Kirk-Othmer Encyclopedia of Chemical Technology.

RENEWABLE ENERGY RESOURCES

The ongoing, continuing drive to develop renewable energy resources began in the energy-short 1970s. Sharply rising oil prices and an increasing dependence on international markets for energy supplies served to shift the focus of planners toward those limitless resources that stand available for exploitation and at the same time are virtually without emissions as a result of their operation. By harnessing the sun, wind, falling water, plant matter, and heat from the earth, it was asserted, the environmental impact of energy use would decrease and the nation would regain its energy independence. In this vision for the future, renewable energy resources would complement fossil fuels and, eventually, emerge as a significant energy source.

The promise of such a scenario spurred legislative incentives for the development of renewable energy technologies. One of the most significant of these was the Public Utilities Regulatory Policies Act (PURPA) of 1978, enacted to encourage development of alternative energy sources and to reduce dependence on oil and gas. The enactment of PURPA obligated utilities to purchase the electricity from cogeneration sources and small power producers, ranging from hydroelectric and wind projects to municipal waste combustors. In the years following its passage, the electricity generated by Qualifying Facilities (QF) defined by the legislation generally has tended to replace electricity from a utility system's least efficient plants, typically older coal- and oil-fired facilities.

The incentives for the development of renewable energy and energy-efficient technologies increased with the continued passage of state and federal legislation, particularly the federal Energy Policy Act of 1992. This act encouraged the production and utilization of renewable energy resources, including advanced technologies. Also, exports of U.S. renewable energy technologies and services were promoted.

Despite such incentives, only about 2% of U.S. electricity needs in the mid-1990s are supplied by renewable energy technologies other than hydropower. Most of the nonhydro renewable power comes through some form of combustion, such as the burning of biomass (wood and agricultural waste), landfill gas, or municipal solid waste. Thus, as of the mid-1990s, only a small fraction of the nation's electricity comes from solar, wind, and geothermal sources.

The limitations on renewable energy's progress to date result from its relatively high cost and the economics of the utility industry, which is faced with an increasingly competitive environment and is generally awash in surplus power. Although renewable energy technologies have overcome a number of formidable technical hurdles to bring costs down and increase reliability, further progress has been prevented by the lower cost of natural gas and the efficiency of gas-fired generating plants.

Nevertheless, as costs continue to decline, the renewable energy market can be expected to grow, particularly if possible global warming trends continue to be linked with greenhouse gases such as those emitted by fossil fuels. Other factors that are increasing interest in renewable energy include niche cost advantages, regulatory pressures, customer service requirements, fuel flexibility, and security.

The extent to which each technology is poised to advance is described in separate discussions of photovoltaics, solar-thermal power, and wind, biomass, waste-to-energy, geothermal, hydropower, and wave energy.

1. Photovoltaic Cells

Since the first photovoltaic (PV) cells were fabricated for the U.S. space program in 1958, PV technology has evolved from once being a very high cost but essential and effective space power source to later becoming a small but diversified and enduring worldwide industry (1–6). Led by firms based in the United States, Japan, and Germany, this industry serves multiple markets (see Photovoltaic cells).

Since the mid-1980s, PV sales have climbed by a factor of four or more to over 60 MW annually, while installed costs have fallen by more than half. In this same period, a substantial consumer market for PV-powered watches and calculators emerged in Japan. The total number of these products in the marketplace in the 1990s numbers in the hundreds of millions.

Conventional power plants, however, range in size from 100 to 1000 MW. To enter that kind of bulk power market, the lowest quoted costs, ca 1995, for installed PV systems, about $6–$7/W, need to decrease by a factor of three or more to the $2/W that is considered competitive with conventional sources of bulk power generation. However, steady progress in advanced PV technologies, such as multilayered thin films and high efficiency concentrator systems, suggests that competitive PV systems may become available before the year 2005. These systems would be capable of generating electricity at 6–8¢/$\mathrm{kW{\cdot}h}$ by offering a net system efficiency of 15% and a system cost of $60–$100/m^2.

Taken as a group, PV cells comprise solid-state devices in which photons of light collide with atoms and transfer their energy to electrons. These electrons flow into wires that are connected to the cells, thereby providing current to electrical loads.

PV systems consist of arrays of cells that are interconnected in panels or modules to increase total power output. Often the systems include sun-tracking equipment, as well as power-conditioning equipment to convert dc to ac. The systems can range in size from a simple one-panel, fixed-orientation unit to a vast field of modules that accurately track the movement of the sun. Electric utilities in Europe, Japan, and the United States have hosted several experimental PV power plants. The largest to date was a 5.5-MW plant at Carrisa Plains, California, built by Siemens Solar Industries (formerly ARCO Solar).

PV cells may be fabricated using one of four production methods. In the traditional method, which still accounts for a large portion of annual production, PV cells are made from slices of single-crystal silicon. In this process, crystalline silicon is grown in pure ingots made from molten silicon, and is then cut into wafers. The wafers are polished and processed into PV cells, which are mounted in modules. The ingot-based technologies of the 1990s also use polycrystalline silicon.

A second method grows silicon ribbons or sheets directly, bypassing the ingot stage. The sheets are cut into cell-size pieces that are processed to make cells. This manufacturing approach consumes less silicon than ingot-based technologies.

Still another method used to produce PV cells is provided by thin-film technologies. Thin films are made by depositing semiconductor materials on a solid substrate such as glass or metal sheet. Among the wide variety of thin-film materials under development are amorphous silicon, polycrystalline silicon, copper indium diselenide, and cadmium telluride. Additionally, development of multijunction thin-film PV cells is being explored. These cells use multiple layers of thin-film silicon alloys or other semiconductors tailored to respond to specific portions of the light spectrum.

Compared to ingot-based and silicon sheet technologies, thin-film modules require less semiconductor material and can be more highly automated; both attributes lead to lower cost. However, the performance of thin-film modules has yet to equal that of ingot-based and silicon sheet technologies.

A fourth category of PV technologies, concentrator photovoltaics, uses small but very efficient cells illuminated with concentrated sunlight. PV concentrators use lenses or reflective devices and track the sun through daily cycles. The tracking maintains the concentrated light at intensities up to several hundred times normal sunlight.

