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THE POTENTIAL OF OCEAN ENERGY CONVERSION SYSTEMS AND THEIR IMPACT ON THE ENVIRONMENT

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ABSTRACT

The oceans occupy almost three-quarters of the Earth's surface and represent an enormous source of nonpolluting, inexhaustible energy. They can provide an alternative energy source that can be phased-in to offset reliance on combustion of fossil fuels and their resultant environmental problems of global warming and air pollution.

While many of the major developed nations have conducted exploratory research and development, and even installed a few commercial facilities, the total operational power available, with the exception of the French tidal power plant, is far less than 100 megawatts. Conversely, the projected available ocean power far exceeds the ultimate energy consumption of mankind, making this option extremely attractive, especially when the environmental implications are considered.

Much of the development —tidal, wave, salinity gradient, current, and wind energy— thus far has focused on electricity production. Of these, relatively little progress has been made with salinity gradients and currents. Tidal, wave, and wind power have good potential for further refinement and they are within an acceptable range for economic competitiveness. Two other options, ocean thermal energy conversion (OTEC) and marine biomass, promise multiple products. The cornucopia of co-products from OTEC and of transportation fuel from biomass might improve the cost competitiveness of these two alternatives. Small scale OTEC systems providing electric power, nutrients for aquaculture, and fresh water are ideal for expanding the economic potential of many small island communities. This application will enable OTEC technology to mature, strengthen commercial utility, and scale up competitively to larger-sized systems providing multiple products beyond energy. In fact, the real attraction of ocean energy is the combination of largely benign (and perhaps even enhanced) effects on the environment and the guarantee that the resource base will be available as long as the sun shines.

1. INTRODUCTION

Since the dawn of the industrial age, the demand for energy has been increasing rapidly, and now is accelerating to keep up with exponential population and economic growth. The combustion of fossil fuels has been meeting the major portion of the needs, followed by nuclear power. However, there is a growing concern about the environmental impact of: fossil fuel combustion causing global warming and air pollution; extracting oil and gas, and oil spills; and dwindling supplies of oil and gas which may be exhausted by the middle of the 21st Century.

One hundred percent safe nuclear power would be an alternative, but society has not been receptive because of potential catastrophic failures and problems of disposing spent radioactive fuel elements. Therefore, alternative energy sources are needed that are nonpolluting, economically competitive, and relatively inexhaustible to meet the burgeoning needs of society.

Solar energy is an inexhaustible, nonpolluting source that has great potential as an alternate energy source for the future. It can be processed directly through thermal and photovoltaic methods currently being applied to solar-heated and powered homes.

Solar energy can also be processed indirectly by converting the dynamic motion of wind, waves, and currents induced by solar winds; converting ocean thermal and salinity gradients; and converting biomass energy derived through photosynthesis.

This paper provides an overview of the state of the practice concerned with the development and use of ocean energy conversion systems and their impact on the marine environment. Extraction of ocean energy resources must be evaluated against continued hydrocarbon resource extraction in addressing the broader concerns of the use or misuse of the marine environment and the impact on the marine and overall global environment.

The oceans cover nearly three-quarters of the Earth's surface and store sufficient energy for many years to come. The many development efforts pertaining to ocean energy extraction include ocean thermal, tidal, wave, current, and salinity gradients. Extracting wind energy in the coastal environment also has good potential. Ocean and wind energy systems may be distant from the consumer and may often rely on resources that vary in magnitude as a function of time on a diurnal and seasonal basis. These problems can be reduced by using some or all of the energy for generating fuels such as hydrogen that can be stored and used on demand.

Each of the ocean energy conversion systems is briefly covered herein regarding: techniques used; international development status; and an assessment of technical, economic, and environmental issues and research needs. An intercomparison of the systems is made and conclusions presented.

2. BACKGROUND

World population has been growing exponentially over the last 40 years and is expected to almost double over the next 40 years, from over 5 billion to about 9 billion. This steady increase equates to: less land per person; a greater need for food, energy, and material resources; and a significant impact on our environment. In the process of continued development and use of resources to meet the burgeoning needs, attention is now being given to protecting the environment and conserving resources for future use by us and following generations. While the population may be doubling in 40 years, the rate of energy consumption is doubling at a present rate of every 12 years. The world's energy demand is currently being satisfied by various forms of fossil fuel and nuclear power. Detrimental effects of our overwhelming reliance on fossil fuels, however, are becoming more and more obvious and the public is clamoring for corrective action.

Power plants and vehicles release gaseous emissions that are transported by clouds and winds aloft and eventually settle down as acid rain to cause terrestrial and aquatic damage. Emitted sulfur and nitrogen oxides react with other compounds in the atmosphere to form acidic particles. The acid kills aquatic life in streams, lakes, and estuaries; pollutes water supplies; destroys terrestrial foliage; acidifies soils; and damages buildings and materials. Power plants are the largest source of sulfur pollution and the second largest source of nitrogen oxides; vehicles are the largest source of nitrogen oxides.

