Ocean Temperature Gradients: Solar Power from the Sea

The sun is the greatest source of energy available, and more than 70 percent of the solar radiation falls on the oceans. Between the Tropic of Cancer and the Tropic of Capricorn the ocean's surface temperature stays almost constantly at 25°C because of the equilibrium between the heat collected from sunlight and the heat lost by evaporation and other processes. Warm water in the tropics moves toward the poles, and ice melts. Cold water at the poles slides into the depths of the oceans and slowly moves toward the equator. In the tropics this cold water provides a nearly infinite heat sink at about 5°C at a depth as shallow as 1000 m. Both the hot surface water and the cold deep water are replenished by solar energy. Even though the temperature differentials in the tropics are not large, as compared with the temperatures of fossil-fuel generating plants, they can nevertheless be used to generate electricity. The extraction of energy from the ocean temperature gradients is certainly technically feasible, and, in fact, far more energy than that consumed throughout the world is potentially available from the seas.

Two major problems with proposals for the exploitation of solar radiation falling on land areas have been the high costs of collectors and the need for some means to store energy from day to night. Proposals for harnessing solar energy directly with photovoltaic cells, similar to spacecraft solar panels, or with systems that collect the sunlight and produce power through a thermal cycle are now being studied (*Science* 17 November 1972, 22 September 1972) but seem to be two or three times as expensive as conventional power sources. Power plants that utilize the ocean thermal gradients are projected to cost very little more than conventional power plants because the sea acts as the medium for both collection of sunlight and storage of energy. Undoubtedly many problems would have to be solved before it would be possible to generate electricity on a massive scale from ocean plants. Just the problem of transmitting energy from a plant at sea to the shore is formidable. However, the potential advantages from the utilization of the sea are great enough that the solar sea power concept, which originated with the French physicist Jacques D'Arsonval in 1881, has recently been rediscovered and at least three groups of U.S. researchers are now actively studying solar sea power.

In 1964 Hilbert Anderson and James Anderson of York, Pennsylvania, suggested the economic viability of a power plant operated by the ocean thermal gradient. Anderson and Anderson, like several others, considered a design with a submerged power plant that would be neutrally buoyant at a depth of 100 or 200 feet. Because of the small temperature differential provided by the ocean, the maximum possible efficiency would be about 5 percent and the actual efficiency would probably be only 2 or 3 percent. The flow of warm water required would be very great, but comparable to the flow through a hydroelectric plant with the same output. The energy derived from 1 kilogram of water flowing through an ocean gradient power plant with hot water at 25°C and cold water at 5°C would be the same as the energy produced from a hydroelectric plant with a pressure differential corresponding to 93 feet of elevation.

The operation of an ocean thermal gradient plant would require almost as much cold water as hot water. The hot water would flow through a heat exchanger, where it would cause another fluid, often called the working fluid, to boil. The vapor would expand through a turbine to produce electricity and then be condensed back to a liquid in a condenser cooled by cold seawater.

A very important and still undecided question is what working fluid to use. The pressure of the working fluid at both the boiling temperature ($\sim$20°C) and the condensing temperature ($\sim$ 10°C) must be considerably greater than atmospheric pressure if the unit is to be submerged. Furthermore, it is necessary to use a fluid with a high vapor pressure to avoid the need for unreasonably large turbines. The working fluid must also have good heat transfer characteristics in order to minimize the size and cost of the heat exchanger and condenser. D'Arsonval suggested ammonia as the working fluid, and present-day researchers agree that the use of ammonia would not require turbines as large as other choices, such as propane or Freon. However, were the ammonia to come into contact with water, the mixture would become quite corrosive and possibly damage the heat exchangers. In 1929 George Claude built a shore-based ocean gradient power plant in Cuba that produced 22 kw of useful power but was an economic failure, probably because it used seawater, which has a very low vapor pressure, as the working fluid.

Because the thermal efficiency of an ocean gradient power plant is so low, the amount of heat that must pass through the heat exchanger in the boiler is enormous as compared to a conventional fossil-fueled plant (approximately ten times greater). The factor that saves the ocean gradient concept from being impossibly expensive, due to heat exchanger costs, is that the walls can be made quite thin. In a submerged system, the seawater's hydrostatic pressure would largely compensate for the vapor pressure of the working fluid. With propane as a working fluid, the vapor pressure of the boiler would be balanced by the ocean's hydrostatic pressure at a depth of 278 feet and the vapor pressure of the condenser would be balanced at 154 feet. Thus it is possible to design a system, if the condenser is situated above the boiler, in which the pressure differential across the heat exchanger walls is almost zero.

Recent research on heat exchangers, particularly those with ammonia as a working fluid, has opened the way to lower costs through designs with much lower thermal impedance. Specific changes of the surface on the side of the working fluid, such as making it rough or corrugated, increase the heat flow in the boilers by providing sites for the nucleation of bubbles and increase the heat flow in the condensers by reducing the thickness of the newly condensed film of liquid.

In addition to electricity, an ocean thermal gradient plant could also produce fresh water. If dissolved gases were removed from the flow of warm water, it could be vaporized in a vacuum evaporator and condensed by the flow of cold water coming out of the generating plant. Anderson and Anderson estimate that the cold water flow from a 100-Mw plant would be sufficient to produce 60 million gallons of fresh water per day.

Offshore ocean gradient plants could also produce hydrogen and oxygen through the electrolysis of water. In fact, it is conceivable that the cheapest way to get power from a submerged power plant to the shore would be to electrolyze the water and send hydrogen to the shore through a pipeline rather than to transmit electricity through underwater cables.

