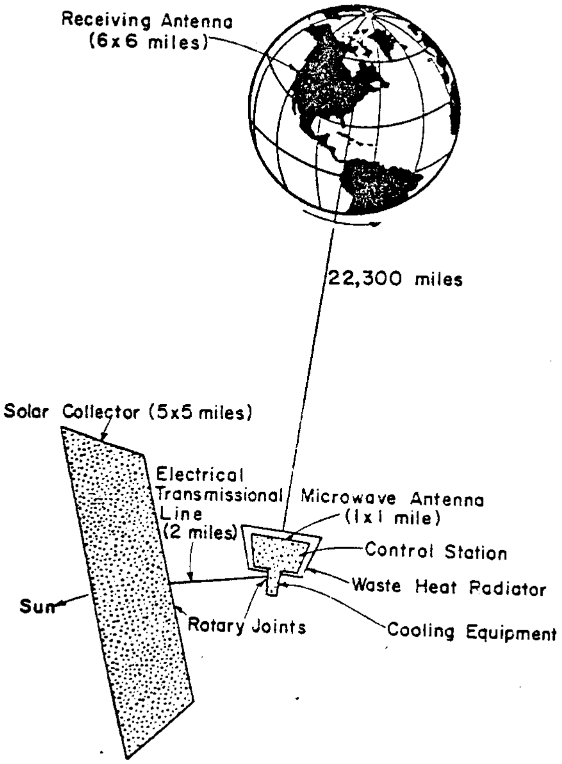


Fig.38 Conceptual View of Satellite Solar Power System (17)

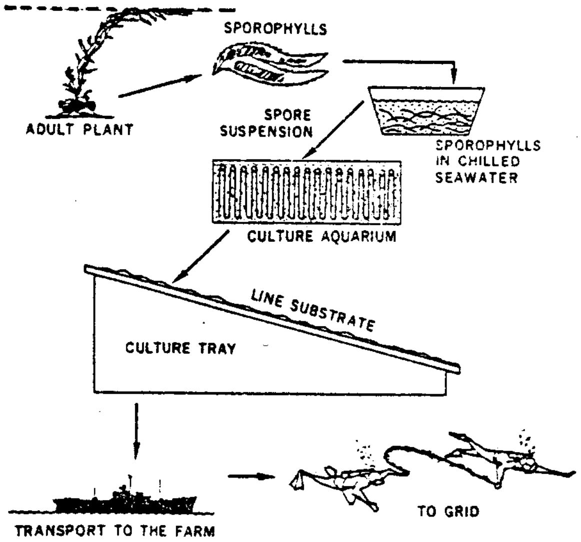


Fig.39 Process Diagram of Kelp Culturing Technique(30)

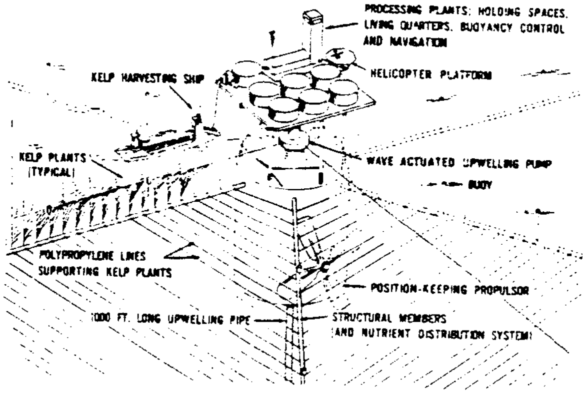


Fig.40 Conceptual Design of 1000-acre Ocen Food and Energy Farm (30)