The phenomenon of global warming over the past century has been attributed to atmospheric accumulation of greenhouse gases, such as carbon dioxide and methane, which act like a blanket to trap the sun's radiant heat. Greenhouse gases are produced by all forms of combustion, especially by automobiles, power generation, and the burning of wood in clearing forested land such as the Amazon rain forest. The environment's ability to assimilate carbon dioxide is being reduced because expanding urban development, deforestation, and destruction of rain forests increase the losses of trees and vegetation —the natural assimilators of carbon dioxide. The processes and capacity of our oceans to assimilate or release carbon dioxide is now well known at this time. Though exact figures cannot be predicted, the general consensus is that global warming will increase and produce deleterious effects impacting agriculture, causing sea-level rise, and affecting quality of life while society adjusts to its effects.

One consensus of researchers agrees that the Earth on average has warmed about

0.6°C over the past century, and if CO_2 levels double by the middle of the next century, global average temperatures may increase several more degrees. The resultant warming would not be uniform over the Earth. It would be least in the tropics and greatest at the poles where it would melt some of the polar ice caps. The melted ice, most of which is now on land, and the thermal expansion of the oceans could cause global sea levels to rise 30 to 60 centimeters (cm). The exact magnitude and timing of worldwide warming continues to be debated by scientists.

The 1980s were the warmest decade in the last century and 1990 is one of the warmest years on record. The 1988 midwestern U.S. drought is a recent example of the effects of a warm, dry summer that affected agriculture productivity, and barges were stranded on the Mississippi River by all-time low water levels. Over the past 50 years, global sea levels have been rising at about 3.0 millimeters a year (three times the rate of the previous 50 years). If this trend continues or possibly escalates, sea levels could rise as much as 30 to 60 cm by the middle of the 21st century, flooding some coastal cities and villages. This will create a concern in designing and constructing homes, buildings, ports, and harbors for future coastal communities (Vadus 1991).

Environmental concerns are not the only reason for past and present endeavours to explore large-scale use of alternative energy sources. The oil embargo of 1973 created sudden, sobering evidence of the magnitude of our oil dependence. This prompted some efforts for conservation and for alternative energy including solar and ocean energy options. However, the oil glut of the 1980s dampened these efforts and consumption of oil increased to even greater levels. More recently, the present instability in the Middle East once again brought attention to our great dependence on oil and further emphasized the need for alternative energy sources.

A global accounting of the amount of discovered and yet-to-be-discovered fossil fuel, when compared with a projection of energy requirements, results in the realization that we will consume the readily-accessible portions of this resource within a relatively short period of time. Oil and natural gas will be essentially depleted by about 2030 and coal will last into the 22nd Century. There periods are very short from a historical perspective and should be within the planning horizon of nations, states, and other communities.

Solar energy has gained perhaps the greatest recent attention, and many approaches to harness the sun's power are now being explored. The major drawbacks to direct usage are intermittent availability and variation in energy intensity. Large storage facilities are necessary for uninterrupted and steady use of solar power. Luckily, a naturally occurring large-scale facility already exists —the tropical oceans.

3. ENERGY SYSTEMS IN THE MARINE ENVIRONMENT

The oceans are the world's largest solar energy collector and storage system. On an average day, 60 million km^2 of tropical seas absorb an amount of solar radiation equivalent in heat content to about 245 billion barrels of oil. If less than 0.1% of this stored solar energy could be converted into electric power, it could supply the equivalent of more than 20 times the current total U. S. electricity consumption (SERI 1989) or about five times the current world consumption.

This incident solar energy is stored either directly or indirectly in various forms within the ocean system. Specifically, this solar power is stored directly in the form of thermal heat, and indirectly as wind, waves, and currents created by the temperature differences between the tropical and arctic waters. The recognition of the availability and potential of these energy forms has led to the development of ocean energy systems to harness solar energy.

The availability of much of this energy is very site-specific and the conversion efficiencies of these systems are very low. While many of the various forms of energy conversion systems have experienced only minor, small-scale commercial-use, the potential for a significant contribution to the world energy economy does exist and there is a continuing interest in the research and development of these relatively clean, safe, renewable energy systems. Presently, the more highly-developed ocean energy systems are ocean thermal energy conversion (OTEC), and tidal, wave, and wind energy. The less-developed ocean energy technologies are ocean current turbines, salinity gradient devices, and biomass conversion.

