Solar Heating and Cooling (3.7)

Introduction and Overview (3.7-1)

Solar radiation is an abundant yet diffuse source of energy. In its diffuse form it can be used for space and water heating; alternatively it can be concentrated to provide industrial process heat or to generate electricty. It has been estimated that solar energy technologies may contribute up to twenty Quads[133] or twenty percent to the national energy budget by the year 2000. (1 Quad = 10^{15} Btu)

The following four major solar conversion technologies are considered here:

- Solar Heating and Cooling
- Solar Thermal Electricity
- Ocean Thermal Energy Conversion (OTEC)
- Solar Photovoltaics

The first technology, solar heating and cooling applied to space heating and water heating, includes very simple systems as well as some of the most advanced technology in the solar field. These low-temperature applications of solar energy are practical for both residential and industrial use. Solar energy can be used to heat structures simply by architectural design that enhances the solar gain of the structure. The efficiency of solar heating can be increased as conservation and other heat retention methods (e.g., insulation) are incorporated into the design.

Another way to absorb diffuse solar energy is to heat air or water in a flat plate collector. This collector is basically an absorbing surface in contact with channels that circulate the air and water to be heated. These components are usually placed in a glazed, insulated box to maximize heat gain.

To generate temperatures greater than 180°F (82.2°C), solar energy must generally be concentrated. This is achieved by focusing the solar radiation that falls on a large collector surface onto a smaller receiving area. Collectors with a reflective surface shaped into a trough can produce temperatures up to 500°F (260°C) in a receiver at the line of focus. Parabolic dish-shaped concentrators capable of focusing sunlight can raise temperatures in the receiver up to 1500°F (185.6°C). Equally high temperatures can be achieved with fields of mirrored, flat solar tracking collectors called heliostats that direct sunlight to a central receiving point. Steam produced from these high temperatures can be used to generate electricity with a conventional steam turbine. Organic fluids that boil at lower temperatures can be solar heated between 200°F and 500°F and used to power a turbine called an organic Rankine cycle.

Photovoltaic (PV) cells generate an electric current by using the sun's energy directly to initiate a flow of electrons within the materials that comprise the solar cell. They can be grouped in flat plate modules or placed at the focus of concentrators with parabolic troughs or Fresnel lenses.

The abundance of solar energy makes it an ideal energy source for decentralized energy systems. Storage methods can extend its use to non-sunny periods. It is a resource that can be "mined" everywhere. Every country has some access to this resource, although not every country has equal access to the technology required to use it.

Solar energy can be used at many levels, from individual remote applications to centralized power stations. The overall ability to mix and integrate these levels gives solar energy its flexibility.

The following discussion of solar heating and cooling, solar thermal electricity, ocean thermal energy conversion, and solar photovoltaics includes a description of the theoretical basis of the technology, its practical applications, an assessment of its current state of development, current or projected costs and energy potential, strategies that will speed commercialization and an analysis of its appropriateness for centralized or decentralized applications.

From the viewpoint of community self-sufficiency a major advantage of passive solar applications (and of the simpler kinds of active systems) is that they can be implemented in most cases with readily available materials and local manufacturing resources and personnel. In an emergency, such as a prolonged breakdown of the national electrical power grid, this local fabrication capability could contribute significantly to survival. Materials like wood, glass, sheet metal and black plastic tubing are easily obtained in most communities, or salvageable from other applications, along with such critical components of active systems as motors, pumps and valves. The skills to install and maintain these systems are present in local manpower pools (electricians, plumbers, carpenters, glaziers, etc.).

On the other hand, solar photovoltaics also offer certain advantages for community self sufficiency. PV power is instantly available once the modules are deployed. They require virtually no maintenance. The stockpiling of solar PV arrays as a source of emergency power for critical needs (along with the requisite storage batteries if 24-hour power in required) could be valuable insurance for many community agencies (e.g. fire, police, health care, local government).

Space Heating and Cooling Applications (3.7-2)

Solar radiation reaching the earth's surface is composed primarily of shortwave visible light and longwave infrared heat.[134] When shortwave solar radiation strikes a surface it is either reflected, transmitted, or absorbed. If the light is absorbed, it is transformed into heat. The heat is either stored in an object, conducted to adjacent cooler objects, or re-radiated to space.

Solar space heating is based on the fact that glass transmits light, but reflects heat. While the shortwave "light" component of solar radiation is transmitted through glass, the longer wave infrared "heat" component is absorbed by the glass or reflected to the exterior. When the transmitted light hits an interior object, the light is absorbed by the object and converted into heat. This heat is radiated from the object to the air in the structure and glass prevents the rapid loss of heat. On cloudy days or at night, interior heat is absorbed by the glass and conducted to the exterior. Heat loss can be minimized by using conservation techniques such as insulating shutters inside or outside the glass.

Heat retention within the structure can be increased by the use of "thermal mass" or materials with high sensible heat capacity such as rocks, water, tile, masonry, adobe, or materials which store latent heat such as eutectic salts. Thermal mass heats up and cools off more slowly than air. Its presence moderates the air temperature changes in the structure by absorbing excess heat during the day and gradually releasing it when the air temperature drops below that of the thermal mass.

There are three basic approaches to solar space heating and cooling and water heating design. They are referred to as passive, active, and hybrid.[135]

Passive approaches rely on both the natural upward flow of hot air or hot water to distribute heat from the point of collection to the point of use or storage and on the conduction of heat from exterior to interior through walls with subsequent re-radiation to interior objects.

Active systems use fans or pumps to move hot and cold air or water in directions other than those they would go if left undisturbed. Thus an active water heating system's storage tank can be below the collector because a pump forces the hot water down, overpowing its natural upward convective motion.

The hybrid approach, uses a mix of the above technologies. Usually the distinction between a hybrid system and an active system is that they hybrid systems use a passive collection technique with an active distribution system.

Passive Solar Heating

In the passive approach to solar heating and cooling, the size and configuration of standard architectural elements are modified so they significantly contribute to the collection, distribution, and storage of solar energy in cool weather and the rejection and ventilation of heat in warm weather.[136, 137]

Thus south-facing glazing is emphasized to maximize winter solar gain. External shading devices and vegetation are employed during summer months to minimize solar gain. Floors and walls can be made massive to store excess collected heat for nighttime or cloudy-day use in the winter. During the summer, the mass effectively reduces the daytime air temperature because of its ability to retain far more heat per cubic foot (meter) than air. It can then be "flushed" of heat at night through ventilation and re-radiation to the surrounding area.

Good ventilation is especially important in passive structures since they usually rely on natural air flow for cooling. By the appropriate choice of the number, size, and location of windows, vents, doors, and chimneys, cool nighttime breezes can be pulled in as the interior hot air is exhausted by convection. While passive cooling works well in hot, dry climates because they become cool at night, it is not effective in hot, humid ones that stay hot all night. However, new techniques in passive cooling are being evolved rapidly to deal with this problem.

The orientation of the structure on its site is also extremely important. The ideal location is one that receives the greatest amount of sunlight between 9:00 AM and 3:00 PM during the winter months. If the structure is located at the northern edge of the sunny area on the site, outdoor shading will be minimized. Generally an east-west long axis takes advantage of solar gain in the winter and minimizes heat gain from the hot western sun in summer afternoons. However, the optimal building geometry does vary significantly in the country's four major climatic regions.

A structure can be warmed or cooled by its relationship to local topography, sun angles, trees and other plants, ground water, precipitation patterns, and other aspects of local climate and geography.

The simplest passive solar design is direct gain. The sun directly enters the living space through large double-paned south-facing windows or rooftop clerestories. The roof angle and overhang are designed to maximize entry of low-angled winter sun and minimize entry of high-angled summer sun. The entering sunlight directly hits the storage materials, such as walls and floors, and transfers its energy to them.

Overall, direct gain design lends itself to successful operation in cool areas with cold but relatively clear winters and hot-dry summers. Cloudy days usually require back-up heat. Increased mass can offer longer storage, but increased mass in very cloudy and foggy climates is not advised because the mass takes longer to heat and adequate storage may rarely be achieved, resulting in underheating.

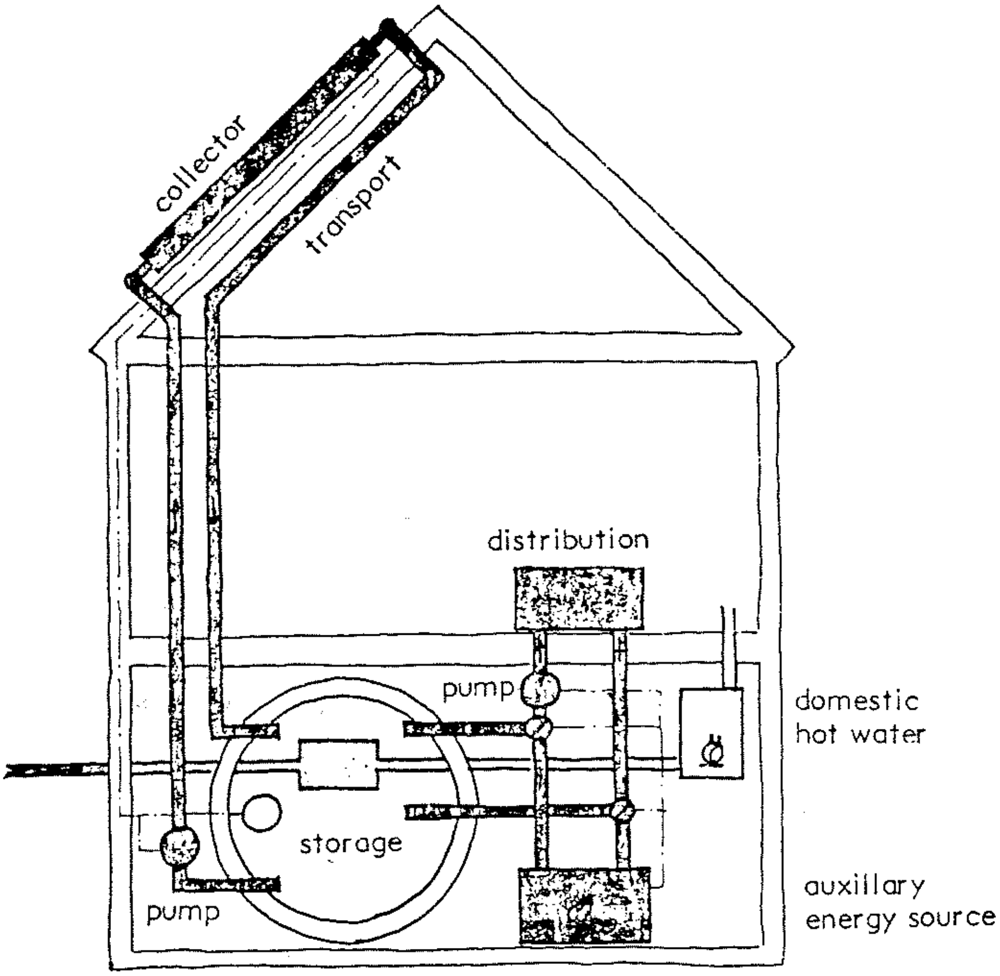
With indirect gain systems, the thermal mass is situated between the sun and the living area. The thermal mass is warmed and transfers its heat to the living areas by either direct radiation or through convection currents of warm air. There are four basic indirect gain strategies: 1) thermal storage walls of masonry or water located behind south-facing windows; 2) ponds of water located on a heat-conductive roof; and 3) a south-facing attached greenhouse that shares a common wall with the structure to be heated; and an air collector located beneath the structure.

Active Solar Heating

Active solar space heating systems use flat plate collectors to heat air or liquids which are circulated to a heat exchanger directly to the point of use or indirectly via rockbed, water or eutectic salt storage.[138, 139, 140] Figure 3.7-1 shows a typical liquid flat plate solar system.

Figure 3.7-1[141]

LIQUID FLAT PLATE SPACE HEATING SYSTEM



Sunlight enters the collector, usually through a glass or plastic glazing and heats the absorber plate—a black metal or plastic surface that is in direct contact with channels through which air or liquid is circulating. The collector is designed to maximize heat flow from the hot absorber plate into the circulating air or liquid. To improve performance heat loss from the absorber plate is minimized by: 1) covering the collector with a transparent glazing to reduce convective and radiant heat losses; 2) surrounding the absorber with an insulated box and 3) coating the absorber plate with a selective surface to reduce radiant heat loss.

Flat plate collectors are generally mounted on a building or on the ground in a fixed position at prescribed angles that vary with the geographic location, collector type and the use of the collected heat. The optimum collector orientation for space heating, or combined space and domestic water heating, is due south. Ideally, collectors should be tilted up from the horizontal at an angle equal to the site's latitude plus fifteen to twenty degrees for space heating and at an angle equal to latitude for water heating. If the angles differ somewhat from optimum, the system will still function, but may require a larger collector area.

Liquid-type solar collectors commonly use water as the heat-transfer medium. Antifreeze and corrosion inhibitors are common additives. The treated water carries heat from the collectors to an insulated storage tank. When heat is needed in the structure, it flows from storage through radiators, or air ducts, if a heat exchanger is used.

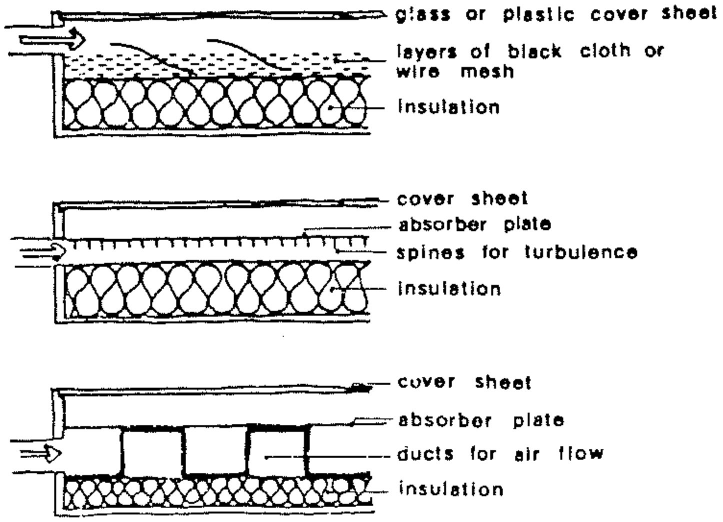
Air-type collectors are used in conjunction with rockbeds, water or eutectic salt storage. Warm air from the collectors flows directly into the building's air circulation system or indirectly into storage. When the rooms are sufficiently warm or when the building is unoccupied, the heated air is diverted to the storage bed, where more heat is stored with each pass through the collector. Rockbed temperatures are stratified: 140°F (60°C) on the top and 70°F (21°C) at the bottom. During the night or cloudy days, heat is removed from storage by circulating cool room air through a warm rockbed.

Air systems are relatively easy to integrate with a conventional forced air heating system found in most homes. Freezing, damaging leaks and corrosion that can occur with liquid systems are eliminated. However, duct length should be minimized to prevent excessive heat loss, and leaks are harder to detect.