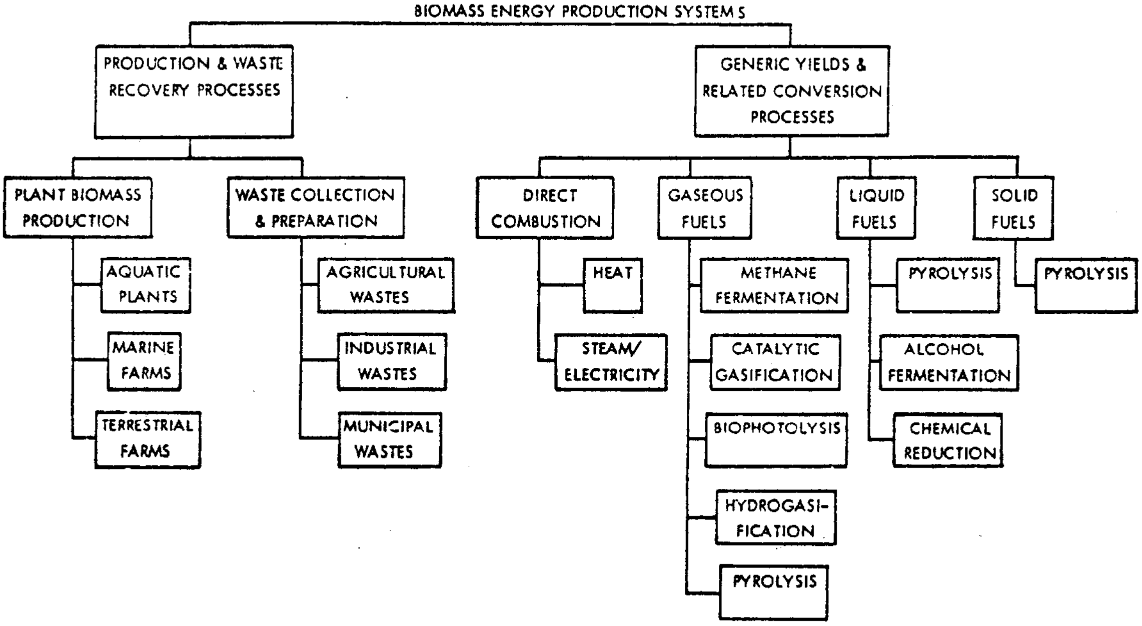


Fig.41 Representation of Biomass Resources and Various Options of Conversion Processes (17)

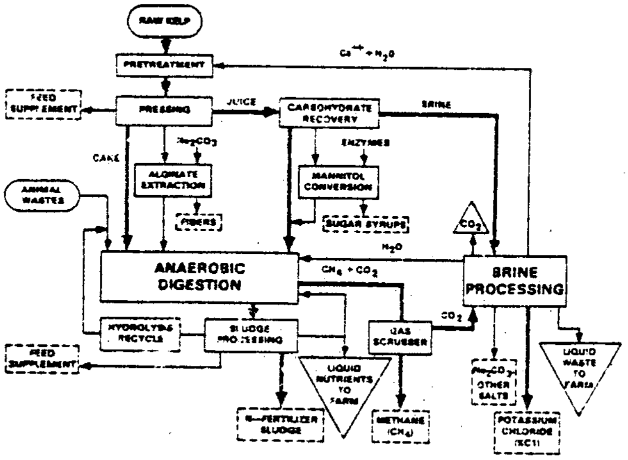


Fig.42 Process Chart for Production of Methane and Other Products from Raw Kelp (30)

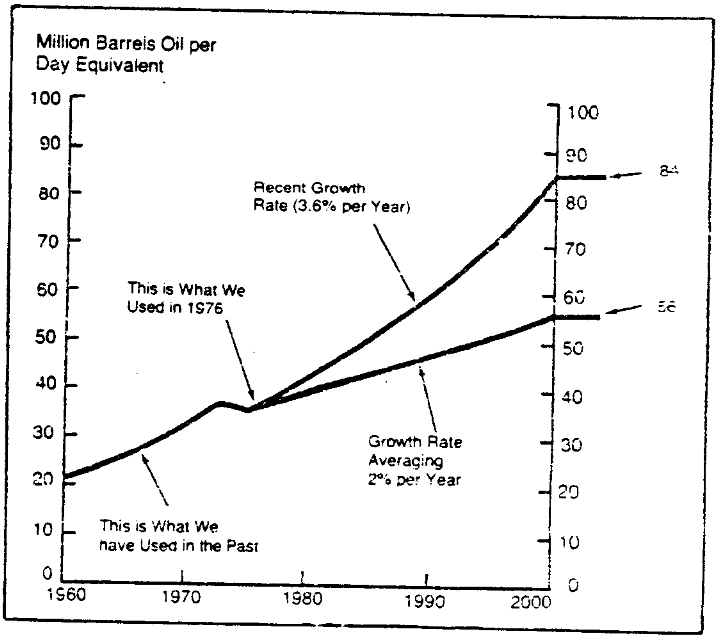


Fig.43 Comparison of Total Energy Consumption of USA from 1960 to 2000 (31)

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