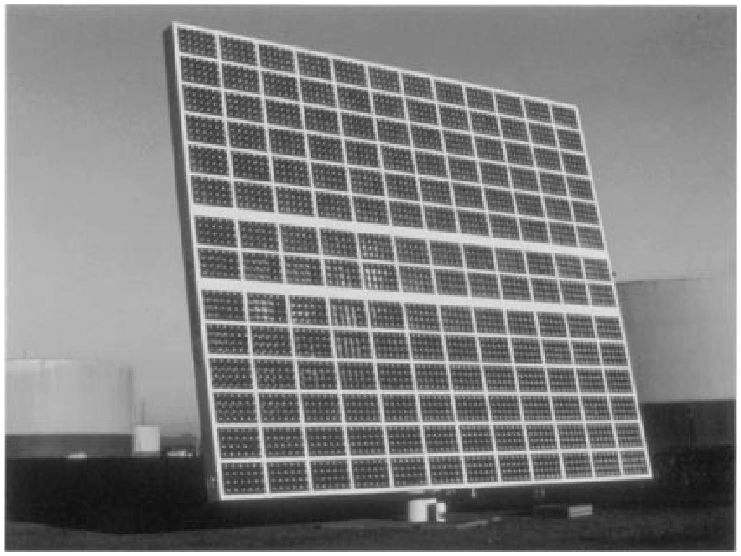

Fig. 1. An integrated high concentration photovoltaic array that achieved a solar conversion efficiency exceeding 20% in a 2000-W testbed (7).

Most current world PV production comes from the classical ingot technologies. Nevertheless, sheet growth, thin films, and PV concentrators hold greater potential for sufficient cost reduction to stimulate large-scale applications.

The evolution of the competing technologies has been marked by ever-increasing efficiencies in converting sunlight into electricity. The earliest PV cells converted <5% of the sun's energy to electricity. By contrast, recent tandem cells designed for use with highly concentrated sunlight have exceeded 30% efficiency in the laboratory.

In the field, commercial-scale electrical energy conversion from sunlight exceeded 20% in an integrated array system patented by the Electric Power Research Institute (EPRI). The system employs an advanced crystalline silicon cell that uses radiation-hardening technology developed for space satellite applications. The system was built by Amonix, Inc., which is leading a team of EPRI contractors to complete and commercialize the innovation. The pace-setting efficiency was achieved in a 2000-W testbed array installed at the Georgia Power Company (Figs. 1 and 2). Individual solar cells (metallized on the bottom side) (Fig. 2**b**) span gaps in the copper conductive layer. In the 20-kW array, 168 such panels (120 W per panel), each containing 24 cells, and additional optical elements form the bottom portion of a box-beam structure. The top part of the structure consists of parquets of Fresnel lenses designed for $250\times$ sunlight concentration. Made of molded acrylic, the lenses in each parquet are arranged in a 4×6matrix. A motorized, computer-controlled pedestal keeps the array pointed at the sun. Based on this array, a 20-kW demonstration system is under construction for utility evaluation at an Arizona Public Service facility.

In addition, other utilities are installing established solar cells in a growing number of tests that may lead to a mass market. The studies may indicate the extent to which solar cells can be used to avoid installation costs for new distribution lines between conventional power plants and remote customers' buildings. Also, among other objectives, PV cells may provide an economical means of helping to supply demand during peak summer periods in northern climates.

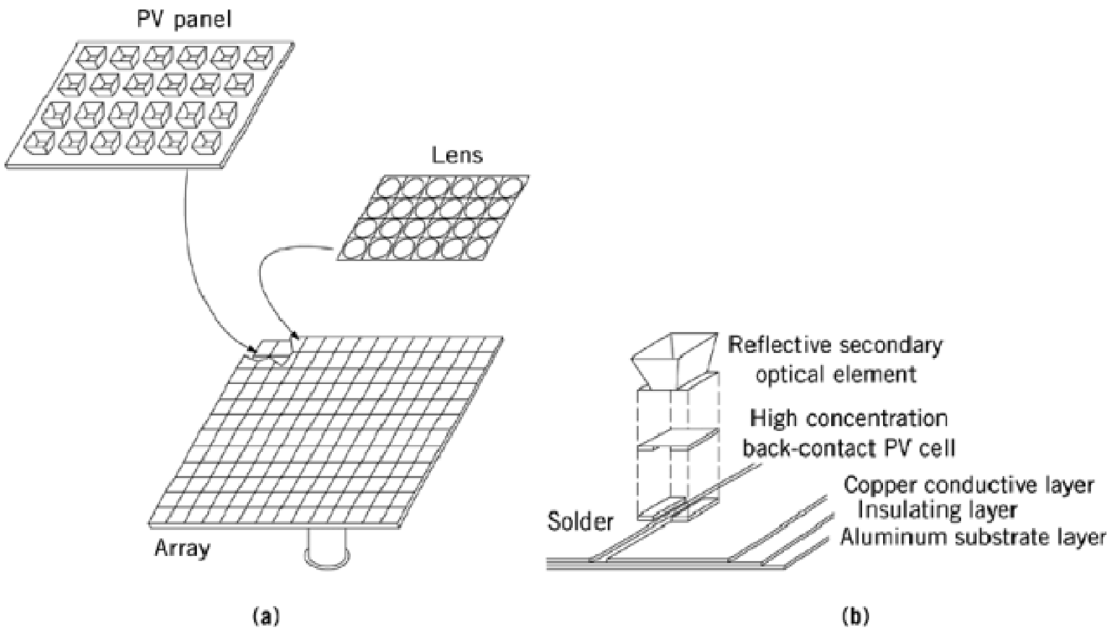

Fig. 2. (**a**) The cell mount design of the integrated PV array of Figure 1, which uses laminated conductive and insulating layers on top of an aluminium substrate in a printed circuit board-type panel (7). The array produces 20 kW at 20°C ambient and 850 W/m^2 direct sunlight, and measures 155 m^2. The lens is a molded acrylic Fresnel lens parquet mounted on the front of the array structure. The PV panel is mounted on the back of the array structure and is made up of (**b**) individual solar cells (7).

2. Solar-Thermal Power

The first solar-electric technology to arouse industry interest was solar-thermal energy (1, 3, 5, 6, 8). Under favorable circumstances, it can be cost-effective, as evidenced by the fact that solar-thermal gas-hybrid plants produce over 350 MW of commercial power in southern California. This power is used during peak demand to supplement that available from conventional generation.

The level of benefits from tax credits and favorable power purchase terms that helped give these installations their start has diminished in recent years. Nevertheless, with the remaining tax credits available and given current (ca 1995) natural gas prices, solar-thermal technology can deliver power at 8–12¢/kW·h and an installed cost of $2500–$3000/kW.