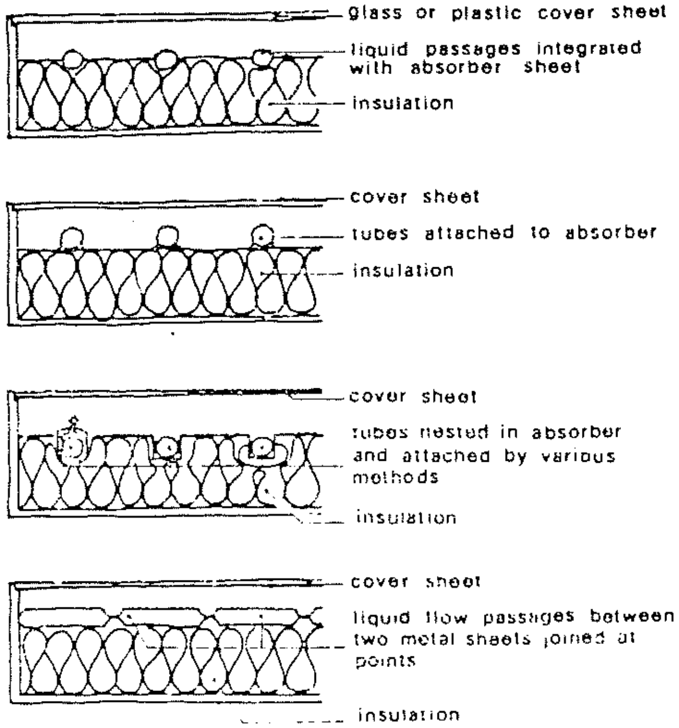
In either kind of system, a back-up system is needed when storage temperature drops below room temperature. The back-up may be a gas, oil, or electric hot water boiler, forced air furnace or an electric heat pump. The back-up system should be large enough to carry the total heating load during extended periods of cold cloudy weather. Figure 3.7-2 shows types of air and liquid collectors.

Figure 3.7-2[142]

AIR AND LIQUID COLLECTORS, CROSS SECTION



A Air collectors



B Liquid collectors

The average household requires 250 square feet of collector for an active heating system. Installed costs average $40-$60 per square foot for the entire system with a total average cost of $10-$15,000. Self-installed systems are one half to two-thirds the price. Costs are somewhat less in new housing.

Solar Cooling Systems

Active solar cooling is a developing technology for which there is a potentially large demand, especially in hot-humid climates where nocturnal cooling techniques are only marginally successful. DOE estimates for 1985 that 75 percent of all residential and commercial structures will have air conditioning units that will require as much electricity annually as electric heating systems.[143, 144]

General Electric Company's Solar Heating and Cooling Program Manager, William Terrill, predicts that new construction and retrofits will create a demand for over three million conventional air conditioning units in the residential market by the mid-1980s.[145] In the commercial market, sales of over three million tons of cooling capacity are predicted (with units ranging up to twenty tons).[146]

There are three basic cooling technologies: absorption chillers, vapor compression chillers, and adsorption or dessicant chillers. Solar energy can be used to totally or partially power any of these systems.

Traditionally absorption chillers have been fired with pressurized hot water or steam. However, solar heated water can be utilized. Regardless of the energy source, absorption chillers have two working fluids, a refrigerant and an absorbent which are circulated in a closed system. The refrigerant is usually water; the absorbent, lithium bromide. An ammonia/water-refrigerant/absorbent combination can also be used.[147]

An evaporator containing the refrigerant is located in the space to be cooled. The heat from the room vaporizes the refrigerant. The vapor goes to the absorber which contains the absorbent solution. The absorbent solution with the refrigerant is pumped to the regenerator, where the heat source is used to vaporize the water from the absorbent. The vapor is condensed and circulated to the room where the entire cycle is repeated.

Solar adapted absorption cooling is the most commercialized of the three cooling technologies. Conventional chillers were originally designed to operate efficiently with pressurized hot water or steam at temperatures between 220° (104.4°C) and 250°F (121.1°C). Now chillers are available that run on temperatures ranging from 170°F (76.7°C) to 195°F. This allows them to be used with selective-surface flat plate collectors. Efficiency and reliability are still problems at these lower temperatures.

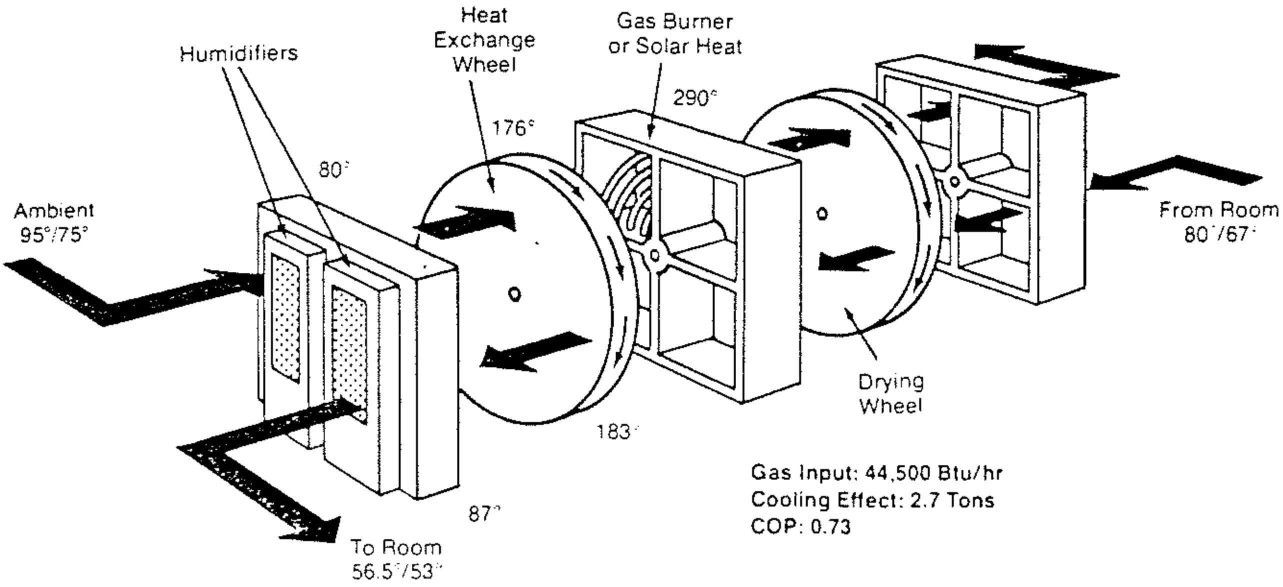
However, conventional chillers can be used with collectors that produce water at higher temperatures. Collectors with cylindrical evacuated tubes or concentrating parabolic trough collectors are capable of achieving the temperatures necessary to power the conventional absorption chiller.[148]

The typical air conditioning unit used today is the vapor compression type. Vapor compression units have a liquid refrigerant that is vaporized by the heat in the space to be cooled. A compressor condenses the evaporated refrigerant into a liquid, discharging heat to the environment in the process. Air conditioning units using an organic Rankine cycle engine are being developed. An organic Rankine cycle engine is a type of turbine that can operate with organic fluids (such as toluene) that are solar heated to temperatures below 550°F (287.8°C). According to Lennox Company, Rankine cycle solar cooling will be cost-effective for commercial and industrial users by the mid-1980s.[149]

Adsorption coolers blow room air over a drying wheel which contains a dessicant such as silica gel, slat crystals or zeolite. The air is dried and heated to 180°F (82.2°C). It is then cooled to near room temperature as it passes through a heat exchange wheel. Then the air is evaporatively cooled to 55° to 60°F (12.8°C to 15.6°C). Solar Energy is used to dry the dessicant. Dessicant systems have received little commercial attention primarily because they consume a large quantity of energy to operate the pumps and fans. Also, the system is large in comparison to the area it can cool.[150] Figure 3.7-3 illustrates an adsorption chiller run on gas or solar heat.

Figure 3.7-3[151]

AN ADSORPTION CHILLER



In summary, passive cooling will work in almost all climates in most new housing as well as some retrofit applications. Active air conditioning systems for retrofit residential use may be integrated into a total space cooling, heating, and water heating package by the mid-1980s. Active solar commercial air conditioning will be cost-effective before residential systems because commercial buildings pay twice as much for cooling energy and have large roof areas. Residential systems will probably never use the organic Rankine cycle vapor compression systems while commercial systems will tend to use absorption chiller units.

Water Heating and Solar/Heat Pump Applications (3.7-3)

Solar water heating is a mature technology. Current research efforts are directed towards developing new designs and materials that can reduce costs. As with space heating, water heating can be accomplished with passive or active techniques. Passive designs circulate water without the aid of pumps by using either thermosiphon action or the water pressure from municipal supplies. Active methods circulate the water throughout the collector and to storage with the aid of pumps. Passive solar water heating is very cost-effective and will be used extensively by the mid-1980s.

The heat pump, often viewed as an energy conservation device, makes use of ambient solar-heated air in the natural environment to heat air or water. The electrical heat pump operates on the same principle as a "reversed" refrigerator. The compressor-driven evaporation and condensation of a refrigerant (such as freon) takes heat from air (or water) and pumps it into living space or hot water. Unlike the refrigerator in which heat is pumped from the interior of the insulated space (to chill food), a home or building heat pump draws heat from the environment into space or water for heating. In addition to the electrical heat pump, heat-actuated heat pumps have been developed which are fired by fossil fuels, such as natural gas.

Today, "reversible" heat pumps operate a standard refrigeration cycle in summer for air-conditioning, and reverse in winter to operate a heating cycle. Most units for household use are compressor-driven air-to-air electric heat pumps. A series of experiments dating back to the 1950s have been conducted on heat pumps using solar collectors to boost performance of the machines, since ambient temperatures below 45°F degrade the performance of the heat pump. With solar collectors, heat pumps can be boosted to operate with higher temperature air. Performance is measured by the COP (coefficient of performance) which is the ratio of the useful work delivered by the system to the units of energy needed to operate the heat pump. Typically, in moderate, southerly areas of the United States, heat pump COP's average 2-3, meaning that ambient air of water is supplying twice to three times the energy required to operate the device.

Electrically-driven heat pumps are also available commercially to heat water. These air-water heat pumps are available at costs ranging from $600 to $800, and compare favorably to solar hot water systems (costing up to $3500 per installation) when electrical resistance water heaters are replaced. These small, efficient heat pumps were marketed briefly in the 1950s, but did not do well in an era of utility resistance and lower electrical rates.

Heat pump technology can be readily combined with solar passive designs, to heat air or water. Solar collectors can be used to boost performance in northern areas. As one recent analysis stated: "All the solar/heat pump concepts that we have identified have break-even solar collection costs considerably lower than the break-even solar collection costs of (solar heating combined with resistance heating)."[152]

The use of solar energy for pool heating is among the most cost competitive solar energy applications. Installed systems cost $15-20 per square foot. Collector area should be at least 50 percent of the pool area or larger if the pool is used in the fall and winter. Pool system collectors are usually a simple unglazed absorber made of black plastic or rubber. Heat storage is provided by the water in the pool. The pool's pump and distribution system circulate the solar heated water.

Solar Thermal Electricity (3.8)

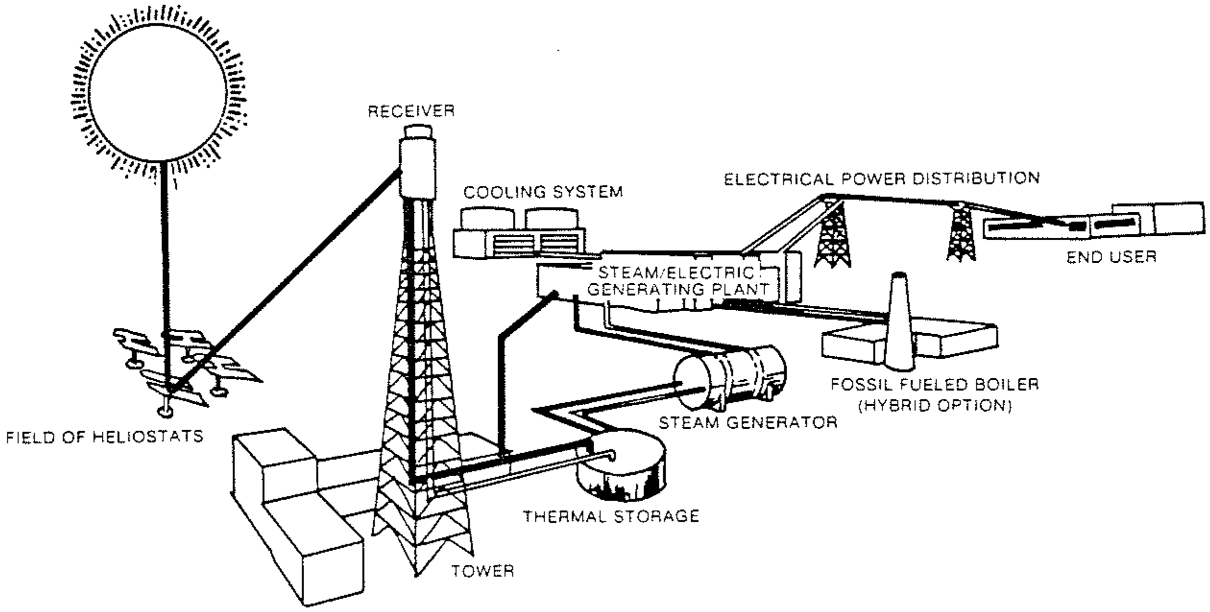
Solar thermal power systems use concentrating collectors to focus solar energy on a receiver. The sunlight can be concentrated so intensely that it is capable of producing temperatures to 1500°F (815.6°C). Water in the receiver may be boiled to produce steam for the generation of electricity or used for industrial process heat.

There are three basic approaches used in the design of solar thermal systems:

1) The central receiver concept separates the collectors from the receiver. Solar energy that is collected by double-axis tracking heliostats (flat mirrored tracking surfaces) is directed to a focal point on a central receiving tower. Figure 3.8-1 illustrates a solar central receiver system.

Figure 3.8-1[153]

CENTRAL RECEIVER SYSTEM



2) The solar "farm" concept uses many parabolic point focus collectors or parabolic trough linear collectors to create steam in a receiver located in each collector. The steam is then piped to a central generator.

3) The distributed receiver concept integrates the collector, receiver and generator into one unit. The collector configuration is either a single-axis or double-axis tracking parabolic dish. Sunlight is focused on a receiver at the focal point of the trough or dish. The generator is located in the unit creating a thoroughly decentralized, autonomous energy source. One prototype reportedly cost about $3000/kW$_e$.

Central receiver systems vary in size from the 100 kw_t unit at the University of Genoa in Italy, the 400 kw_t system at the Georgia Institute of Technology, the five MW_t at Sandia Labs in Albuquerque, New Mexico, to the ten MW_e system under construction near Barstow, California.[154]

In all of these systems a field of heliostats reflect sunlight to the central receiver on top of a tower. Water or liquid sodium pumped to the receiver is converted to steam and returned to the ground to drive a turbine generator.

Design parameters such as heliostat size, tower height, and area of land covered depend on the amount of electricity desired. The Barstow system covers 130 acres, with 1,818 heliostats.[155] Heliostats can range in size from four to ten square meters and the diameter of the field in which they are distributed is generally two to three times the height of the tower.[156] Generally three to six acres are required to produce one megawatt of electricity.