Another possible product of a thermal gradient plant is food. Not only does the cold water brought up from the ocean depths provide a heat sink, it also is rich in nutrients. Natural upwellings of the cold water from the ocean depths are sites enormously rich in marine life, and the artificial upwelling necessary to provide cold water to an ocean gradient plant could also be used to cultivate algae, crustaceans, and shellfish. One of the natural upwellings, in the Humboldt current off Peru, supplies almost one-fifth of the world's fish harvest.

At an experimental station on the north coast of St. Croix, U.S. Virgin Islands, researchers from the Lamont Doherty Geological Observatory have successfully cultivated shellfish with water pumped up from a depth of 870 m. Three polyethylene pipelines, each about 3 inches in diameter, bring up about 40 gallons of water per minute into shallow tanks, about 1 m in depth. In the nutrient-rich water, unicellular algae grow to a density 27 times greater than the density in surface water, and are in turn consumed by filter-feeding shellfish such as clams, European oysters, and bay scallops. The scallops grow to market size in 6 months, considerably faster than the usual rate of growth in nature. Lobsters, shrimp, and other crustaceans can feed on those shellfish that have been culled from the tanks because they are growing too slowly. Experiments with lobsters from the Massachusetts coast fed in this way show that they grow at a greatly accelerated rate.

Plants for growing shellfish would, of course, have to be located onshore. Although a shore location may not be the most ideal one for the generation of electrical power, the combined return from power, desalinization, and food production—sometimes referred to as mariculture—could make such plants economically viable at a much smaller scale than would be the case for plants devoted to power production alone. According to Oswald Roels, at Lamont Doherty, a 7-Mw power plant that also produced 6×10^6 U.S. gallons of fresh water per day could be

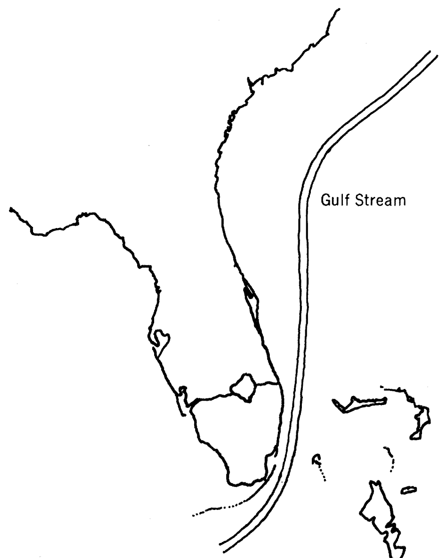

Fig. 1. Approximate course of the Gulf Stream between the mainland of Florida and the Bahama Islands.

built at a cost of about $250 per kilowatt. For a mariculture demonstration plant planned to operate at 95 m^3 (25,000 gallons) per minute, it is estimated that the average annual yield of shellfish would be worth about $1 million, an annual income of $125,000 per hectare ($50,000 per acre).

Plants that combine power production with food and water production appear to be ideally suited to tropical islands, but, to supply the power needs of the continental United States, it is highly unlikely that the transmission of power generated in the tropics will ever prove economically viable. However, the Gulf Stream approaches quite close to the southeastern coast of the United States and carries enough warm water to supply the nation's power needs many times over, even if inefficient solar sea power engines are used.

Anderson and Anderson have estimated that 182×10^{12} kw-hour of electricity, or about 75 times the expected U.S. demand in 1980, could be generated from the thermal gradients of the Gulf Stream, which has a flow of 2200 km^3 per day and a temperature differential varying from 16°C to 22°C (Fig. 1).

At the University of Massachusetts, Amherst, William Heronemus and his associates are preparing preliminary designs for a submerged plant to produce power from the Gulf Stream. In the Straits of Florida, between the coastline and Little Bahama Bank, the Gulf Stream flows very close to the shore, and one proposed site for testing the ocean thermal gradient concept would be at the western edge of the Gulf Stream, about 25 km from Miami. The configuration currently proposed by the Massachusetts researchers is a modular design with six turbines in each of two hulls, hooked together to look something like a submarine catamaran. Each hull would be 480 feet long and 100 feet in diameter, probably made of reinforced concrete. The axis of the hulls would be at a depth of 250 feet, providing clearance over the top for protection from wave motion and hurricanes.

Towers to the surface would provide ventilation and access to the crews that would man such a power station, but would probably not be visible from the shore. The station would be slightly buoyant and ride up against two or more tethers, which could carry the cold water conduit, and would probably carry the electrical or hydrogen transmission line for connection to the shore. According to Heronemus, the tethers could be anchored to the ocean floor, the Blake Plateau at the proposed site, by either anchors set in the plateau or with gravity anchors. The station would generate approximately 400 Mw of electricity.

The environmental effects of solar sea power plants have thus far been only cursorily studied. Both Clarence Zener, of the Carnegie-Mellon University, Pittsburgh, Pennsylvania, and Anderson and Anderson predict that the effect of the large-scale extraction of power from the ocean thermal gradients would be a net increase in the thermal energy stored in the ocean. These estimates are based on the supposition that the absorptivity of the ocean's surface layer would increase if large amounts of colder-than-usual water were discharged, so that the solar radiation would more than make up for the heat extracted for power.

Although the extraction of large amounts of power from the ocean's thermal gradient sounds extremely ambitious, research on the concept dates back several decades and new estimates of the costs appear to offer the hope that it would be competitive with other sources, even at present prices. Transmission of power to shore is already being considered for offshore nuclear generating stations. Very much study is needed to improve designs and substantiate the cost estimates that are now available, but solar power from the sea may well turn out to be a source of clean energy that has been overlooked for too long.

—William D. Metz