Solar-thermal technology uses tracking mirrors to concentrate sunlight onto a receiver. In turn, the receiver absorbs solar energy as heat, warming a fluid that then drives a turbine generator. Most solar-thermal plants require cooling water.

Solar-thermal receivers may be centralized or distributed. Central receiver systems use fields of tracking mirrors, or heliostats, to focus sunlight onto a tower-mounted receiver (Figs. 3 and 4). Distributed receivers use point-focusing parabolic dishes or line-focusing parabolic troughs to concentrate sunlight. Solarthermal power plants may be entirely solar or they may be hybrids that use fossil fuels to boost power output or extend operating hours.

The pioneering 10-MW Solar One plant in Barstow, California, produced the most successful central receiver tests. The plant was funded primarily by the U.S. Department of Energy (DOE) and operated by Southern California Edison Company in the early to mid-1980s. EPRI provided technical evaluations of the

Fig. 3. The 10-MW Solar One plant, which advanced solar thermal power through the use of tracking mirrors to concentrate sunlight onto a central tower-mounted receiver.(Courtesy of Southern California Edison.)

experiment. The general conclusion drawn from Solar One and other experiments was that further substantial engineering development was needed.

Based on the results of the Solar One plant, Southern California Edison formed a consortium that included DOE and EPRI to construct a Solar Two Project. Solar Two will convert the idle Solar One central receiver plant from a water/steam system to a molten salt system, thereby improving efficiency and operating performance. With the molten salt technology, solar energy can be collected during the day and stored in the salt to produce electricity when needed. The three-year demonstration is scheduled to begin in late 1996.

Central receiver systems not only require components that can withstand severe and frequent thermal cycling, but in addition they entail long warmup times and exhibit slow transient responses. As a result, energy production from the best systems have been about half of that expected. As development complexities became apparent, government support was curtailed and industrial commitment waned.

The future of distributed receivers using dish concentrator systems may rest with the development of several components, beginning with a highly efficient, easily maintainable power conversion unit that can convert concentrated solar energy into electricity. Stirling engines, which are being developed for other applications, appear to be the most appropriate choice for this function. If they become commercially successful and sufficient means to support system development efforts materialize, this category of solar-thermal technology may be pursued.

By contrast, trough concentrators are supplying the 350 MW of commercial power. Several plants, all using line-focusing parabolic troughs to concentrate sunlight, were placed into service in the mid- to late 1980s by LUZ International Ltd. The solar-hybrid plants use natural gas to supply 25% of the electricity produced. Assisted by state and federal tax credits and favorable long-term energy purchase agreements with utilities, LUZ shouldered most of the financial risks of development and commercialization. Although the company was unable to continue in business, its operating plants demonstrated that solar energy technology can be made viable.

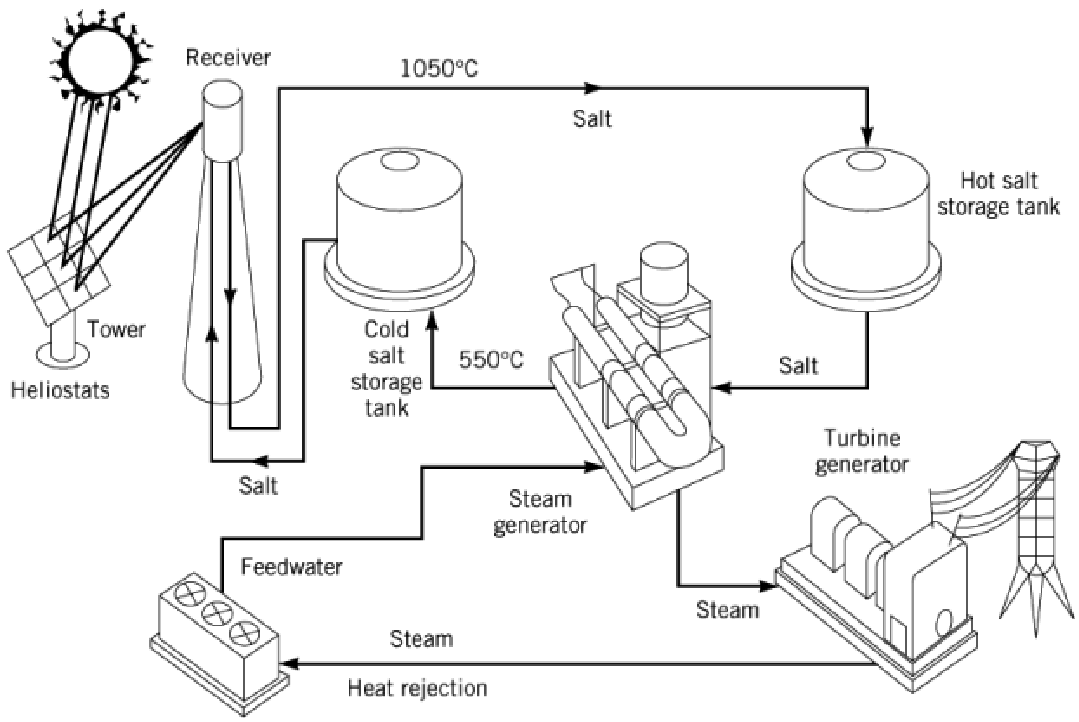

Fig. 4. In the Solar Two Project a molten salt system shown in the scheme replaces Solar One's water/steam system. In operation, "cold" molten salt is pumped from a storage tank to a receiver on a tower. Sunlight reflected from a field of sun-tracking mirrors heats the salt in the receiver to 1050°C. The heated salt then flows down into a hot storage tank where it is pumped to a heat exchanger to produce the steam that drives a turbine. Some of the hot molten salt can also be stored to produce steam on demand at a later time. Salt cooled to 550°C in the steam generator recirculates through the system and is reheated in the receiver. Courtesy of Southern California Edison.

2.1. Passive Solar Power

The largest opportunity for solar power may be in building and process design, among other applications that take advantage of natural lighting and cooling. Such applications will not generate electricity, but will reduce demand for commercially generated electricity. Window technologies and various architectural techniques allow passive solar methods to be readily incorporated into new building designs. Potential heating and cooling energy savings of 15–20% can often be achieved at comparable construction costs. Widespread use of passive solar devices and methods may require energy efficiency standards for building systems.