The installation at Barstow at a cost of $140 million has dominated the federal solar energy research budget for the past few years. The cost of electricity produced will be $10,000/kw installed capacity, or $.60 to $.90 per kilowatt hour.[157] However, the system at the Georgia Institute of Technology costs only one tenth of that amount ($1000 per kw installed capacity).[158]

Frank Duquette, Manager for McDonnell Douglas Energy Program Development, states that the price per kilowatt hour will drop to $.08 - $10 per kwh when heliostats can be installed at $6 to $7 per square foot.[159] About 75 to 85 percent of the system cost is attributable to the heliostats.[160]

Current research at Sandia Labs and the Georgia Institute of Technology is exploring the use of different working fluids such as molten salts for use in receivers to work in conjunction with organic Rankine cycle engines as generators to improve efficiencies.[161]

Power towers are a more efficient way of using solar energy to produce electricity than are "farms" of concentrating collectors because the energy is transported as light rather than heat. Parabolic troughs focus sunlight in a line concentrating it up to 30 to 50 times.[162] The receiver contains a fluid in a glass-lined tube with a selectively absorbent surface that is located on the line of focus. It can reach temperatures of 572°F (300°C). Effective day-round performance requires that the collector track the sun on at least one axis. A variant of the parabolic trough collector uses tracking Fresnel lenses which are less sensitive to tracking errors than mirrored systems.

Parabolic trough applications include industrial process hot water, steam for industrial applications, or electrical production and space cooling with organic Rankine cycle systems.

Annual efficiencies in existing demonstration projects are only eight to thirty percent.[163] Nine percent of the U.S. end-use energy demand is for low temperature industrial process heat (less than 550°F (or 287.8°C).[164] This is an ideal market for trough or other collectors. Parabolic trough collectors will probably be able to satisfy a good portion of this demand as production costs decrease and techniques for integrating the systems into industrial processes improve. Efficiencies of 40 percent can be expected by the early to mid-1980s. Other demonstration projects use linear concentrators to power irrigation and well pumps. Energy farms using hundreds of parabolic trough collectors are in the conceptual phase now.

Double-axis tracking parabolic dish collectors focus solar radiation to a specific point and are capable of concentrating the light up to 1000 times, producing temperatures of 1500°/1700°F (816.6° - 926.7°C). Because of exacting structural requirements these collectors are the least commercialized of the concentrating collectors.[165]

Applications include the production of process steam and generation of electricity via a traditional steam generator or an organic Rankine cycle engine.

General Electric Company is providing a total solar energy system for a knitwear company in Shenandoah, Georgia which consists of 100 collectors that will power a 400 kw Rankine steam engine and produce waste heat that will be used for 350°F (176.7°C) process steam. Jet Propulsion Laboratory is designing a one megawatt solar array for use at the community level.[166]

Omnium G, located in Anaheim, California, is the only company in the U.S. offering a commercially available parabolic dish collector. It is six meters in diameter and concentrates 1000 times. It produces 7.5 kw of electricity and waste heat can be used to produce 80 gallons (302.8 liters) of 180°F (82.2°C) water per hour.

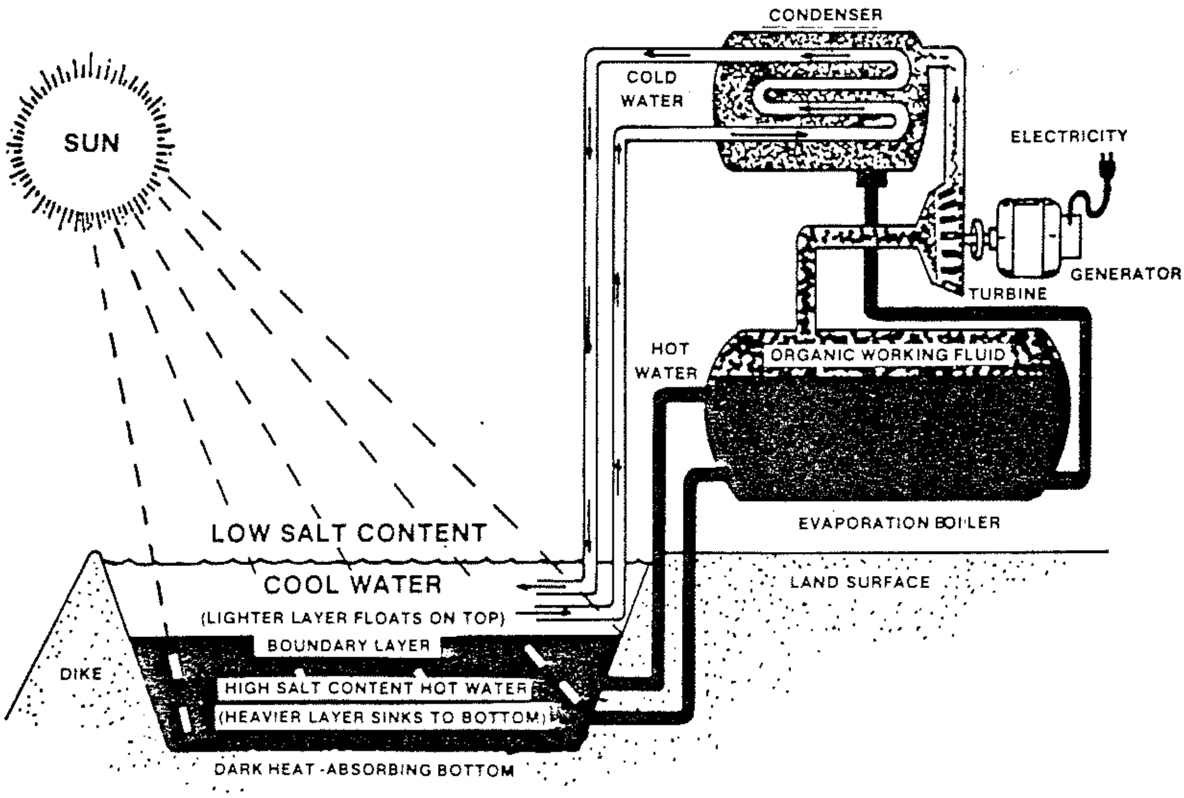
Centralized systems can produce large amounts of energy in areas that receive high solar radiation and where other land use options are limited. However, decentralized collection systems have greater flexibility because they can operate in a modular fashion, adding or deleting units according to demand. Energy use at the site of production reduces transmission lossess when electricity is distributed over long distances. It enables the use of waste heat that cannot be economically transported over long distances. Use at the site of production reduces the ecological impact of energy production. Decentralized systems also reduce the vulnerability to large-scale energy shortages.

Another type of solar thermal electricity system is the solar pond. Salt gradient solar ponds are natural phenomena that can be artificially created and used as sources of heat, electricity, or both. A rule of thumb is that they can produce about one MW of electricity per 50 acres of pond area.[167] The optimal economics for electricity-producing ponds is probably between twelve and sixty MW, although small ponds at about five MW can be constructed without a large cost penalty. The ponds are inexpensive to construct compared to other energy sources. They are very stable under conditions of environmental stress, require relatively short lead times for constructing, can start up power generation on only a few minutes' notice, are modular by nature, use a low-maintenance, proven technology to generate electricity, and present very limited environmental problems.

Solar ponds contain water in three layers of different densities.[168] The top layer contains the least salinity and density. The bottom layer is very saline and dense. Solar radiation penetrates the water where the light is converted to heat; the heat is then trapped in the bottom saline layer. It does not rise and escape for two reasons: first, it is trapped in the denser salty water; and second, the middle boundary layer (the density gradient or salinity gradient) acts as an insulating blanket. Consequently, the pond is both the solar collector and the storage medium. Figure 3.8-2 illustrates how solar ponds can generate electricity.

Figure 3.8-2 [169]

SOLAR SALT POND GENERATING CONCEPT



The saline gradient boundary is the crucial layer in the pond since it is the only one that does not provide convection.[170] The top layer, exposed to air and wind, is affected by fluctuations in temperature and by the wind. Thus it loses energy because of convection. The bottom layer loses some heat to the ground by conduction at night and the temperature difference created in the saline layer initiates a small pattern of convection within the layer. The bottom-layer conduction losses are not large, but they do occur.

The saline gradient will form naturally if a pond is constructed of two layers, the lower one saline and the upper one fresh water. However, experimenters have found it more expedient to build the gradient into ponds by injecting layers of progressively less saline water over the top of a saline bottom layer. Layers that are disturbed tend to reform although the pond will lose some energy during the process.

The heat stored in the pond can be tapped in two ways. First, a heat exchanger can be run through the bottom layer of the pond and the heat used directly to condition space or water. This application requires minimal maintenance and is suitable for small ponds such as the 180-foot (54.9 meter) by 120-foot (36.6 meter) pond built by the City of Miamisburg, Ohio.[171] That pond is used to heat an outdoor swimming pool in the summer and an adjacent recreational building in the winter. Even at the end of February 1978, the pond (with ice on its surface) was 83°F (28.3°C) at the bottom. It is the largest direct heat application in the U.S. and cost Miamisburg $70,000 to build. The liner and 1100 tons of salt required the biggest share of the capital expenditures. The total cost was $3.20 per square foot.

Using solar ponds for thermal energy can be cost-effective for applications on small to medium scales. Such ponds might provide some of the heat required for multi-family dwellings, collections of single-family dwellings, or for large buildings such as commercial greenhouses or industries that use low - to medium - temperature heat. There is also a possibility that such ponds could run absorption chillers in the summer.[172]

The second way to tap the heat in a pond is to pipe the saline layer through an external heat exchanger, using the heated water in organic Rankine cycle engines to generate electricity.[173] This requires maintenance by trained personnel.

The Israelis were the first to experiment with solar ponds and began operating a 150 kw pilot solar electrical power station in 1979 at Ein Bokek on the Dead Sea. The plant collects heat in a rubber-lined, 70,000 square foot pond.

There are experimental saline ponds producing electricity in New Mexico, Nevada and Virginia,[174] but only one is currently being considered as precursor to commerical-scale production in the U.S. Feasibility and design studies, being coordinated by the Jet Propulsion Laboratory in California, have been funded by the Department of Energy, Department of Defense, State of California, Southern California Edison, and Ormat Turbines, Ltd. (the Israeli manufacturer of organic Rankine cycle turbines used at Ein Bokek), at a cost of $650,000.

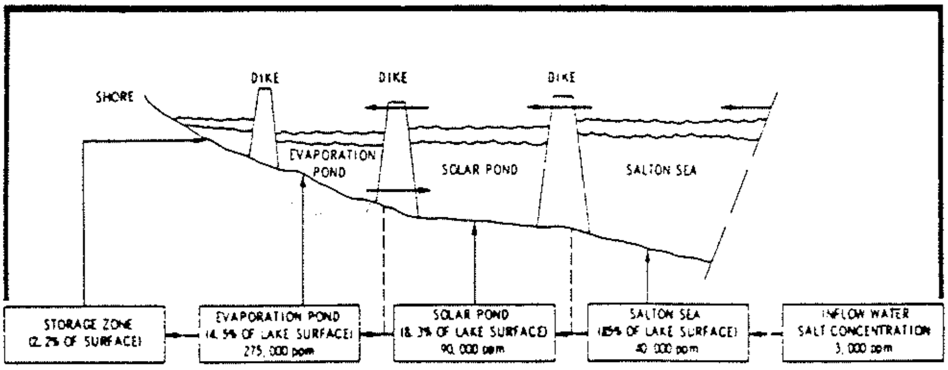
The studies are looking at several sites in the U.S. including the Great Salt Lake in Utah and the Salton Sea in the Imperial Valley in southern California. The Sea was created accidentally between 1905 and 1907 when heavy rains caused water from the Colorado River to flood the headgates of an aqueduct and fill the Salton Sink. By the time the flow was diverted years later, the Salton Sea had formed.[175] Over the years the Sea has become a wildlife refuge, popular sport fishing area, and sink for drained agricultural water. There is also a Naval base nearby.

The first pond to be built at the Salton Sea would cover about 250 acres and would generate five MW of electricity.

While the five MW plant was being built, feasibility studies would be done on building a 600 MW plant in twenty MW modules. The larger plant would require fifteen percent of the Sea's surface, or 50 square miles, (129.5 square kilometers) and would provide power for 500,000 to 1,000,000 people. Figure 3.8-3 illustrates how the Salton Sea solar pond would use a series of dikes to develop the necessary salinity and density gradients for electricity generation.

Figure 3.8-3 [176]

SALTON SEA SOLAR POND CONCEPT



Solar ponds show a great deal of promise, but like any other technology, there are trade-offs. Some of their limitations include:

1) The energy the ponds produce fluctuates seasonally and is subject to wind influence. The wind's impact can be minimized by windbreaks, screens, and other devices. However, seasonal fluctuation is natural, and pond output is lowest when heating requirements are highest.

2) For solar electrical ponds, there is a difference between peaking capacity and continuous operation capacity. The pond at Ein Bokek, for example, is rated at 150 kw, but only at peak production. The pond could sustain about 35 kw in summer and fifteen in winter at continuous operation.[177]

3) Since there have been few demonstrations of solar ponds, there will probably be many unanticipated problems. They are not likely to be serious enough to prohibit construction or prevent effective operation, but they could raise costs. For example, at the Miamisburg pool there has been some problem with corrosion of the copper heat exchangers in the pool, with settling of the sand used as foundation material, and with consequent leakage through the strained plastic liners.[178]

Solar ponds have several advantages as means of producing energy, however, including:

1) They produce no pollutants, no wastes, and use very little makeup water. The only obvious environmental hazard they present is the possibility of saline water leaking into underground water supplies.

2) The stored heat is available for electrical production at any time and on a few minutes' notice. This characteristic could be valuable for backup electrical capacity.

3) Because the storage is so accessible, solar ponds can deliver peak power ten or more times the power they provide in continuous operation, a feature that could be significant for peak power production.

4) The turbines used in saline ponds, specifically the Ormat models have demonstrated over some 30 million engine-hours (in applications that include fossil-fuel use) that they are extremely reliable and require very low maintenance. Forced outages at solar ponds have been at an average rate of two percent.[179]

5) Construction of saline ponds uses conventional earthworks techniques, without specialized personnel. This is important both for developing countries and for remote locations.

6) The ponds are most cost-effective in sizes from twelve to sixty MW, so large facilities would be built most economically in clusters of ponds. This modularity permits additions to capacity in small increments, as required.

7) Although the sizes of twelve to sixty MW are most cost-effective, ponds as small as five MW can be built with only small cost penalties. Consequently, the ponds can be constructed in many sizes depending on the application.

8) In case of attack, the ponds would have to sustain a direct hit before they were incapacitated. The modularity of the facility would allow partial operation of the plant even if some ponds in the complex were damaged. The most vulnerable parts of the system would be generating equipment, transmission lines, and heat exchangers.

Ocean Thermal Energy Conversion (3.9)

The oceans are massive natural storage basins for solar energy. The difference in temperature between the sun-warmed surface of tropical seas, and the colder deep water, chilled by polar currents, represents a potentially enormous energy resource. Tapping this energy, however, requires complex and costly equipment of tremendous size. OTEC (Ocean Thermal Energy Conversion) is a concept for using oceanic temperature differentials to release stored solar energy to drive a turbine. In principle, this is no different from any other heat engine that extracts usable energy from a temperature difference. In practice, OTEC presents challenging engineering, economic and institutional problems.

In the 1920s French chemist, Georges Claude built a 22 kw generating plant at Matanzas Bay, Cuba. This pilot plant required about 80 kw of electricity to run its machinery. The existing technology of the time was simply too crude to permit Claude's daring design to produce net energy.[180]

At present, the most promising potential OTEC technology is a closed cycle, using a working fluid such as ammonia, freon or propane, which varporizes when warm ocean water is pumped into an evaporator. The vaporized working fluid expands through a turbine, which drives an electrical generator. The vapor is then condensed by pumping cold water through a heat exchanger (condenser), and returned to the evaporator to begin a new cycle.

The plant would be moored to the ocean floor, and connected by underwater transmission cables to a power grid ashore. Some concepts envision floating industrial complexes, where OTEC electrical power would be used to produce ammonia, aluminum, hydrogen, or other energy-intensive products.