3. Wind Power

Like solar-thermal technology, wind is providing utility customers with electricity (3, 6, 9, 10). The technology is advancing despite the expiration of favorable tax credits in the mid-1980s. About 17,000 mid-size wind turbines, nearly all of them in California, are producing approximately 1500 MW of electricity and more are planned. Many of these turbines are operated by Kenetech Corporation, the world's largest developer of wind power. The electricity produced costs 7–9¢/kW·h, and state-of-the-art technology reduces this amount to 5¢/kW·h (constant dollars). However, even this amount exceeds the present cost of wholesale gas of about 2–3¢/kW·h. Total installed costs for state-of-the-art wind systems range from $900–$1200/kW.

Wind turbines have had a varied history. Once widely used for electric power generation in remote areas in the United States, for example, they eventually fell into disuse by the 1940s as a result of rural electrification. In the 1970s, interest in wind revived in the face of the energy shortages. Government and industry combined efforts to develop, build, and test over a dozen new turbines, the largest of which was capable of generating several megawatts. However, their imposing size and complexity and the high costs associated with their operation and maintenance discouraged potential commercial developers. Even the turbines on the order of hundreds of kilowatts were not yet cost-competitive with conventional forms of electric generation.

In the early 1980s, favorable tax credits and energy rates for independent power producers encouraged the development of wind farms in California based on 50–100-kW turbines. Simpler and relatively easy to design, build, install, and repair compared to the earlier, larger-size turbines, this new generation of wind machines was also relatively reliable and provided lower cost electricity than the previous generation. Nevertheless, as numerous manufacturers were drawn into the business and wind farms came into existence in California, machines of widely varying effectiveness were deployed. However, enough of the wind farms pulled through to renew utility interest.

Typical wind turbines consist of rotor blades mounted atop a tower and connected by gears to a drive shaft that spins a generator. Another common design is the vertical axis turbine, which has an eggbeater-shaped rotor attached directly to a vertical shaft. The rotor blade length and wind speed determine the amount of electric power that can be delivered. In general, wind speeds of at least 6.7 m/s are sought for power generation.

Most of the best locations for wind projects lie outside California. Several northern Rocky Mountain states and Northern Plains states possess substantial resources. Also, the Northeast and Texas have considerable wind resources. In all, about 14 states each possess a wind energy potential that is equal to or greater than that of California.

A cooperative alliance of Kenetech Corporation, Pacific Gas and Electric Company, Niagara Mohawk Power Corporation, and EPRI has developed an advanced, utility-grade variable speed wind turbine that can deliver 300 kW. Commercially available and in widespread use, the turbine uses advanced power electronics to increase turbine efficiency, improve power quality, and lengthen turbine life. Future efforts are directed at developing turbines capable of individually producing 500–1000 kW for eventual deployment in a large-scale power role.

Traditionally, wind turbines have operated at constant rpm to produce 60 Hz a-c power. Because the extra torque generated by wind gusts must be absorbed by the drive trains of constant speed wind turbines, they require heavier designs than comparable variable speed models. By contrast, variable speed turbines employ a power electronic converter between the generator and the utility power line. The converter allows the rotor and generator to speed up with gusts or stronger winds, without increasing drive-train torque. The increased rotational energy is converted into additional electricity. Energy capture increases by 10% or more, and stresses on the turbine are reduced. The variable speed design produces wind power at a cost of 5¢/kW·h, a level that is also achieved in moderate wind resources by other, fixed speed turbines, eg, the AWT-26, Z, and Z-46.

In Europe, government policies (ca 1995) are calling for a steadily increasing commitment to wind power. Combined, the European programs call for the installation of at least 4000 MW by the twenty-first century, a level that would dominate world production. Environmental concerns are the incentives behind Europe's wind targets. With over 2000 MW of wind power already installed, Europe is well on its way to achieving its goal.

4. Biomass Fuel

Concern over possible global warming trends has been linked with steady increases in greenhouse gases, such as carbon dioxide, CO_2. This gas is emitted whenever fossil fuels or biomass materials, such as wood and agricultural wastes, are burned. When used as a renewable fuel, however, the CO_2 released by biomass during combustion ideally equals that consumed when the fuel was grown. Thus, biomass should not contribute to CO_2-related global climate change (3, 6, 11).

Global demand for electricity can be expected to eventually increase substantially over the levels of the mid-1990s. In that event, only a massive expansion in the use of biomass and other nonfossil fuel sources can slow the annual increase in global CO_2 emissions.

Also, wood fuel is low in sulfur, ash, and trace toxic metals. Wood-fired power plants emit about 45% less nitrogen oxides, NO_x, than coal-fired units. Legislation intended to reduce sulfur oxides, SO_x, and NO_x emissions may therefore result in the encouragement of wood-burning or cofiring wood with coal.

In the United States, up to about 4×10^{15} Btu/yr of biofuels are consumed for electricity generation, raising process heat, and domestic heat. Furthermore, much of the energy needs of many nations are met by biofuels, including wood and wood waste, spent pulping liquors, bagasse, and municipal waste. Some use is also made of dried corn cobs, rice hulls, and a wide variety of agricultural wastes used in niche applications.

About 6000 MW of electricity generating capacity in the United States is based on the operation of several hundred wood-fired plants. Most of them are owned by paper companies and saw mills, which burn their own scrap wood to generate heat and electricity, primarily for on-site use. Excess electricity is commonly sold to utilities. Fewer than 10 of the country's wood-fired plants, generating less than 300 MW, are actually operated by utilities; other wood-fired plants have been built and are operated by independent producers. The largest units range between 50–60 MW.

Extensive efforts are underway to use wood and agricultural wastes as fuel, including an increasing emphasis on capturing these materials. Also, traditional direct combustion technologies used for electricity generation have been joined by developments in the use of circulating fluidized-bed technology for biofuels, and cofiring as a technology for using biofuels in pulverized coal and cyclone boilers. Existing and emerging gasification technologies are also under study for use in supporting conventional combustion turbine technology or for integrated gasification–combined cycle (IGCC) systems. Experiments continue with direct-fixed gas turbines.

The higher utility energy cost of a wood-fired plant, compared with the corresponding cost for a coal-fired plant, arises from the higher costs entailed in collecting and transporting wood and the lower energy heating value of wood relative to coal.