OTEC offers several clear advantages. Power could be generated 24 hours a day, in contrast to other solar technologies. Hence, OTEC could provide a constant source of baseload power, without the need for massive storage of electricity. OTEC plants would probably have minimal adverse environmental impacts. Figure 3.9.1 illustrates a conceptual OTEC system.

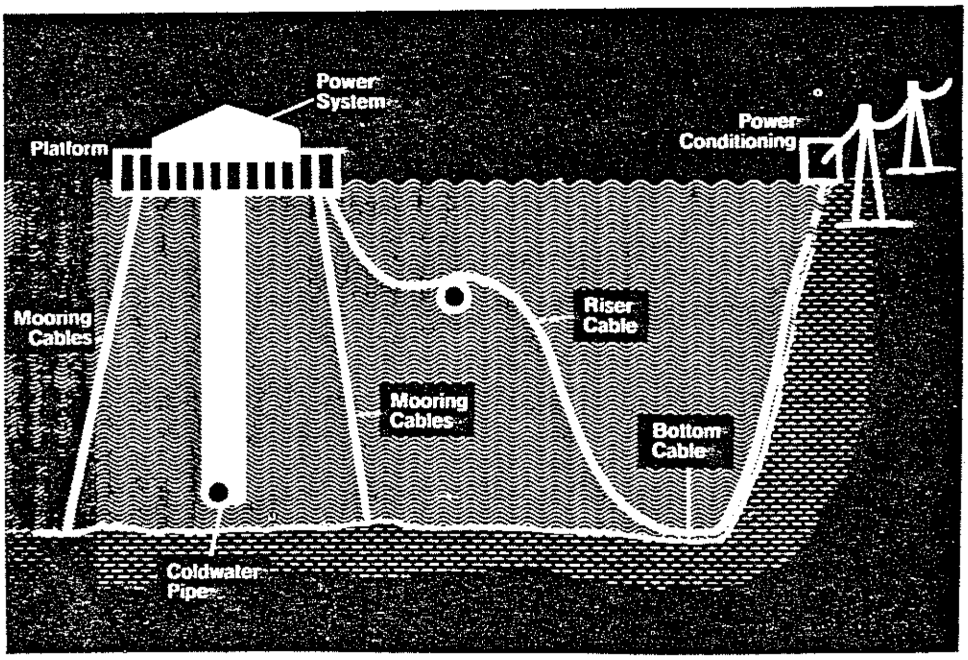
There are four major constraints on the location of an OTEC plant:

1. There must be a minimum temperature difference of about 38°F between the surface water temperature and the colder deep water. Moreover, this difference must exist within about 2500 - 3000 feet of the surface (otherwise the energy required to pump the heavier cold water to the surface becomes prohibitively great). On the other hand, the depth cannot be greater than about 6000 feet, due to the limitations of present mooring technology.

2. There must be relatively low-velocity currents.

Figure 3.9-1[181]

DIAGRAM OF AN OCEAN THERMAL ENERGY CONVERSION SYSTEM



3. There must be a minimal risk of storms (wind and wave action that would impose excessive stresses on the structure).

4. There must be close proximity to the market for the energy produced. At present, the maximum feasible length of the underwater power transmission cable is about 180 miles.

In general, the requisite temperature differentials are to be found within about 26 degrees of latitude north or south of the Equator. In U.S. territorial waters, the only viable sites are the Gulf of Mexico and Hawaii.[182] It should be noted that these are regions that already enjoy abundant solar energy that could be tapped with simpler, more decentralized technologies.

There are presently three principal technical problems which must be overcome if OTEC is to be commercially viable. These are biofouling, the engineering of the submarine power cable, and the construction and deployment of the cold water pipe.

Biofouling refers to the attachment of marine organisms to the vital heat exchanger surfaces, thereby reducing the rate of heat transfer and ultimately obstructing the flow of circulating water. Filters can be installed to keep larger animals such as mussels and barnacles out, but this cannot prevent the entry of microscopic organisms such as diatoms, bacteria and protozoans. Gradually a slimy film would form on critical surfaces, requiring down-time for cleaning, or potentially costly and environmentally hazardous measures such as chlorination.

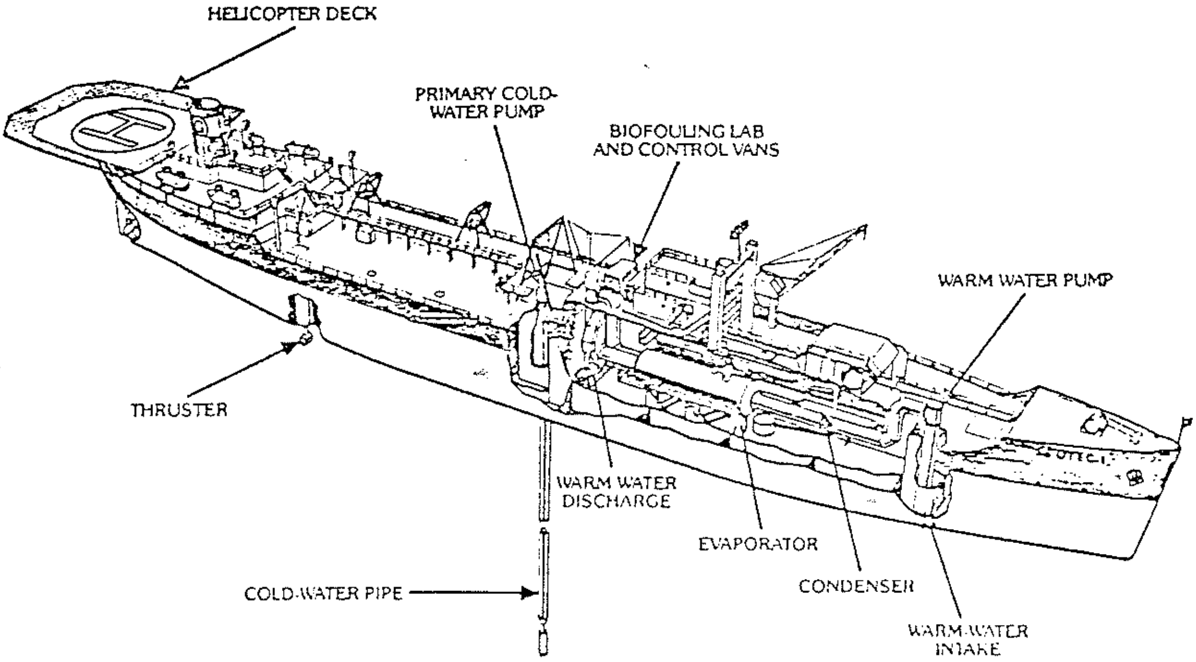
There are several problems associated with the design of the "riser" cable that would connect the OTEC platform with the submarine power cable on the ocean floor. It would be subject to great stresses due to platform motion and the chafing action of the seabed. With the present state of th art, the cost of underwater transmission lines exceeds $1 million per mile. For an OTEC site distant from the shore, the cost of a single cable could equal the capital cost of the plant itself.[183] In addition, there is no known method to disconnect or reconnect the OTEC to the cable if the need should arise due to severe weather conditions.

Another major technical challenge is the cold water pipe. A 400 MW OTEC plant, for example, would require a volume of cooling water seven times the flow rate of the Potomac River. This would necessitate a pipe with a diameter greater than 100 feet. No pipe of this dimension has ever been constructed for use in a sea environment. The magnitude of the engineering feat has been described as "20 to 30 Baltimore Harbor Tunnel tubes, hanging vertically in the deep ocean."[184] Along with these specific problems associated with the deployment of an operating OTEC system, there are the traditional difficulties of working in a hostile marine environment: corrosion, maintenance and dependence on shore-based support facilities. A 400 MW OTEC plant would require pumps, motors and turbines larger than any now in existence. Experience with ship machinery indicates that major pieces of equipment require a periodic overhaul, typically lasting one to three months every two years or so.[185]

In order to gain operating experience with a baseline OTEC design, the DOE has modified a WWII tanker as a floating test bed, the SS Ocean Energy Converter, which is now operating off Hawaii. (See Fig. 3.9.2)

Figure 3.9-2[186]

THE S.S. OCEAN ENERGY CONVERTER



Major components of this prototype system include heat exchangers with over 44 miles of one-inch titanium tubing packed into a 13-foot diameter 55-foot long shell. The costly titanium is resistant to corrosion and strong enough to withstand frequent cleaning. Another crucial component being tested is the 2,100 foot long cold water pipe, consisting of three polyethylene tubes, each four feet in diameter, and weighted at the bottom. The $41 million prototype will be used to evaluate heat exchanger technology, long-term biofouling and corrosion effects, cleaning techniques and environmental impacts on the marine ecosystem. With this data, DOE will have a basis for predicting future cost and performance parameters of full-scale OTEC systems.[187]

The economics of commercial OTEC systems are highly uncertain. Estimates of the cost of generating OTEC power very widely, depending on the assumptions made by the estimator, the size and location of the proposed system, and assumed rates of inflation. Estimated capital costs of an OTEC plant have ranged from $1000 to $3700 per kw. A report on OTEC by the Office of Technology Assessment notes, however, that early commercial nuclear powerplants actually cost two to three times the amounts originally estimated.[188]

OTEC systems are, by nature, highly centralized and capital-intensive units. Because they operate on such a narrow temperature differential, they must move enormous volumes of water to generate useful amounts of power. As a result, they must be very large, and correspondingly vulnerable to enemy action, as well as the perils of the sea. As high-value symbolic targets, they might invite destruction, even in a conflict short of general war. For the cost of a single OTEC installation, a large number of dispersed, decentralized shore-base solar energy systems, using various technologies of greater maturity could be deployed far more quickly. DOE does not anticipate commercialization of OTEC before the 1990s, and other estimates have pushed this time frame well into the 21st century. These systems will require considerable further research and demonstration programs to prove their viability.

Solar Photovoltaics (3.10)

The photovoltaic effect, whereby an electric current is produced when light strikes certain materials, was first reported by the French physicist E. Becquerel in 1839.[189] In 1905 it was explained in a classic paper by Albert Einstein. For many years the photoelectric effect was merely a scientific curiosity. The first practical application was the selenium photocell used in light meters.

Photovoltaic technology demonstrated to be reliable and effective; its biggest drawback today is its expense. It currently costs about $7 to $10 per peak watt (Wp) for modular systems, and $15 to $20 for installed systems. Today's cells are already economical to use in some remote locations such as isolated pueblos or channel buoys. By 1983, PV will be competitive with remote diesel generators. If manufacturers continue to meet the Department of Energy's schedule of price goals, solar cells may be economical to use on residences and in intermediate load-center applications such as schools and businesses by 1986, and in utilities' centralized systems by 1990.[190] In fact, it is estimated that central station PV systems will be cost-competitive for oil-fired, sunbelt municipal utilities as early as 1986. Table 3.10-1 gives the estimated costs of PV arrays to the year 1990 of the DOE National PV Conversion Program, as recently updated by Energy and Defense Project.

Table 3.10-1[191]

KEY MILESTONES FOR NATIONAL PHOTOVOLTAIC CONVERSION PROGRAM

	Array price in 1980 dollars per week watt	Production, rate peak megawatts per year
End of FY 1977	11.0	—
End of FY 1978	7.0	—
End of FY 1982	1.4 - 2.8	20
End of FY 1986	.70	500
End of FY 1990	.14 - .42	50,000

During the 1954-58 National Space Program effort, the United States needed electrical supplies for its orbiting satellites. Solar cells that powered nearly all U.S. satellites were produced using the Czochralski method of growing crystals that had been perfected in the 1940s and 1950s. These cells were pure silicon, reliable and effective at more than ten percent efficiency, but cost around $200 per peak watt. By 1961, costs went down to $175 per watt.[192]

With the oil embargo of 1973, PV research efforts intensified. The federal government devised a program called the Low-Cost Solar Array (LCSA) Program in 1975 that funneled millions of dollars to researchers. In Fiscal Year 1980, federal funding amounted to $160 million.[193] Private interests have also begun investing heavily in the technology; over $200 million according to some estimates.

To lower costs, experimenters today are working to improve manufacturing techniques and to find new materials and designs that are more efficient or economical.

Once fully developed, photovoltaics will be flexible and diverse enough to use at different levels of centralization and could replace one Quad per year of primary fuel by the year 2000.[194] Budget-conscious homeowners may want simple flat-plate arrays of silicon panels that collect only the incident sunlight. Large businesses might choose arrays of gallium-arsenide cells that concentrate the sunlight to 500 times the intensity of the incident light (500 suns), that track the sun's path, and that use a special fluid to cool the solar cells and collect heat for space conditioning or for industrial processes. Utilities, on the other hand, might combine the two and use large arrays of flat-plate collectors for simple electrical generation along wth a few arrays of concentrating collectors to provide heat for their own operations.

Whatever kind of cell is used, it will produce direct current. The current can be inverted to the 60-cycle alternating current that utilities require, and then transmitted throughout an existing grid. If the electricity is not needed when it is produced, it can be stored in various devices ranging from batteries to pumped water reservoirs.

During the day when electrical demand is highest and when production from photovoltaics is also highest, utilities may buy the power from dispersed producers and simply transmit it to where it is needed. At night, when both demand and PV production are down, the utilities may sell power from other sources, such as hydroelectric plants.

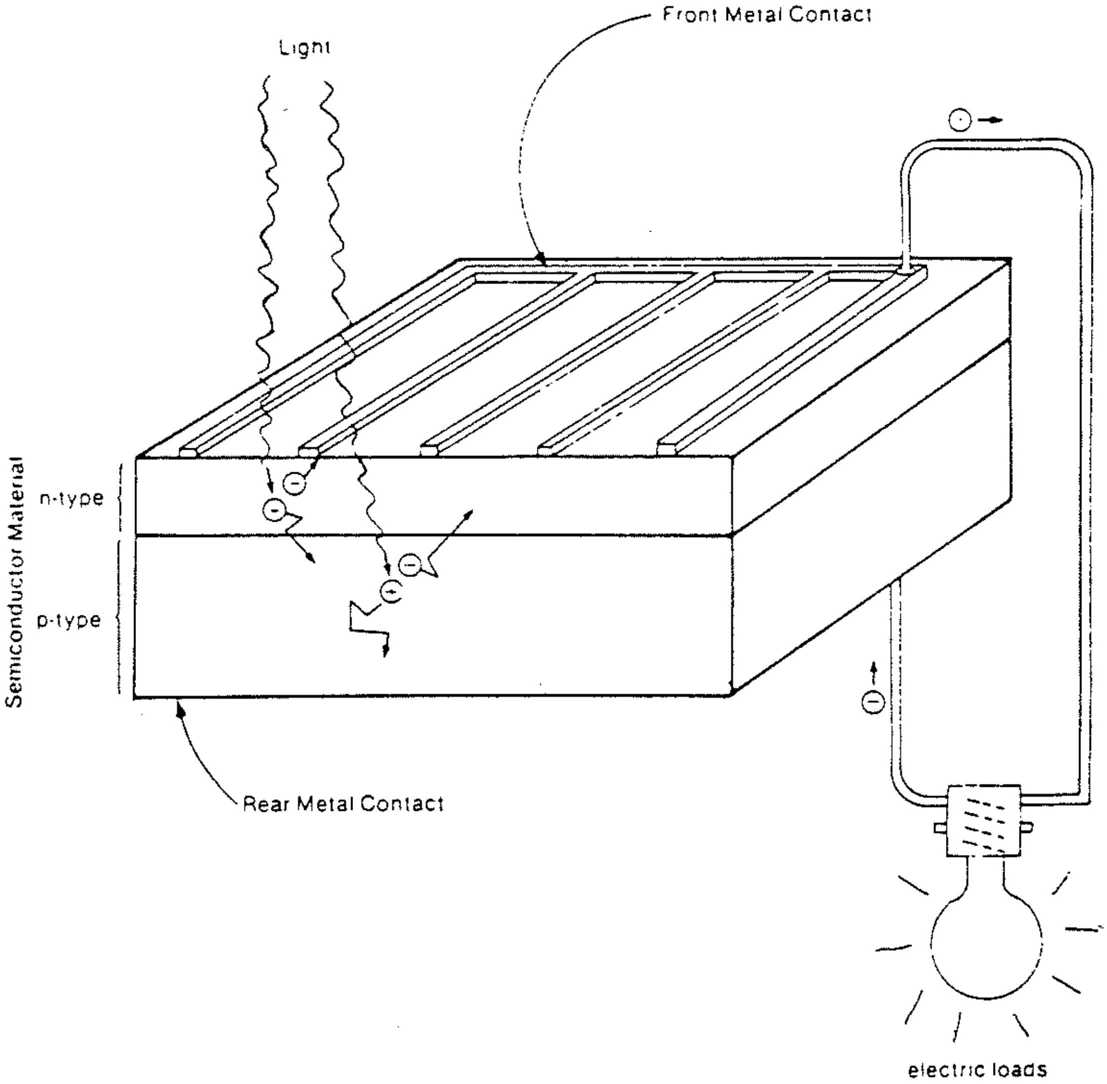
When sunlight strikes silicon, photons that are moving with more energy than 1.1 eV (electron volts) knock electrons out of the valence bonds that connect them to the neighboring atoms. The negatively-charged (n) electrons leave behind positively-charged (p) "holes" that neighboring electrons may move into. They in turn leave "holes" and if the flow can be made to move in a given direction, the electrons will flow in one direction and the "holes" in the other. Figure 3.10-1 illustrates a typical photovoltaic device.