Short-rotation woody crop (SRWC) practices offer one means to reduce wood collection costs. The SRWC programs seek to develop a steadily replenishable, predictable supply of wood for energy production. For example, SRWC plantations, focusing mainly on fast-growing, short-lived hybrid willow trees, use many typical agricultural practices, including fertilizers and pesticides to maximize yields of genetically improved trees. The fastest growing hybrids have produced growth rates exceeding 24.7 dry tons/ha/yr. The first harvests are expected three to four years after planting. Sponsors for such efforts include the U.S. Department of Energy, EPRI, Empire State Electric Energy Research Corporation, New York State Electric & Gas Corporation, and Niagara Mohawk Power Corporation.

Also, EPRI is investigating whole-tree burn power plants that will dry and burn SRWC fuel without requiring tree trimming, wood chipping, or other fuel preparation. The concept involves the combustion of tree crops from farms distributed within a 40-km radius of a given plant.

Harvested and delivered whole, the trees are dried in an air-supported fiber glass dome structure over a 30-d period by using waste heat from the combustion process in the adjacent plant (Fig. 5). Trees leave the dome on the conveyor and, at the boiler wall, batches are cut into sections to fit the boiler. These sections are about 8.5 m long for the 100-MW facility studied by EPRI and the Minnesota Power & Light Company.

In theory, whole-tree-energy plants have the potential to be more efficient than existing wood-fired generators, which are fueled by chipped wood with a relatively high moisture content (45%). The dried whole trees have a moisture content below 25%, and whole-tree plants potentially can be built to have a greater capacity and to employ high pressure, high temperature steam.

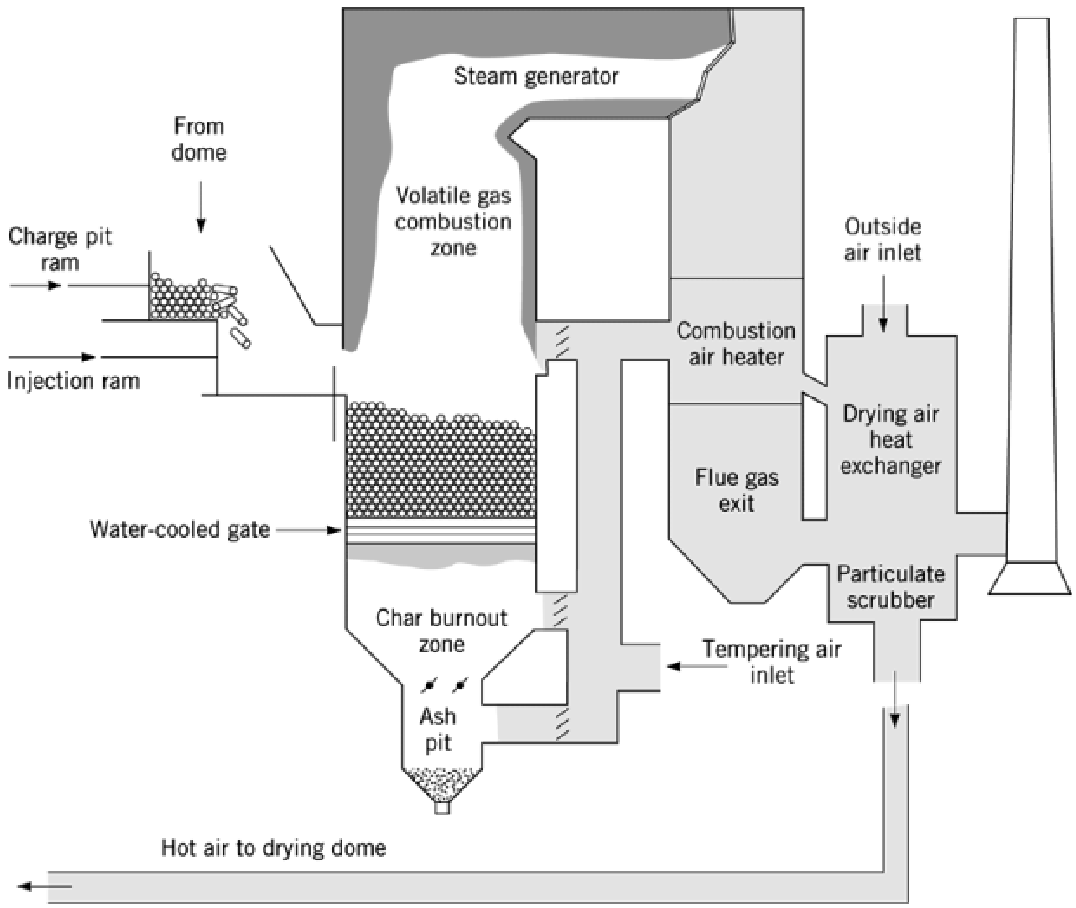

Fig. 5. Developmental concept for a process for the conversion of trees to electricity (12). Dried trees are cut into sections that will fit the boiler chamber. Successive rams push the trees into a charge pit, and then into the furnace. Although larger than a gas-fired boiler, the whole-tree-energy boiler is otherwise similar. The greater height helps achieve a high heat-release rate and complete combustion. Cinders from the burning bed of trees fall through a grate into an area where any remaining carbon in the material burns away. Air is fed into the boiler both below and above the bed of trees to promote complete combustion. Waste heat is fed into an adjacent tree-drying dome.

5. Waste-to-Energy

Large quantities of municipal solid waste (MSW), comprised mostly of residential and light commercial waste, are generated in the United States at the rate of approximately 180×10^6 t/yr. Although the composition of MSW varies according to the source and time of year in which it is generated and collected, MSW generally comprises paper, cardboard, wood, plastic, garbage, food and beverage containers, metal, glass, organic material from yards, appliances, and miscellaneous materials, such as rugs, blankets, shoes, mattresses, and telephone wire.

The conventional means of disposing of MSW is by landfilling. About 75% of MSW is disposed of in this manner, with the balance handled by converting waste to energy (about 15%) and recycling. However, because landfills are becoming a less acceptable solution, alternative means of disposing MSW have been advanced (Fig. 6).