A difference in potential is maintained between top and bottom halves of the cell. The boundary where the positively (p) and negatively (n) charged material meet is called the p-n junction. Junctions in silicon are made by introducing chemical impurities, or "dopants", into the material. One half is doped to have more electrons than can be bonded to the silicon, producing a p-type silicon, and the other half is doped to have fewer electrons.

The action at the p-n junction is complicated and not intuitively obvious, but the result is that light-stimulated electrons on the p side travel across to the n side. The flow is picked up by metal contacts arranged in a grid pattern on the n side. The electron flow (direct-current) moves down wires attached to the metal contact, is turned into work of some sort, and then the electrons flow back with a little less than their original energy down a wire to a metal contact plate on the p side, where they re-enter the cell to be excited by the sun.

Figure 3.10-1[195]

A TYPICAL PHOTOVOLTAIC DEVICE

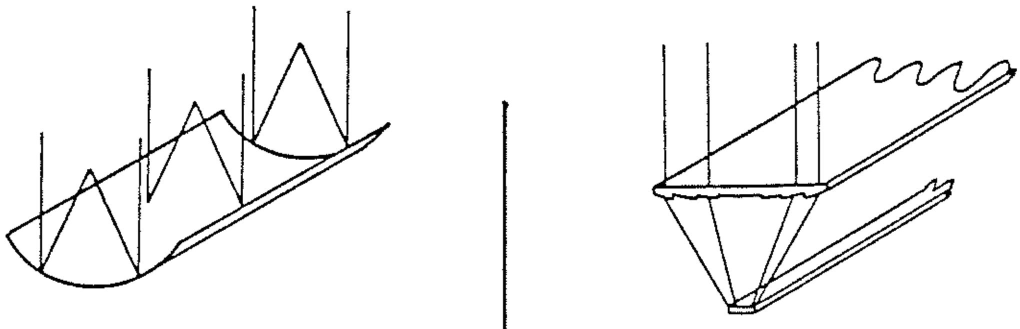


Electron movement is slowed or stymied at crystal boundaries, so larger crystals, that reduce the number of boundaries, provide current more efficiently. Masses of smaller crystals are less expensive to produce, and non-crystalline material is even less expensive, so some approaches trade good crystals' efficiencies of eighteen percent for the much lower rates of six or seven percent for amorphous materials.

The amount of light captured is also a significant variable. Solar cells are commonly coated with nonreflective materials to reduce the amount of light that simply bounces off, and concentrator systems use mirrors or Fresnel lenses to focus more light on the cell. The concentrating systems' power is usually measured in "suns" (i.e., multiples of the normal incident sunlight). Some experimental systems produce 10,000 suns of concentration. Figure 3.10-2 illustrates several concentrator designs.

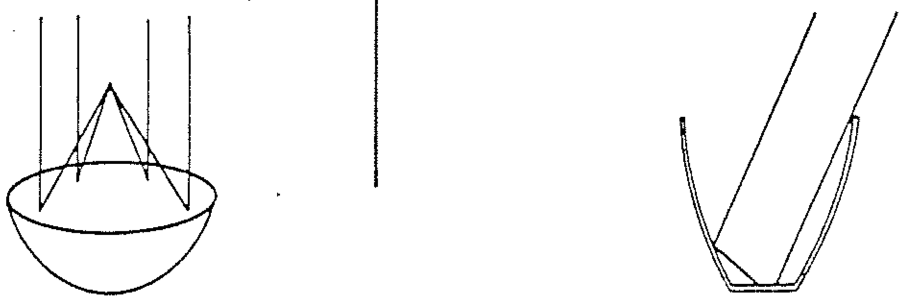
Figure 3.10-2[196]

SAMPLE REFLECTING OR REFRACTING CONCENTRATOR DESIGNS



REFLECTING PARABOLIC CYLINDER

REFRACTING CYLINDRICAL FRESNEL LENSES



REFLECTING PARABOLOID

REFLECTING COMPOUND PARABOLIC CONCENTRATOR

Other approaches to capturing more sun utilize more of the light in the spectrum. Silicon's electrons require light moving with 1.1 eV before they are knocked out of their bonds. Up to a point, the electrons will be stimulated more by more energetic photons, but beyond a certain energy level the excess simply produces heat in the cell. Therefore, the more energetic the photon, the more likely its energy is to be wasted. In 1972, Dr. Joseph Lindmayer developed the "violet cell" that can convert more of the high-frequency ultraviolet waves into electricity. Newer research applications combine different materials, each with a different energy threshold.

When PV systems are assembled, they contain several components. The individual cells, often round and about three inches in diameter, are packaged in groups of twelve to forty in flat protective boxes called panels by the industry and modules by the government. The panels are grouped into an array, which may be of any size, from the area covered by two or three panels to the size of a football field or larger.

To maintain their angle toward the sun, the arrays are supported by mounting racks. The racks may be stationary, or they may pivot so that the array can track the sun and catch the maximum light available.

The electricity generated must be transported by wires to a storage or distribution system. Storage may take many forms, from pumped-water reservoirs to arrangements of batteries or fuel cells.

When the PV system is connected to an established electrical grid, it requires a current inverter which changes the direct current to 60-cycle alternating current.

The baseline technology is still very expensive but has nearly reached its theoretical limits of efficiency. Research is now directed at reducing the cost of the silicon, finding less expensive manufacturing methods for silicon crystals, finding new useful forms of silicon, finding new materials, and trying new designs that reduce the amount of silicon needed.

The Department of Energy expects the next order of magnitude cost improvement for PV's to occur in manufacturing technique. Paul Maycock, Director of DOE's Photovoltaic Program has stated that costs can be halved just by automation once production volume warrants the capital investment.[197]

Current explorations into manufacturing focus on improving the growth of silicon cyrstals. The baseline technology in the Czochralski method (or CZ method) in which a seed crystal is suspended in a quartz crucible of molten silicon and is slowly drawn upwards, then allowed to cool. The crystal, which would otherwise grow with its grain at angles, grows straight because the forming cylinder is rotated slowly. This is a slow batch that process requires a new quartz crucible with every ingot because the crucible cracks in cooling. The cylindrical crystal is sawed into slices about 400 microns thick. They become the familiar circular three-inch solar cells after being cleaned, doped on one side, and imprinted with contacts.

The CZ process is expensive because slicing the discs reduces between 40 and 60 percent of the ignot to fine sand. Investigators are looking into replenishing the silicon in the crucible to produce longer cylinders; making cylinders of greater diameters; improving the sawing techniques; and recycling the silicon if it has not been contaminated.

Other investigators are exploring ways of making rectangular crystals that can be grown in ribbons continously instead of relying on batches. Rectangular crystals would pack together more efficiently than circular ones, and would gain more electricity per unit module area.

In addition to silicon there are other materials that will work in solar cells if the cells are in concentrating arrays. Varian Associates in Palo Alto achieved in 1978 a 28 percent efficiency, the highest ever reported for solar cells, in an experimental arrangement that combined gallium arsenide and silicon cells to respond to different wave lengths in the spectrum. Varian's usual efficiency for its gallium arsenide concentrating cells is about seventeen percent. The advantage of gallium arsenide is that its performance is not as seriously affected as silicon's at higher temperatures.

Another new combination is cadmium sulfide and copper indium selenide. Boeing produced a cell using these materials with an efficiency of 9.4 percent. This is not far from DOE's goal of ten percent efficiency for thin-film devices. It is also a good example of the rate of progress being made in photovoltaics; the efficiency increased from 6.7 percent to 9.4 percent in less than a year.

Researchers are also developing new designs, such as concentrating arrays of thermophotovoltaic cells. These are more energy-intensive than the usual flat-plat systems because they require active cooling and sometimes tracking mechanisms to follow the sun. Thermophotovoltaic systems also sacrifice maximum efficiency at either their heating or generating tasks in order to achieve about a 30 percent overall efficiency at both.

Other new designs provide a photovoltaic roof shingle for homes (from ARCO), a multilayered sandwich of silicon wafers that are illuminated from the edge (expected to reach an efficiency of up to 30 percent), and cells of pure silicon that are not doped, but instead have the n an p material printed on the back in a pattern like interlocking fingers. This design is expected to reach twenty percent efficiency after some improvements are made; it has already reached fifteen percent.[198]

While researchers work on making photovoltaics more economical, the Department of Energy is building demonstration projects using baseline technology to show that photovoltaics work today. In 1979, the DOE spent $27.5 million over three years to build systems under the Federal Photovoltaic Utilization Program (FPUP). The first 53 installments cost $500,000 and were built for the Forest Service, the Navy's Material Command, the Indian Health Service, and the Tennessee Valley Authority, all at remote locations.[199]

One of the locations is Schuchuli, Arizona, an Indian pueblo of 96 people. The PV supply will provide them with 3.5 kw for lights in all houses and the community house, a washing machine, a sewing machine, a water pump, and fifteen small refrigerators.[200]

One PV installation that has received widespread notice is a 283 kw unit at the Phoenix Sky Harbor International Airport. At peak generation it will provide enough electricity to power 40 average homes in Phoenix.[201] It is being built by a team composed of Arizona Public Service Company, Motorola's Government Electronics Division, the City of Phoenix, and the Arizona Solar Energy Commission. It will use 7200 concentrator modules on 30 large arrays. The total array will require ten acres at the airport and will power half of the south concourse of a new airport terminal.

There are several major obstacles at present to the rapid commercialization of photovoltaics. These include a projected shortfall in the production of high-purity silicon crystal, the lack of ready capital for expansion of the industry, the threat of foreign competition for markets (Japan, France, Germany and Italy all have active PV research and development programs) and unresolved questions about the socioeconomic and environmental impacts of the rapid development of new technology.

A shortfall of silicon is the most immediate problem. New processes now being developed may not be ready in time to relieve the shortage. No governmental solutions have been offered to date, and silicon producers are reluctant to invest the massive amounts of capital required to assure production until they have a more solid indication of demand.

One of the best hopes of solving the silicon supply problem will be using a metallurgical grade instead of semiconductor grade. This approach has been incorporated into several research programs including Crystal Systems which has achieved a cost production rate of $3 per kilogram. ARCO Solar has also proposed that silicon manufacturers produce a "solar grade" of silicon, which would be more pure than metallurgical grade silicon and less than semiconductor silicon.

Another major problem for photovoltaics is that producers won't scale up their manufacturing efforts until demand has been demonstrated; demand, however, depends on the low prices that mass production would bring. This natural pattern of development may be too slow to meet DOE's timetable. To change the pattern, one side or the other must be deliberately stimulated. Most observers suggest massive purchases by government, far in excess of what is currently planned.[202] For 1980, the Department of Energy is spending over $4.5 million on new PV systems for federal building and facilities. Industry spokespeople are calling for $1.5 billion, ten-year photovoltaic "Manhattan Project" as a way of developing the industry quickly.[203]

Other unresolved questions include the environmental problems of toxic substances created in cell manufacture and use, and the social impacts of the rapid development of the new technology. The DOE's Solar Energy Research Institute (SERI) is beginning to study environmental hazards, but little information has been available until recently because both materials and processes have been in such a state of flux.

While photovoltaics appear to be an environmentally benign technology, especially in comparison to the massive combustion of fossil fuels, there are possible adverse effects involved in the mining, refining, manufacture and ultimate disposal of photovoltaic cell materials.

Silica dust, for example has been associated with a chronic occupational lung disease, silicosis. The manufacture of silicon devices involves possible exposure to a number of hazardous chemicals (phosphine, boron trichloride, hydrochloric acid and hydrogen cyanide, among others).[204]

Arsenic and cadmium are two of the elements used in some advanced PV cell designs, and both are well known as toxic environmental pollutants. Fortunately, only small quantities of these metals are required, even for a massive expansion of PV technology. To ingest a toxic dose of gallium arsenide for example, a person would have to eat about 200 square feet of flat-plate arrays.[205] The long service life (up to twenty years) and encapsulation of PV cells would tend to limit the release of toxic substances into the environment, although there might be risks of occupational exposure in manufacturing.

The manufacture of PV cells is, itself, a highly energy intensive process. Under existing technology (the CZ method) approximately 7000 kwh is required to manufacture a cell with a peak output of one kw. This means the device must operate for about four years to "pay back" the energy consumed in making it.[206]

Although cheaper, less energy intensive methods for producing PV devices are being developed, a massive expansion of the industry is likely to require major inputs of energy from other sources. In the long term, of course, the goal should be to power the solar industry with renewable energy sources exclusively.

In addition to being energy intensive, the solar photovoltaic industry is presently labor intensive. Expansion of this technology is therefore likely to create jobs, many of them in trades and geographic areas now suffering from high unemployment. Although production of the devices may become increasingly automated, installation in onsite applications will probably remain a semi-skilled occupation allied to the conventional building trades (electrician, carpenter, sheet-metal worker, etc.). The PV industry must, however compete with the semiconductor industry for top research and engineering talent, and shortfalls of some critical skills might develop if the industry expands very rapidly.

Other barriers to photovoltaic development are institutional in nature and include such problems as restrictive building codes (although this seems less of a problem with PV than with solar thermal systems), and uncoordinated utility buy-back and interfacing programs.

Photovoltaics are ideally suited to residential or other on-site applications. A major question is storage. Remote locations will certainly require storage making the system more expensive but still competitive with diesel or other generators by 1982. The development of advanced batteries may bring down storage costs. This is a major goal of current DOE research. On-site locations that could be connected to the utility grid can take advantage of buy-back arrangements and use utilities' production power at night.