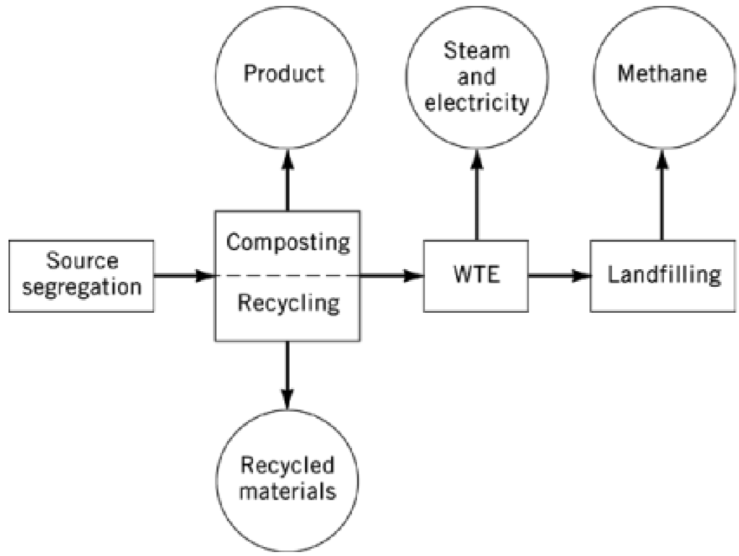

Fig. 6. An integrated approach to the management of municipal solid waste (MSW), advocated by the U.S. EPA, that links source segregation, recycling, waste-to-energy (WTE), and landfilling in a single system. Source segregation refers to the separation of compostable and recyclable components from the balance of the trash at the point where MSW is collected. In source reduction (not shown), another action to reduce waste to landfills, changes are made in the way goods are packaged, distributed, and used (12).

The hazardous components of MSW, ie, household chemicals, oily wastes, and lead and other metals in batteries, can leach from landfills and contaminate both surface water and groundwater or enter the atmosphere. Increased regulation to improve landfill integrity has led to impermeable liners and drainage and water quality monitoring systems. As a result, in many urban areas, land is either no longer readily available for new landfills or is available only at high cost.

Burning of MSW can reduce the volume of landfill space needed by over 80%. Moreover, MSW represents an available energy source of about 1.5×10^{15} kJ/yr (1.4×10^{15} Btu/yr) that could provide about 5% of the nation's annual electricity consumption. However, compared to coal, MSW is a poor fuel. Although MSW has a low sulfur content, it may be high in chlorine, aluminum, and some trace metals, including lead and cadmium. The nonhomogeneity of MSW and its high and variable moisture and ash content cause difficulties in maintaining good combustion on a continuous basis.

Nevertheless, plants are disposing of MSW through combustion and recovering energy in the form of steam for electric power generation (3, 13). Two commercial technologies are (*1*) mass burning of MSW as received, using a facility designed for nonuniform, high moisture slow burning materials and (*2*) processing MSW into refuse-derived fuel (RDF), which is then burned at a cofired or dedicated facility. In cofired plants, RDF and coal are fired simultaneously, whereas at dedicated waste-fired plants, RDF is burned and coal is used only as a backup. Both methods begin by removing unacceptably large items, as well as others, such as discarded gas cans, that might explode during waste processing.

The manufacture of RDF (Fig. 7) entails moving the waste through a series of separators that successively reduce the feed by size and weight; a magnetic separator removes ferrous metals for recycling. Much of the heavier material comprises metal and glass, which can also be recycled. The lighter fraction contains most of the combustible material in the form of a light uniform fluff, RDF, which is conveyed to the power plant for burning. The small residue of unburned waste (ash) can be further treated to remove aggregates and remaining metals before placement in a landfill.

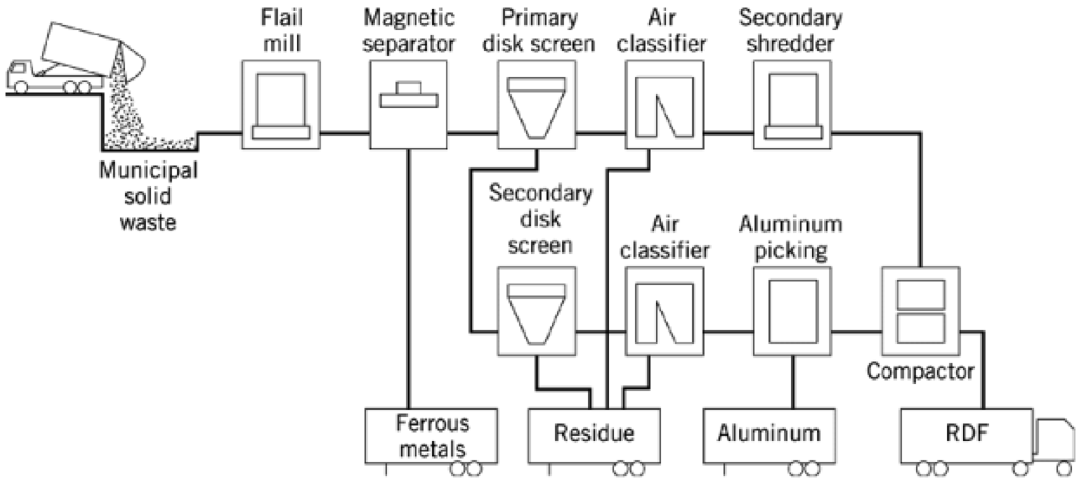

Fig. 7. Scheme demonstrating how MSW can be converted into energy by first processing MSW into refuse-derived fuel (RDF) (12).

An economical means of generating electricity from waste material is to employ a combustor that can burn several different waste materials as fuel. One such option is the fluidized-bed combustor (FBC) which can efficiently burn a variety of inexpensive fuels and comply with environmental regulations. The fuels in the several FBCs in operation in the United States range from RDF, wood, and coal in one to RDF and wastewater sludge filter cake in another. Several FBC units in the construction stage are designed to burn more RDF. In Japan, over 100 FBC units are burning MSW as part of that country's MSW disposal program.

Of the 140 or so waste-to-energy power plants in operation in the United States, over 80% use mass burn, and the balance employ RDF. For the most part, this waste-to-energy (WTE) generating capacity is either owned or being built by organizations other than electric utilities. The utilities own 10 of the 100 plants with an MSW-processing capacity of more than 200 t/d, and purchase energy from 70 others.

By substantially reducing the volume of landfill space needed for MSW disposal, WTE can extend the life of a landfill. In fact, most of the revenues that go to WTE plant operators come from the payments for waste disposal services called tipping fees, and not from electric sales.

5.1. Tires

As with MSW disposal, state and local communities have sought increased utility assistance in waste tire management. In the United States, scrap tires are generated at the rate of one tire per person per year, and only 20% are reused or recycled in some fashion. Stockpiles exceed 2×10^9 scrap tires (see Recycling, rubber).

Landfill operators do not want these tires, and many refuse to accept them or charge high waste disposal fees. Whole tires tend to rise gradually in a landfill, because they fill with methane gas and are less dense than the surrounding moist degrading material. Thus, illegal tire piles abound, posing a fire risk and a health hazard because they make an ideal breeding place for mosquitoes and vermin.

Ironically, scrap tires make good fuel, either whole or as shredded chips, commonly called tire-derived fuel (TDF). Each tire has the heat energy of 3.2×10^5 kJ (300,000 Btu), or about the amount of energy in 13.6 kg (30 lbs) of coal or 9.4 L (2.5 gal) of oil. Also, tires are moderate in both sulfur and ash compared with bituminous coal and do not adversely affect emissions quality.

As an interim measure, burning scrap tires and recovering the energy assists in the solution to the problem of growing mountains of tires, as it reduces the use of nonrenewable fossil fuels. However, the utility industry has long been reluctant to burn materials other than conventional fuels, even though pulp and paper mills and cement kilns have burned mixes of tire chips for many years. In general, the potential savings in fuel costs failed to provide sufficient incentives to offset possible environmental concerns, operational difficulties, and costly equipment modifications. That situation is changing as utilities and other industries are required to adapt to a changing social and economic climate.

Several utilities are burning or have successfully test-burned TDF. For example, the results of a pilot project at Wisconsin Power & Light (WP&L) were so successful that the utility installed its own system to shred tires, thereby assuring a steady supply of uniformly sized tire chips. The tire processing plant will enable the utility to manage about 20% of the 5×10^6 waste tires generated each year in Wisconsin.

The WP&L cyclone boiler will burn TDF continuously with coal, as about 5% of its fuel mix, with little or no modification. By contrast, pulverized-coal boilers, which account for about 80% of the coal-fired capacity in the United States, probably cannot burn tire chips without significant modifications. In these boilers, which burn very fine coal particles in suspension, the heavy chips will fall from the area where best combustion occurs.

Another furnace that does not require fuel preparation is the stoker boiler, which was used by New York State Electric & Gas Corporation (NYSEG) in its TDF tests. At NYSEG, the stoker boiler, which has a 1649°C (3000°F) flame temperature (as does the cyclone boiler), has routinely blended low quality coal, and more recently, wood chips with its standard coal to reduce fuel costs and improve combustion efficiency. In the tire-chip tests, NYSEG burned approximately 1100 t of tire chips (smaller than 5×5 cm) mixed with coal and monitored the emissions. The company determined that the emissions were similar to those from burning coal alone. In a second test-burn of 1900 t of TDF, magnetic separation equipment removed metal from the resulting ash, so that it could be recycled as a winter traction agent for roadways.

5.2. Landfill Gas Recovery

This process has emerged from the need to better manage landfill operations. Landfill gas is produced naturally: anaerobic bacteria convert the disposed organic matter into methane, carbon monoxide, and other gases. The quantity of methane gas is substantial and could be utilized as fuel, but generally is not. Most of the methane simply leaks into the surrounding atmosphere.

Not all of the gas is wasted. About 300 MW of electricity is generated from landfills. A variety of electric generation systems have been employed by a small number of developers. Most projects use simple technology and are small (2–10 MW). However, an EPRI study has estimated that landfill gas resources in the United States could support 6,000 MW of generation if utilized in 2-MW-sized carbonate fuel cells. Construction on the world's first utility-scale direct carbonate fuel cell demonstration was begun in California. If successful, EPRI estimates that precommercial 3-MW plants based on this design could become available by the end of this decade at an installed cost of $17,000/kW.

At some landfills, operators have installed flares to combust the gas without recovering any energy. Typically, these cases arise because electricity sell-back rates are too low to justify generation equipment, and laws require a reduction in methane emissions.

6. Geothermal Power

Although geothermal power generators date back to the early years of the twentieth century, research and development since 1960 have introduced technologies that allow widespread use of geothermal resources of varying quality (14). The principal advances have been in technologies and techniques for exploration, drilling tools, brine handling, power system components, and environmental control. As a result, the installed capacity of geothermal electrical energy worldwide in 1995 reached about 6800 MW (2000 MW in the United States), over 25% of which was achieved since the mid-1980s. Almost 16×10^3 GW·h of geothermal electricity was produced in the United States in 1991.

Because the geologic systems may contain steam or both steam and liquid water, the means to recover energy varies accordingly. If only steam is present, the least common geothermal resource, the steam is fed from the well directly to a steam turbine, which drives an electric generator. If water is also present in a compressed state, a flash-steam cycle may be used: the liquid water flashes into a mixture of hot water and steam by the time the water reaches the lower pressure surface. The steam is then fed to a turbine, and the heat in the hot water may be used elsewhere. Alternatively a newer binary technique uses moderate-temperature geothermal fluids to vaporize low boiling-point organic fluids, which then drive turbogenerators.

The foregoing electric energy is derived from hydrothermal systems, the most commonly used geothermal resource. The systems' hot water or steam are trapped in fractured or porous rocks. Temperatures of the fluids can be as high as 350°C. The high temperature systems used for generating electricity often occur near young volcanoes or where the earth's crust has thinned. Low to moderate temperature systems can be used for direct heating applications.

The most widespread geothermal resource is hot dry rock (HDR), consisting of rocks rich in thermal energy but lacking entrapped water or steam. Harnessing HDR energy would entail drilling a deep well into the hot rock, which is then fractured by the injection of water under high pressure. The fractured zone becomes an engineered reservoir into which surface water is continuously injected and then recovered as hot water or steam. HDR systems are technically feasible, but not yet economical.

Two other localized regions of concentrated heat that are potentially extractable are geopressured geothermal systems and magma. The geopressured geothermal systems comprise hot, high pressure brines containing dissolved methane. Most known geopressured systems are not economical at current (ca 1996) natural gas prices. Pressures can reach 142 MPa (1400 atm). Magma resources comprise partially or completely molten rock, such as may be found in the vicinity of relatively recent volcanic activity. The high temperature of magma, above 650°C, conceivably could be used for producing electric power or high temperature industrial process waste. However, producing magma energy is not yet technically feasible.