Other dispersed or small-scale applications might be private citizens' combining arrays for clusters of homes, utilities' using PV arrays on a neighborhood or district scale as load levelers, or using PV arrays for remote mechanical tasks, such as running irrigation systems. Over 90 percent of the harvested cropland in California is irrigated, and 98 percent of the irrigation pumps are electrically powered. A major disruption of the electrical power grid would be catastrophic for agriculture. The modular nature of PV systems makes them well-adapted to irrigation pumping. At the University of Nebraska, a 25 kw PV system has been used to irrigate 80 acres of corn and soybeans since 1977. The system operates ten hours per day, pumping up to 1,800 gallons per minute. During the winter, the electricity is used for crop drying. At present, research on direct current pump motors is being carried out at the Nebraska test facility. DC pumps would avoid the small but inevitable losses involved in inverting PV output to the AC required by conventional pumps.[207]

Biomass Energy (3.11)

Biomass is a form of solar energy and is therefore a renewable energy source. Biomass may be defined as any form of plant matter, living or dead. The photosynthetic process allows plants to convert solar energy into chemically stored energy in the form of polymeric hydrocarbons (carbonhydrates).

In comparison to other energy technologies biomass has a relatively low conversion efficiency (approximately one to two percent). Table 3.11-1 gives a rough comparison of energy efficiency ratings for biomass with other solar technologies.

Table 3.11-1[208]

ENERGY EFFICIENCY RATINGS

Biomass	1% - 2%
Solar Heating	40% - 90%
Photovoltaics	6% - 35%
Wind Electric	30% - 47%
Solar Thermal Electric	4% - 20%

However, biomass is somewhat unique because it is the only form of solar energy which directly converts and stores energy as a hydrocarbon. Coal, petroleum and natural gas are fossil forms of biomass created over long periods of time. Biomass, because of its low efficiency, requires large amounts of land to capture sufficient quantities of solar energy. Its unique storage and conversion properties, however, make it very attractive from an energy management point of view.

Because the U.S. has vast areas of land available for the growth of biomass and because many current agricultural and foresting practices produce high quantities of waste and residue materials, biomass appears to be a very significant source of energy. Various studies have estimated the biomass potential for the year 2000 to be between seven and twenty Quads.[209]

Most frequently used waste materials have been wood from the forest products industry, municipal solid wastes, agricultural processing wastes, and livestock manures. The forest products industry has for many years practiced biomass energy production. This is largely a result of the economic benefits of using by-product wood wastes in a combustor/boiler to produce process steam and frequently, cogenerated electricity. The key to the cost-effectiveness of these operations is in the hidden transporation cost. The transportation cost of the fuel is covered in the high value of the principal end product (i.e., lumber, paper, furniture, etc.) because using the waste materials actually increases the profit margin through reduced fuel bills to the manufacturer.

The current contribution of a biomass to national energy production is estimated to be slightly less than two Quads ($2x10^{15}$ Btu per year), or just under one million barrels of oil per day. Nearly all of this energy is produced by the forest products industry.

Because of the high cost of fuel oil energy production from biomass has been expanding. The contribution of biomass is expected to expand to between four and eleven Quads over the next ten years.[210]

Residues from crops and forestry harvesting, although attractive because of their large volume, have not been widely used to date. High transporation and collection costs of these materials have made them non-cost-effective when compared with the cost of conventional fuels. These residues, however, have in the past two years become quite attractive to existing consumers of woody biomass. A case in point is the Eugene, Oregon Water and Electric Board (EWEB), a city-owned, public utility which has expanded its existing wood-fired electrical generating facility. Wood waste supply for the plant is based on locally available sawmill residues. Currently the EWEB is seeking fuel suppliers to guarantee supplies of forest slash in order to ensure additional fuel supplies for expansion of the power facilities at the lowest cost to their customers.

The concept of sustained yield energy farming, in which crops are grown exclusively for conversion to energy, is one which has received increasingly more attention. The economics of this type of biomass production/utilization are much more tenuous given the general low cost of competing energy supplies. In energy farming, the end product of energy produced must compete with the average cost of conventional energy. The current cost of competing fuels, however, has not proven high enough to justify a commercial venture at this time.

An example of cost-effective energy farming is that of growing grain to produce alcohol. The by-product of alcohol production is a high protein cattle feed. The cattle generate food for human consumption and their waste manure provides energy (when converted to methane gas) for process heat to fuel the distillery. Further, direct combustion of nonfermentable crop residues such as corn stalks is possible.

In addition to vast quantities of forestry residues and agricultural waste, there is a substantial amount of urban waste available for conversion to energy. These wastes are referred to as municipal solid waste (MSW) and sewage.

The energy potential from these waste streams has been estimated to be between one and three Quads per year. To date there have been numerous problems with waste-to-energy facilities associated with MSW. This can largely be attributed to the difficulty of handling this non-homogeneous material. A recent Office of Technology Assessment (OTA) report on MSW thoroughly examines these difficulties.[211]

In contrast to the problems of producing energy from MSW, sewage has for the past century been a significant contributor of energy for the purpose of operating municipal wastewater treament (MWT) facilities. The use of anaerobic digestion for treating sludge from municipal sewage is widely practiced. A by-product of this treatment is the production of a methane-rich gas having about 60 percent of the heating value of natural gas. Anaerobic digestion is a biological fermentation process in which methane-forming bacteria decompose solid organic matter which release a gas (biogas) composed of carbon dioxide and methane. This gas is typically burned in a boiler or internal combustion engine with a generator. In most cases there is more gas available than required, but most of the excess is either used on-site or, more commonly, flared. While this is a very small quantity of energy (about 0.02 Quads), it is a reliable source that could play an important role in an emergency situation. This resource is currently underutilized, realizing only about 60 percent of its potential.

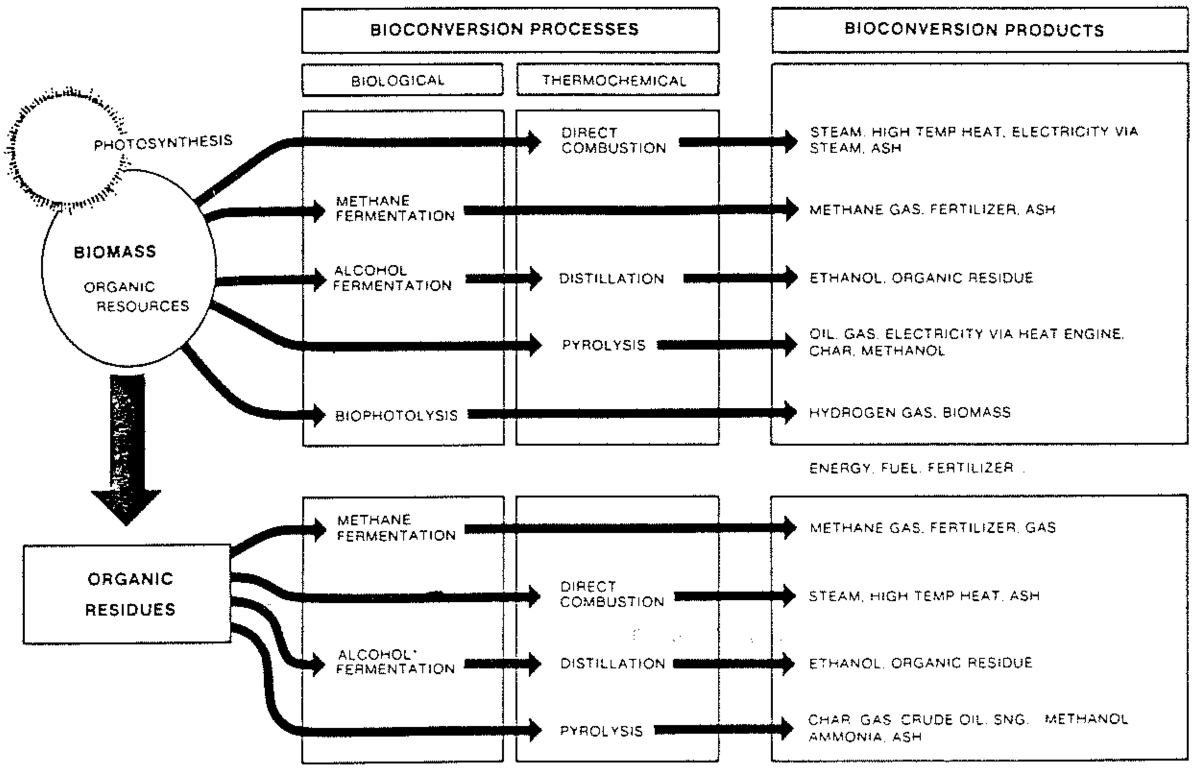
Beyond these land-based biomass resources from the forest, agricultural lands, energy farms, MSW and MWT, there are also aquatic biomass resources which have potentially much higher yields than the terrestrial resources. Aquatic resources fall into two very broad categories: 1) Fresh Water Systems, and 2) Oceanic Systems. Fresh water species such as algae, duckweed, and water hyacinths promise to approach photosynthetic rates of land-based crops like sugar cane, which exceed silviculture (forestry) production by as much as a factor of two to three. Ocean farming of species of giant kelp along the coast of California shows some promise, but current experiments have yielded limited results.

The most formidable barrier to the extensive use of the various biomass resources is the availability of reliable economic, off-the-shelf hardware to harvest, process, load, convert and utilize the energy. The energy type required or desired will often dominate the choice of conversion technology since different processes are required to deliver the desired energy type.

Figure 3.11-1 gives an overall perspective on the variety of feedstocks (biomass resources), conversion technologies (bioconversion processes), and energy and by-product end uses (bioconversion products) that are potentially available to the society from the utilization of biomass.

Figure 3.11-1[212]

BIOCONVERSION PROCESSES AND PRODUCTS



*REQUIRES HEAT AND OR CHEMICAL OR ENZYMATIC TREATMENT

There are five basic technologies which fall into two basic conversion methods, that of thermochemical and biochemical. Thermochemical conversion of biomass is essentially the burning or high temperature degradation (conversion) of the material to release the stored solar energy from the complex organic compounds (polymeric hydrocarbons). The two methods for thermochemical conversion are direct combustion and pyrolysis.

Direct combustion is burning in the presence of enough air (oxygen) to convert all the chemical energy into heat. In pyrolysis or gasification, the other type of thermochemical conversion, the biomass is partially oxidized so as to give a resulting gaseous form of energy, pyrolytic oils and char (like "charcoal").

Direct combustion (DC) of dry biomass (50 percent moisture) is the most widely used and best developed of the conversion technologies. The energy products which are available from this thermochemical conversion process are high temperature heat (400°F-2000°F) (204.4°C-1,093.3°C), steam and electricity via steam. The applications range from simple box stoves for residential heating to complex multistage steam turbine generators for electrical production. The economics of electrical generation by this method generally dictate that systems be larger than 200 kw installed capacity. The steam requirement for such power production is typically $4x10^6$ Btu per hour or greater depending on the outlet pressure from the turbine.

Direct combustion of biomass can also be done in conjunction with coal. Coal typically has five to ten times as much ash content as biomass but the heat contents of the two resources are reasonably close (8,000 Btu/lb. or 17,637 Btu/kg wood vs. 12,000 Btu/lb. or 26,455.5 Btu/kg coal). They are also similar in their solid fuel combustion characteristics.

The limitation of direct combustion is that it cannot be easily adapted to many current energy uses such as internal combustion engines (ICE), gas turbines, or gaseous and liquid fuel combustion equipment. To adapt woody or dry biomass to operate such devices it is necessary to convert the solid fuel to gaseous state. This is accomplished through a thermochemical process known as pyrolysis which is defined as the thermal decomposition of the solid fuel in the absence of oxygen.

Pyrolysis is a natural part of the solid fuel combustion process and in a typical fire the long orange flames are the combustion of the pyrolysis gases when they contact air. These combustible gases are principally carbon monoxide and hydrogen with traces of methane and other hydrocarbons. Typically systems use a limited supply of air to assist in the partial combustion of the fuels.

These units which use air are typically referred to as air-fed gasifiers or simply gasifiers. These gasifiers produce a gas with a heating value typically ranging from 100 to 200 Btu per standard cubic foot (scf) (147.9-295.9 Btu per standard cubic meter) or about ten to twenty percent the heating value of natural gas which is principally methane gas.

Variations on this basic principal range from pure oxygen-fed pyrolysis units producing 300-500 Btu/scf (443.8-739.6 Btu per standard cubic meter) gas to steam-fed gasifiers which require internal heating elements to sustain the process. The producer gases from these systems can be further processed through a reforming catalytic conversion.

These gasifiers are commonly referred to either as pyrolysors or medium Btu gasifiers (MBG). MBG's require much more sophisticated controls, equipment and engineering than the low Btu gasifiers (LBG's). Typically LBG's are well suited to small-scale applications while MGB's require rather large-scale applications with subsequent large fuel requirements.

Battelle Pacific Northwest Labs has given a comparative analysis of Low Btu gas and Medium Btu gas:

> Development of biomass gasification and indirect liquefaction technologies are midterm development activities because

these technologies are not expected to have a substantial impact on U.S. energy supplies for ten to twenty years. Biomass gasification technologies can be divided into processes which produce a low Btu gas and those which produce a medium Btu gas.

Low Btu gasification technology is commercially available for most types of biomass feedstocks. Many of these commercial processes are based on low Btu coal gasification technologies and the gas produced can best be used as fuel for supplying process heat, process steam or for electrical power generation.... The versatility of low Btu gas is limited and its use is subject to the following limitations:

1. The low heating value of the gas usually requires that it be consumed on or near the production site in a close coupled process.
2. Substitution of low Btu gas for natural gas as a boiler fuel usually requires boiler derating and/or extensive retrofit modifications.
3. The high nitrogen content of low Btu gas precludes its use as snythesis gas for most chemical commodities which can be produced from snythesis gas.

Medium Btu gas (MBG) offers the following advantages over low Btu gas:

1. Boiler derating is usually less severe when substituting MBG for natural gas than when substituting low Btu gas for natural gas.
2. MBG can be transported moderate distances by pipeline at a resonable cost.
3. MBG is required for the synthesis of derived fuels and most chemical feedstocks and commodities which can be produced from synthesis gas.

The major disadvantage of MBG is that its production by conventional means requires the use of an oxygen-blown gasifier which is expensive to operate due to the cost of the oxygen.

If thermoconversion of biomass is to achieve its maximum potential for augmenting existing U.S. energy supplies in the midterm, the following two points will have to be considered:

1. Barring serious coal production constraints, biomass conversion will have to be cost competitive with synthetic fuels produced from coal.

2. Thermochemical biomass conversion must have an impact on the availability of liquid fuels and chemical feedstock supplies as well as supplementing gas for heating purposes.