6.1. Geothermal Heat Pumps

Also called ground-source heat pumps, geothermal heat pumps (GHPs) use the earth as a heat source for heating or as a heat sink for cooling (Fig. 8). This arrangement reduces electricity consumption by about 30% compared to air-source heat pumps. Because of this capability, many U.S. electric utilities and rural cooperatives have promoted the use of GHPs through marketing programs and financial incentives. The result has been that about 200,000 GHPs supply 3,200 GW·h of thermal energy annually to residences and commercial buildings throughout the nation, as of the mid-1990s.

7. Hydropower

Falling water has been used to generate electricity for over 100 years (3, 15). The first hydroelectric (or hydro) power plant was built at Niagara Falls in 1879. In succeeding years, hydro plants were built at other natural waterfalls, as well as artificial ones created by dams, at most of the nation's best sites. In the mid-1990s, hydropower energy accounts for about 93,000 MW or about 12% of the electric generating capacity in the United States bulk power market. The United States also imports some hydropower from Canada. Moreover, the average generating cost of hydropower is less than 3¢/kW·h.

Hydropower provides an essential contribution to the national power grid: its capability to respond in seconds to large and rapidly varying loads, which other baseload plants with steam systems powered by combustion or nuclear processes cannot accommodate. Also, ownership is spread over a broad base. The owners

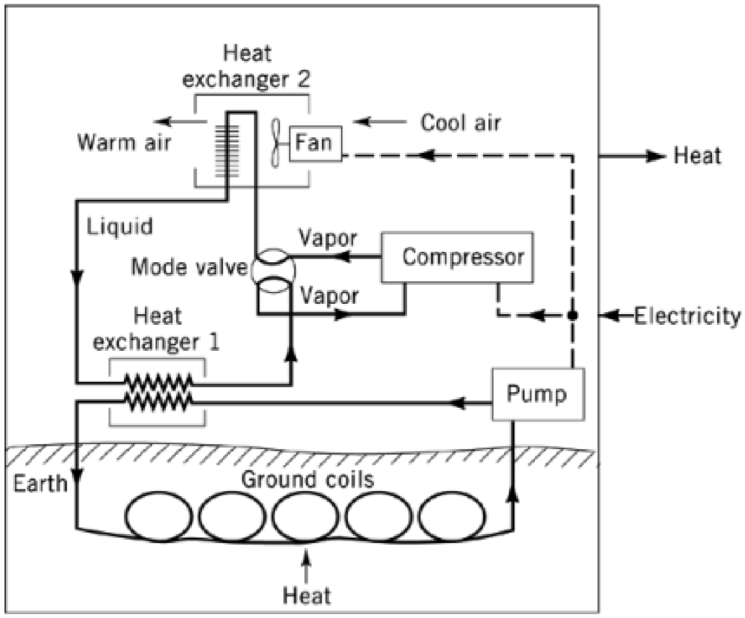

Fig. 8. Geothermal heat pump (GHP). This pump uses the earth as a heat source for heating or as a heat sink for cooling. A water and antifreeze mixture circulates through a pipe buried in the ground (vertically or horizontally) and transfers thermal energy to a heat exchanger in the heat pump. The heat exchanger works through a water-to-refrigerant loop. In a typical reversible heat pump, the ground loop heat exchanger rejects heat from the condenser or delivers heat to the evaporator, depending on the mode of operation.(Courtesy of Princeton Economic Research, Inc. (Rockville, Maryland).)

comprise federal and state agencies, cities, metropolitan water districts, irrigation companies, and public and independent utilities. Individual persons also own small plants at remote sites for their own energy needs and for sale to utilities.

The amount of electricity that can be generated at a hydro plant is determined by two factors: head and flow. Head is the distance in elevation between the highest level of the damned water to the point where it goes through the power-producing turbine. Conventional hydro plants must have a head of water that is at least 3 m high to provide sufficient water pressure to operate the turbine. Flow is the rate of water moving through the system. In general, a high head plant needs less water flow than a low head plant to produce the same amount of electricity.

Some hydro plants use pumped storage systems, among the most reliable energy storage systems available. Pumped storage systems use recycled water instead of tapping free-flowing water. After flowing through the turbine, the water resource is pumped, usually through a reversible turbine, from a lower reservoir back to an upper reservoir. Whereas pumped storage facilities are net energy consumers, ie, more energy in total is required for pumping than is generated by the plant, they are valuable to a utility because they operate in a peak-power production mode, when electricity is most costly to produce. The pumping to replenish the upper reservoir is performed during off-peak hours using the utility's least costly resources.

Because the best sites for hydropower dams have already been developed, construction of additional large, conventional plants is unlikely. However, existing projects could be modified to provide additional generating capacity. Also, many existing dams not equipped for electricity production (only about 3% of the nation's 80,000 dams are used to generate power) could be outfitted with generating capacity. Other opportunities for development are offered by small or low head (from 3 to 9 m) hydro plants at new sites. These concepts have helped to tap vast hydropower resources.

8. Wave Energy

Ocean waves are formed by the wind driving water toward shore. The wave energy depends strongly on wind speed; the energy is a fifth-power function of speed. Most methods to convert this irregular and oscillating low frequency energy source to grid power employ pneumatic, hydraulic, or hydropower technology (16).

Pneumatic systems use the wave motion to pressurize air in an oscillating water column (OWC). The pressurized air is then passed through an air turbine to generate electricity. In hydraulic systems, wave motion is used to pressurize water or other fluids, which are subsequently passed through a turbine or motor that drives a generator. Hydropower systems concentrate wave peaks and store the water delivered in the waves in an elevated basin. The potential energy supplied runs a low head hydro plant with seawater.

The world's total capacity of grid-connected electric power derived from wave energy is less than half a megawatt, distributed among several demonstration plants. The largest unit, the 350-kWe Tapered Channel plant in Norway, uses the hydropower approach. The plant was developed by Norwave AS and has operated continuously since 1986. Based on this durability, two commercial orders were placed from other parts of the world.

In the United States, other experimental wave-energy systems have been investigated in California and Hawaii, including a 30-MWe heaving-buoy design.

8.1. Tidal Power

Tidal power is caused by the gravitational pull of the sun and especially the moon, as they pull at the earth. Reacting to this pull, the ocean's waters rise, causing a high tide where the moon is closest. The difference between low and high tide can range from a few cm to several meters. Harnessing tidal power for electricity production by the use of dams requires a tidal difference of at least 4.5 m, a requirement met at few locations in the United States. Thus, the principal demonstration sites of tidal power are in Canada, China, and France.

9. Notes

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