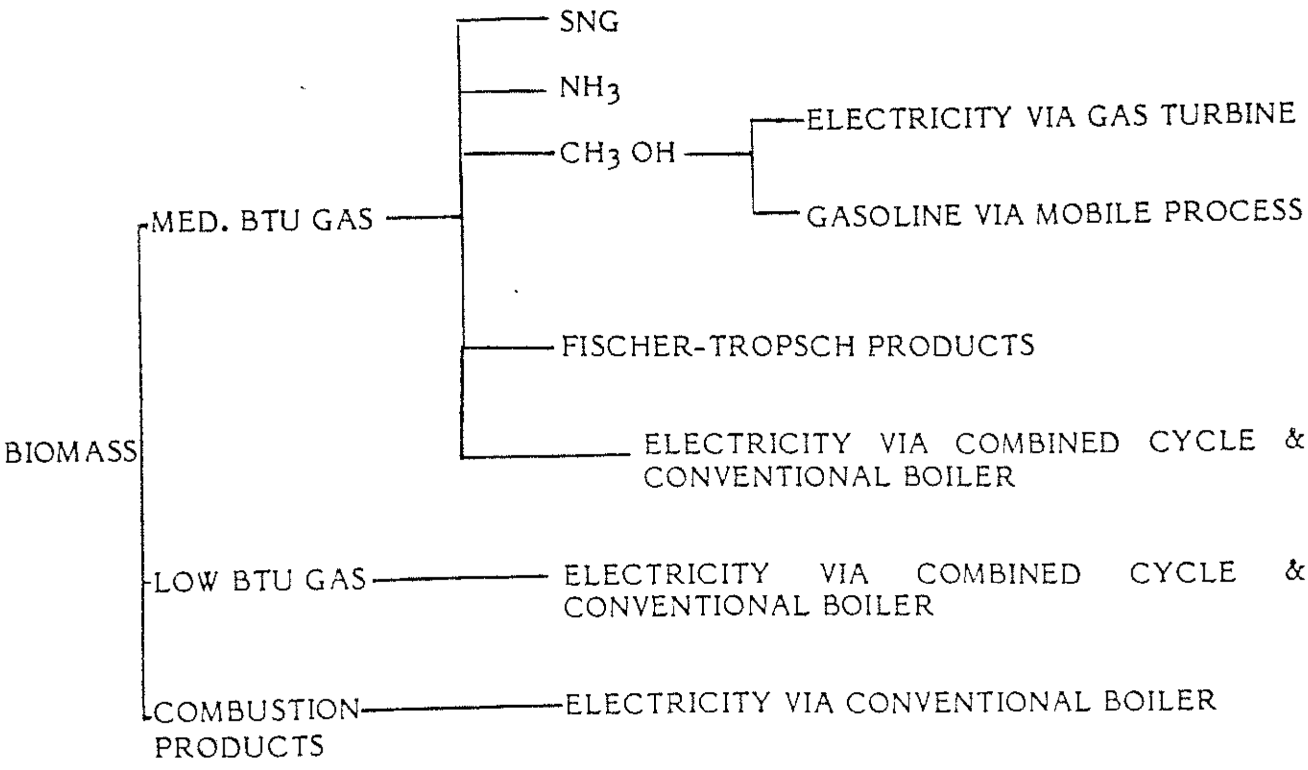
Biomass has two potential advantages over coal. First, biomass is a renewable resource and coal is not. Second, and more important from a thermo chemical conversion stand point, biomass is more reactive than coal. It has the potential for gasification at lower temperatures, without the addition of oxygen, to produce MBG. There are activities also directed toward improving the competitiveness of biomass gasification through the use of catalysts and unique gasification reactors to produce directly specific synthesis gases for the production of ammonia, methanol, hydrogen, and SNG. Success in these efforts could eliminate the necessity for external water gas shift or methanation reactors when producing these commodities.[213]

The California Energy Commission and the University of California, Davis, have successfully demonstrated that LBG can effectively be used in existing boilers using natural gas.[214]

Figure 3.11-2 shows the versatility of a MBG process. The drawback for such a process is primarily the large quantities of biomass required to justify such an operation and the additional requirements for pure oxygen and/or steam as opposed to air for oxidation.

Figure 3.11-2[215]

THERMOCHEMICAL CONVERSION PATHWAYS FOR FUELS FROM BIOMASS



A typical MBG facility would require an input of about 1,000 tons per day (tpd) (907,184.7 kg/day) biomass. This could be supplied by a city of 1,000,000 population and would produce about 50,000 gallons (189,270.6 liters) of methanol per day (about 25,000 gallons or 94,635.3 liters gasoline equivalent). Assuming a yield of six dry tons per acre-year with a ten year crop rotation, a 1,000 tpd (907,194.7 kg/day) plant would require about 1,000 square miles (2,590 square kilometers) of forest to sustain such a facility. This would require an area with a minimum transportation radius of about 30 miles (48.3 kilometers) and more than likely 50 miles (80.5 kilometers) would be necessary. The 1,000 tpd feedstock requirement is dominated by the economy of scale for equipment, especially compressors which are required to operate at about 30 atmospheres.

Many schemes have been suggested for conversion of biomass to other products. These range from methane gas, commonly referred to as SNG (synthetic natural gas), crude oil, gasoline, charcoal and many combinations of these fuels.[216, 217] Typically, a higher reaction temperature maximizes the producer gas output from a given biomass feedstock. The lower the reaction temperature, the more pyrolytic or crude oil generated from the process.

From an economic viewpoint both direct combustion and low Btu gasification appear to be competitive even with regulated natural gas prices. Medium Btu gasification and its numerous by-product capabilities do not appear to be competitive with the current cost of imported oil or with the projected cost for MBG from coal.

Current successful applications of direct combustion and to a more limited extent LBG, are confined to operations in which the feedstock is a part of a forestry, agricultural or municipal processing facility. In this case, the feedstock is either a waste or a residue which must be disposed of or removed from the facility. This results in a fuel which is either free or for which a credit can be taken because of cost incurred for hauling the waste to a dump or transporting the residue to a land disposal site.

Biochemical conversion of biomass refers in general to biological processes which rely on microorganisms. The primary and most widely used biological processes for energy conversion of biomasss are anaerobic (in the absence of air) fermentation processes which rely on specialized microorganisms. It is, however, possible to produce hydrogen gas from water and sunlight by photosynthetic microorganisms. A system has been reported which uses a nitrogen-fixing, blue-green algae.[218]

This process has been termed Biophotolysis. Hydrogen is removed from the water when the blue-green algae are stressed. This stress is induced by creating a condition of nitrogen starvation. This creates a "...sustained catalytic decomposition of water by sunlight."[219] The economics of this process are not well established, but it does not appear to be feasible in the near future.

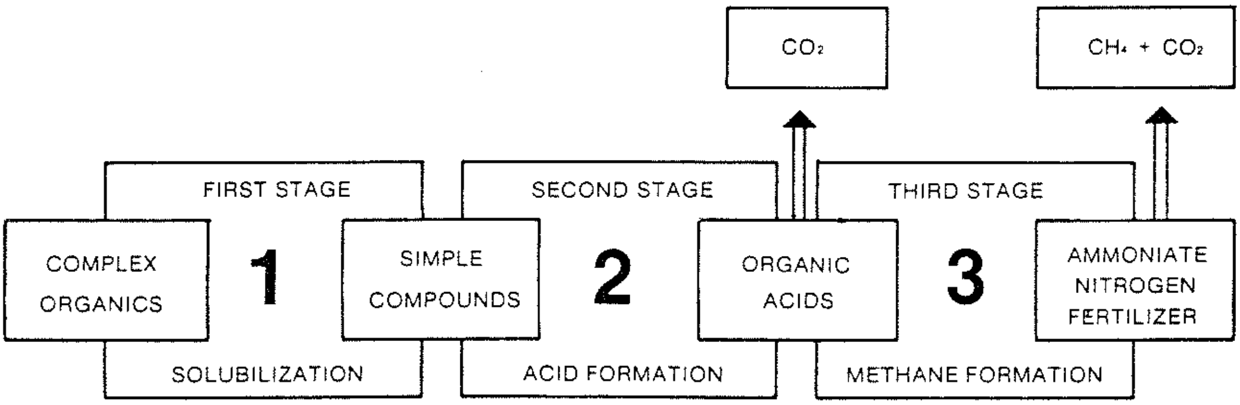
The biological conversion technologies which are currently in use are all fermentation processes. These processes are all anaerobic and are likely to be the predominant method available for this conversion.

There are two types of fermentation processes useful for conversion of biomass to energy. These are methane fermentation (also known as anaerobic digestion) and alcohol fermentation.

Methane fermentation (anaerobic digestion) has been widely used as a part of municipal sewage treatment. Microorganisms decompose organic matter. The resulting gas from this decomposition is referred to as biogas and is a MBG of 500-700 Btu/scf (739.6-1,035.5 Btu/square cubic meter). The biological production of methane is a very complex process wherein cellulose and other complex organic materials (proteins, cabohydrates, fats, etc.) first go through an enzymatic transformation. The solubilized organics are then converted by other bacteria into organic acids which in turn form hydrogen and carbon monoxide as a part of their metabolic process forming methane and carbon dioxide. The methane bacteria are strict anaerobe (oxygen is toxic) and require carfeul temperature control for reliable, sustained yields. Figure 3.11-3 shows this process.

Figure 3.11-3[220]

METHANE FERMENTATION (ANAEROBIC DIGESTION)
A THREE STAGE PROCESS



The bacteria are strict anaerobe and prefer mammilian body temperatures although they are adaptable in a range of 10°C to 60°C. Typical large tanks have been used to insure ideal conditions in sewage treatment plants.

Alcohol fermentation or ethanol production is a very old process that has been primarily practiced and refined for the purpose of producing beverage alcohols. First a sugar or starch material is ground or mashed so that a yeast fermentation can proceed. Only a simple sugar can be fermented so that starches must undergo an enzymatic treatment and cooking to form simple sugars which the yeast can then convert to alcohol. In a second step the alcohol must be concentrated through distillation to remove the water since the fermentation process can only produce an alcohol concentration of fourteen percent. Successive distillation steps can produce pure 99.9 percent ethanol. This is accomplished through an energy intensive process of removing water by the heat of vaporization.

Typically two columns are used to produce a 95 percent alcohol water. A specialized third column is used to produce 99.9 percent ethanol. Ethanol has about two-thirds the heating value of gasoline on a gallon-for-gallon basis. Ethanol can be burned in a solution of water as low as 50 percent, but 80 to 90 percent are preferred for combustion purposes.

Ethanol has about twenty percent greater heat value than methanol. Ninety-nine percent solutions can be blended with gasoline as a fuel stretcher and octane enhancer. Ethanol can achieve higher efficiency than gasoline when used in a modified ICE since it can be used at higher compression ratios without the knock problems associated with gasoline. Fermentation has distinct advantages as well as disadvantages over the thermochemical conversions. Table 3.11-2 gives a comparative analysis of fermentation versus thermochemical conversion technologies.

Table 3.11-2[221]

FERMENTATION COMPARED TO THERMOCHEMICAL CONVERSION

	Fermentation (F)	Thermochemical (TC)
Conversion efficiency biomass to energy	Depends on biodegradable material	Conversion to heat and electricity are superior to F process
Quality of energy produced	Very high, alcohol and methane gas	More expensive to duplicate alcohol, but electricity is best quality for cost
Biomass feedstocks	Accepts wet biomass readily but poor in cellulose and lignocellulosic materials	Must be @ 50% moisture or severely affects Btu/lb. but will burn lignin readily
By-products	Fertilizer and/or livestock feed, fiber, etc.	Ash and charcoal
Environmental concerns	Water pollution potential, odor, solid waste disposal greater than TC	Air pollution, carcenogenic materials from ash and creosote, solid waste much less than F

The most important aspects of fermentation are its abilities to produce high quality energy. Methane fermentation (anaerobic digestion) yields a MBG which is distinctly different from the pyrolytic MBG. This gas (as implied by the process name) yields a methane-rich gas as opposed to a carbon monoxide and hydrogen gas that is created in the pyrolysis process. Rather than a synthesis process, the methane-rich MBG needs to have carbon dioxide removed to become SNG or pure methane. This process has been demonstrated and is commercially available at several locations.[222, 223] Typically the biogas which is methane-rich MBG can be used on site in very slightly modified equipment which has been operated on natural gas. The biogas is composed of 50-70 percent methane and 50-80 percent carbon dioxide with a trace of hydrogen sulfide and other gases.

Methane fermentation works best with wet biomass feedstocks of high cellulose content. It does not work well with hard to degrade materials like woody biomass which contain high percentages of lignin or lignin-bound cellulose. These hard to degrade materials generally require some form of pretreatment including combinations of heat, grinding acid or alkaline hydrolysis.

Methane fermentation can contribute to both energy production and provide useful by-products like animal feed and fibers. Typically this process has been applied to municipal sewage treatment (MST) as a stabilization process for the heavy solids (sludge) found in urban wastewater.

Methane fermentation has been widely researched, domonstrated and promoted for extracting energy from livestock manures in confined operations.[224,225] This process has also been widely applied to municipal solid waste through the extraction of the gas from old landfill sites.

Alcohol fermentation or ethanol production is an age old process that has received a high degree of engineering development for the production of beverage alcohol. Although the engineering for beverage alcohol and the economics of its operation have been increasingly refined over the years and the level of sophistication is very high, the process for making alcohol for fuel use needs some additional development to improve energy efficiencies and to lower cost for competition with other fuels.

Currently available technologies for ethanol production rely heavily on starch or sugar crops as a feedstock. These feedstocks fall into several categories. These include the following list:

1. Energy Crops: These crops are grown specifically for conversion to energy. This is not widely practiced now, but it appears to be on the increase on a small scale for farm production and use.

2. Excess Agricultural Crops: These are the grain stockpiles of the Midwest which currently provide the bulk of feedstocks for fuel alcohol production.

3. Agricultural Residues: These are those crops and residuals left in the field. Manure would also be included in this category since it is commonly returned to the land as a soil amendment. Most of these feedstocks are high in cellulose which would require special pretreatment. A notable exception to this would be fruit waste from regions such as Florida, South Texas, California, Washington, and Oregon. These wastes are sugar and can be readily fermented to ethanol.

4. Agricultural Process Waste: These are the waste and residues from processing facilities such as canneries, fruit packing houses, creameries, milling operations, etc. There are a variety of feedstocks from these facilities ranging from easily fermentable resources like fruit-packing waste to more difficult substrates like cheese whey and finally to cellulosic and lignocellulosic materials like cotton gin trash and stalks.

5. Municipal Solid Waste: These are urban wastes which are for the most part cellulosic and lignocellulosic materials. The hetrogeneous nature of this feedstock has made it one of the most difficult to convert.

6. Wood: This resource is a lignocellulosic material which is subject to the same restraints discussed under "Agricultural Residues."

Because of the chemical similarity in the fuels, methanol (wood alcohol) is frequently compared with ethanol (grain alcohol). Methanol can be synthesized through the thermochemical gasification of biomass, coal, natural gas or other hydrocarbon fuels. Ethanol can also be synthesized from hydrocarbons via a thermochemical process utilizing ethlyene either as a by-product in petroleum distillation or from the synthesis of natural gas.

Ethanol via fermentation of biomass and methanol via MBG gas synthesis from biomass will compete for the same resources if one assumes that cellulosic hydrolysis technology is a near term option. There is considerable professional disagreement whether biomass methanol will be cheaper than biomass ethanol from the cellulosic feedstocks.

Table 3.11-3 gives DOE projections for alcohol production from biomass resources in the U.S. Table 3.11-4 describes a number of feedstocks immediately available for ethanol production, and Table 3.11-5 gives those feedstocks that are potentially available for ethanol production.

Table 3.11-3[226]

PROJECTED MAXIMUM ALCOHOL PRODUCTION FROM U.S. BIOMASS RESOURCES

(Billion gallons per year)

	1980		1985		1990		2000	
Biomass Feedstock	Ethanol	Methanol	Ethanol	Methanol	Ethanol	Methanol	Ethanol	Methanol
Wood	23.5	86.3	21.8	80.2	20.2	74.2	25.8	95.0
Agricultural residues	9.1	33.4	10.3	38.1	11.3	41.5	13.1	48.1
Grains:								
Corn	2.3	---	2.1	---	0.9	---	---	---
Wheat	1.2	---	1.4	---	1.6	---	2.0	---
Grain sorghum	0.4	---	0.3	---	0.3	---	0.3	---
Total Grains	3.9	---	3.8	---	2.8	---	2.3	---
Sugars:								
Cane	---	---	0.2	---	0.7	---	0.7	---
Sweet sorghum	---	---	0.2	---	3.0	---	8.3	---
Total Sugars	---	---	0.4	---	3.7	---	9.0	---
MSW	2.2	8.6	2.3	9.2	2.5	9.9	2.9	11.6
Food processing wastes:								
Citrus	0.2	---	0.2	---	0.3	---	0.4	---
Cheese	0.1	---	0.1	---	0.1	---	0.7	---
All Other	0.2	---	0.3	---	0.3	---	0.3	---
Total processing wastes	0.5	---	0.6	---	0.7	---	0.9	---
Total	39.2	128.3	39.2	127.5	41.2	125.6	54.0	154.7

Based on the following biomass-alcohol conversion factors: Wood and agricultural residues - 173 gal. methanol per dry ton, 47 gal. ethanol per dry ton. Corn - 2.6 gal. ethanol per bushel. Wheat - 2.7 gal. ethanol per bushel. Grain sorghum - 2.6 gal. ethanol per bushel. Sugars - 136 gal. ethanol per ton, fermentable sugars. MSW - 100 gal. methanol per dry ton, 25 gal. ethanol per dry ton. Citrus waste - 107 gal. ethanol per dry ton. Cheese waste 95 gal. ethanol per dry ton. Other food processing wastes - 90 gal. ethanol per dry ton.

Table 3.11-4[227]

BIOMASS FEEDSTOCKS IMMEDIATELY AVAILABLE FOR ETHANOL FUEL PRODUCTION

Biomass Feedstock	Percent of total that is available to be converted to ethanol	Quantity available		Net feedstock cost[1] (including co-product credits) per gallon of ethanol	Million gallons per year ethanol
		Million dry tons	Million bushels		
Cheese whey	80	0.9	—	$0.22	90
Citrus waste	80	1.9	—	0.80	210
Other food wastes	50	1.7	—	0.50	150
Corn	7	1.8	70	0.63	180
Grain sorghum	7	.3	13	0.60	30
Total		6.6			660

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[1] 1977 dollars.

Notes: This table shows the quantity of ethanol that could be produced from currently available biomass without (i) diverting to the production of energy crops, or (ii) necessitating any change in USDA land set-aside or diversion policy to take account of grains raised for ethanol production.

The table indicates immediate feedstock availability for production of 660 million gallons of ethanol annually, at a weighted average feedstock cost of $0.60 per gallon ethanol. The grain feedstocks represent only 5 to 7 percent of existing corn and grain sorghum stocks, and consist principally of distresed and substandard material. Thus, all the feedstocks shown in the table can be regarded as "waste" materials.

Table 3.11-5[228]

BIOMASS FEEDSTOCKS POTENTIALLY AVAILABLE FOR ETHANOL FUEL PRODUCTION

Biomass Feedstock	Material potentially available for ethanol production		Net feedstock cost[1] per gallon of ethanol	Production potential, million gallons per year ethanol
	Million dry tons	Million bushels		
Cheese whey	0.9	—	$0.22	90
Citrus waste	1.9	—	0.80	210
Other food wastes	1.7	—	0.50	150
Corn	16.0	640	1.10	1,660
Grain sorghum	2.7	110	0.98	280
Sugar Cane	2.6	—	1.52	150
Wheat	11.4	420	1.36	1,130
Municipal solid waste (MSW)	43.0	—	0.20	1,100
Total				4,770

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[1] 1977 dollars (including co-product credits).

Notes: This table shows the quantity of ethanol that could be produced if: (i) USDA eliminates all future set-aside and diversion programs, and all existing grain land is brought into productive use; and (ii) cane sugar surpluses and 50 percent of all municipal solid waste (MSW) are converted to ethanol. No new or marginal cropland is assumed to be brought into production, nor are agricultural residues, wood residues, or sweet sorghum potential included.

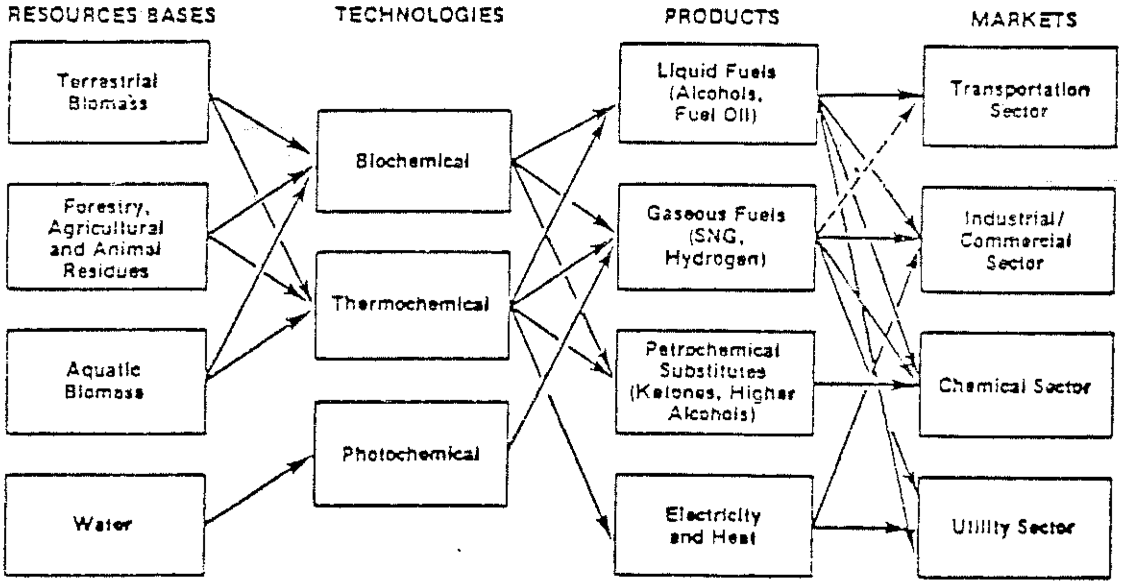
The table indicates immediate feedstock availability for production of 4.8 billion gallons of ethanol annually, at a weighted average feedstock cost of $0.91 per ethanol gallon. Of this, 1.1 billion gallons comes from wheat, which may be judged too expensive ($1.35 per gallons ethanol), and another 1.1 billion gallons comes from MSW.

There is considerable competition and disagreement over which biomass resource should be used with which technology to give which type of energy. To this already complex matrix of choices there are two other factors to impose: The first of these is economics, and in conjunction with economics is the competing use of these resources to produce chemical feedstocks rather than energy.

Figure 3.II-4 provides a graphic overview of biomass resource bases, technologies, products and markets, and Table 3.II-6 compares and contrasts the various biomass conversion processes.

Figure 3.II-4[229]

FUELS FROM BIOMASS



With the possible exception of direct combustion, all of the conversion technologies are either in a state of rebirth from previously abandoned technologies as is the case for gasification and methane fermentation, or they lack from being proven, field tested, reliable systems as is the case for cellulosic ethanol and methanol synthesis.

Table 3.11-6[230]

BIOMASS CONVERSION PROCESSES

Process	Biomass Inputs	Output	Overall Efficiency (%)
Direct combustion	Dry[b]	Steam,	65-70
		electricity	15-25
Cogeneration	Dry[b]	Steam and electricity	65-70
Gasification, with oxygen	Dry[b]	Medium-Btu gas	40-60
		Methanol	35-50
Gasification, with air	Dry[b]	Low-Btu gas,	50-85
		Steam[c]	65
		Electricity	10-20
Pyrolysis	Dry[b]	Pyrolytic oil, char, low-Btu gas	45
Anaerbic digestion	High moisture (sewage sludge, aquatic biomass, etc.)	Medium-Btu methane gas	35-50
		Electricity	5-10
Ethanol fermentation (followed by distillation)	Sugars (sugarcane juice, molasses, hydrolyzed cellulose, etc).	Ethanol	30

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[a] Based on the percentage of biomass input (higher heating value) converted to fuel (or steam), less the required internal fuel needs of the conversion process.

[b] Up to 50% maximum moisture allowable without drying (e.g., wood chips, MSW, field-dried agricultrual residue).

[c] Steam generation with low-Btu gas exhausting from a gasifier in a conventional oil or gas boiler (close-coupled gasification) would allow much higher efficiencies, approaching those of direct combustion.

The following general statements can be made regarding the current status of the technologies discussed thus far:

1. Direct Combustion (DC) is currently economic with some limits on the amount one must pay for fuel. It is very clear given the current instability in the price of oil that long term contracts for biomass fuels at higher than average petroleum fuel cost is probably a good investment. The conversion technology is well established. The next technological breakthrough for this particular area would be in the harvesting, transportation and marketing of fuels like forest slash and agricultural residues which have heretofore not been marketable as fuel. As the price of imported oil and synthetics affect the petroleum markets, marginal fuels like slash will become attractive; but there is a great need for reliable harvesting equipment and techniques.

2. Low Btu Gas (LBG) air-blown gasifiers are a reborn technology which have in the past achieved moderate levels of sophistication capable of sustaining petroleum-starved countries during wartime. Although competitive in price with conventional fuel (even regulated natural gas), gasifiers are not typically competitive with DC systems. They also suffer greatly from a lack of longterm operation and subsequent proof of reliability. Their small scale, versatility and portability suggest a successful future beyond the capability of DC systems. This appears to be especially true in applications like off-road vehicles, for farm use and for the portable generation of electricity.

3. Medium Btu Gas (MBG) oxygen/steam-injection gasifiers are limited because of their large through-put requirements, i.e., 1,000 tpd (907,184.7 kg per day) or greater. Like the LBG air-blown systems they suffer from lack of reliability testing. These will probably not be competitive in the near term (1985) with conventional fuels and will not necessarily compete with their likeness in the coal synthetics arena. Clearly, if they cannot be downsized from the 1,000 tpd (907,184.7 kg per day), they will not be able to compete for the same resource which will be used for cellulosic fermentation systems some of which appear to be coming on line in the pre-1985 period.

4. Methane Fermentation (MF) with by-product credits for refeeding effluent to cattle as a replacement for alfalfa, MF using current sewage treatment technologies appears to be competitive with regulated natural gas on operations with 100,000 head and larger. Since nearly

75 percent of the animal populations in confinement are on farms with less than 1,000 head, there is a critical need to commercialize a low-cost nonconventional system. This appears to be occurring in the dairy industry where payback periods of seven to ten years are acceptable. Covering of anaerobic lagoons also appears attractive since these structures release biogas to the atmosphere. The rebirth of this technology from its abandonment after WWII in Germany and France has yielded new applications of reliable, low-cost systems to the farm. In agricultural canning and packing operations these systems could compete with ethanol facilities. These systems can also complement ethanol facilities. Their near term application on farms is imminent. Of crucial concern here are the on-farm energy use patterns which are as yet poorly understood. The use of ICE/generator sets will prevail in the small scale (1,000 head) situations.

5. Alcohol Fermentation (AF) Although not economic without subsidy, the current subsidy makes these facilities very economic with returns on investments running in excess of twenty percent. Current reliance is on grain and to a limited extent sugar feedstocks. The production of this high grade motor fuel can play a significant role in stabilization of agricultural production as well as providing an exclusive fuel to support that production. This new industry will see the greatest economic growth in the coming near term because of its popularity. The promise of cellulosic conversion technologies is essential to avoid both food versus fuel issues and net energy concerns. Cellulosic technologies appear to have a chance of success in the near term. Their production costs, however, will probably need an initial subsidy. The small scale nature of this technology gives it a distinct advantage over methanol synthesis via MBG from the same or similar cellulosic feedstocks.

To realize the four to five Quads (10^{15} Btu per year) of biomass energy that could be realized in the near term, there is a massive feed for capital investment. The $1.4 billion provided by the Energy Security Act is encouraging but insufficient to provide what is needed to make a transition to commercialized biomass technologies.

Current motor gasoline consumption is roughly 108 billion gallons per year. Capital investment in alcohol fermentation is roughly $1.00 to $1.50 per million gallons ($.26-$.40 per million liters) per year capacity. To achieve a two percent goal as suggested by the Office of Technology Assessment, it would require an investment of about $2-$3 billion.

Geothermal Energy (3.12)

Geothermal energy occurs as a result of radioactive decay deep within the earth and internal tectonic activity. Geothermal "hot spots" capable of yielding the energy equivalent of 1.2 trillion barrels of oil lie untapped in the western U.S. and parts of the Gulf Coast according to the U.S. Geological Survey (USGS). In its second national assessment of geothermal resources, the USGS estimated that the upper portion of the earth's crust contains 32 sextillion Btus of heat energy, 6.4 sextillion of which are harnessable "under reasonable assumptions of improvements in technology and economics."[231]

Three different types of geothermal resources interest electrical energy developers. The most extensive geothermal resource in the U.S. is in the form of hot dry rock. According to the Department of Energy, hot dry rock resources are "geologic formations at accessible depths which have abnormally high heat content but contain little or no water." Extraction of usable energy from these formations would require a heat transfer fluid such as water to be circulated through the rock. Though the extent of usable hot dry rock resources in the U.S. is very large (possibly as large as 32 million Quads, with thirteen million Quads at temperatures higher than 150°C) DOE doubts that it will contribute substantially to domestic energy supplies for some time to come.[232]

The next most plentiful are geopressured hydrothermal resources which are hot water aquifers containing dissolved methane. These aquifers are trapped under high pressure in deep sedimentary formations along the Gulf Coast of the United States. Three forms of energy are derivable from these resources: thermal, kinetic, and dissolved methane. Data on geopressured hydrothermal aquifers comes from nearby petroleum operations, and points to large reserves particularly in a wide belt stretching along the Gulf of Mexico from Mexico to Mississippi, and in two areas between northeastern Texas and Florida. More information on the number, location, size, permeability, and methane content of the aquifers is necessary to know whether such reserves are economically exploitable. This information is currently being gathered.

Least plentiful, but already in use in many parts of the world, are convective hydrothermal resources. These are systems of hot water and steam, heated by relatively shallow masses of hot rock, and trapped in fractured rocks or porous sediments overlain by impermeable surface layers. These systems are classified according to whether they produce steam or liquid. Rare, "vapor-dominated" (dry steam) reservoirs are used for generating electricity. "Liquid-dominated reservoirs outnumber vapor-dominated reservoirs by about twenty-to-one among known hydrothermal resources. Steam from these reservoirs can be separated from the liquid and passed through turbines to generate electricity.

The Department of Energy has described how geothermal resources are distributed across the United States:

1. The Central Pacific Coast Region is an area of high temperature, moderate-to-high salinity, liquid-dominated hydrothermal resources.

2. The Gulf Coast Region is an area of geopressured, moderate temperature, low-to-moderate salinity hydrothermal resources containing large amounts of dissolved methane.

3. The Northwestern Region is an area of moderate temperature, low-to-moderate salinity, liquid-dominated hydrothermal resources.

4. The Southwestern Region is an area of high-temperature, low-to-moderate salinity, liquid-dominated hydrothermal resources and moderate-temperature resources.

5. The Midwestern and Eastern Region is an area of low-to-moderate temperature, low-salinity hydrothermal resources, in localized areas of shallow igneous intrusives heated in part by traces of naturally radioactive elements.

Figure 3.12-1 indicates Known Geothermal Resources Areas (KGRA's) for the continental U.S. Note too, the variety of proposed and on-line projects which range from electricity generation to commercial district heat applications.