3-1. Ocean Thermal Energy Conversion (OTEC)

The basic concept of ocean thermal energy conversion is to extract energy from the temperature difference between surface and subsurface oceanic waters. Solar energy has been absorbed and stored as heat in the upper layer of the ocean; cooler water transported from the polar regions lies below. The cost of energy recovery drops as the temperature differential increases. The temperature difference between the surface layer and water 1,000 meters deep is at least 20-degrees Celcius in equatorial areas all year. Further north or south, the maximum temperature difference is less and it varies throughout the year. Because of the relatively small temperature difference, enormous volumes of warm and cold water must pass through the facility to generate a given power as compared to cooling water requirements of a typical fossil-fueled generating plant. However, the availability of huge quantities of ocean thermal resources allows the possibility of very large OTEC baseload plants. OTEC plant concepts range from shore mounted plants with ocean intake pipes to fixed and moored offshore plants to drifting plantships. Ideal OTEC resources are in the tropical and subtropical regions.

OTEC techniques are based on either the closed- or open-cycle concept, with hybrid combinations also gaining in interest (Takahashi and Trenka 1989). In the closed-cycle plant, warm surface water is used to evaporate an enclosed auxiliary working fluid such as ammonia or Freon. The vaporized working fluid drives a turbine which, in turn, drives an electrical generator. Cold water from a depth of 1000 meters is used to condense the vapor after it has passed through the turbine, much like in a steam power plant. The working fluid returns to the evaporator to be recycled.

The open-cycle system, attempted by Claude in Cuba in 1930, uses the warm sea water as the working fluid. The pressure above the warm water is lowered sufficiently for the water to boil and vaporize. This vapor is used to drive the turbine and cold, deep water is required to condense the water vapor exiting from the turbine.

Table 1 lists most of the main OTEC development projects over the past decade, ranging from proposed to constructed, tested, and evaluated. Until economic feasibility is demonstrated, none have been developed for commercial operations.

While the French were the first to suggest and construct energy conversion systems for extracting stored solar energy from the sea, the 1979 Mini-OTEC project conducted in Hawaii was the first to demonstrate net positive electricity. Since then OTEC development in the U.S. has been primarily sponsored by the Department of Energy, with limited involvement from the private sector. From the early- to mid-1980s the interest focused on 50-MW closed-cycle designs. Since then the effort has concentrated primarily on the conceptual development and design of small, island-based open-cycle plants (Rogers 1988). Present efforts by the U.S. Department of Energy have involved the design and construction of a 165-kW Net Power Producing Experiment (NPPE) open-cycle plant in Hawaii for experimental use in the 1993 time frame to develop models for performance prediction in determining technical and economic feasibility.

Several nations besides the United States are interested in developing full-scale OTEC plants (SERI 1989). Japan has completed design studies of a 10-MW floating plant and a 3-MW shelf-mounted plant to be located off the coast of Okinawa. This was one of a series of activities that included constructing experimental plants on the Japanese Island of Tokunoshima and on the Republic of Nauru, and completing design studies for other locations in the western Pacific. This research continues and is focused on the possibility of constructing small, closed-cycle plants in the small, oil-dependent islands of the Pacific. The Taiwan Power Company

Table 1.— OTEC Development Projects

Country	Location	Year	Size (KW)	Type (Cycle)	Comments
USA	Hawaii	1979	50	Closed	Mini-OTEC (Built & Tested)
USA	Hawaii	1981	1,000	Closed	OTEC-1 (Thermal Exch Test Only)
USA	Hawaii	1984	40,000	Closed	Proposed (Inactive)
USA/UK/CAN	Hawaii	1991	180	Closed	Planned
USA	Hawaii	1993	165	Open	Experimental (DOE)
Japan	Nauru	1981	100	Closed	Built & Tested
Japan	Kyushu	1982	25	Closed	Built & Tested
Japan	Tokunoshima	1982	50	Closed	Built & Tested
Japan	Univ of Saga	1985	75	Closed	Thermal Exch Test Only
Taiwan	East Coast	1991	5,000	Closed	Proposed (Inactive)
France	Tahiti	1985	5,000	Closed/Open	Proposed (Inactive)
France	Africa	1985	3,000	Closed	Proposed (Inactive)
UK	Caribbean	1982	10,000	Closed	Proposed (Inactive)
UK	Hawaii	1989	500	Closed	Proposed (Inactive)
Sweeden	Jamaica	1983	1,000	Closed	Proposed (Inactive)
Netherlands	Bali	1982	250	Closed	Started (Inactive)

completed studies on the feasibility of placing 50-MW plants on the eastern coast of that country (Takahashi and Yuen 1989). The company projected that such plants will become competitive with oil-fired and coal-fired plants in the mid-1990s. The Pacific International Center for High Technology Research (PICHTR) completed a strategic plan for Taiwan, proposing a $72-million, 5-megawatt, multi-product, closed-cycle system.

GEC-Marconi, a British firm working with Alcan International of Canada, reported preliminary design work on a small, land-based, closed-cycle OTEC plant that it plans to build and operate at Keahole Point in Hawaii. This plant, as proposed with Hawaiian Electric Renewable Systems, will provide the technical basis for scaling up to commercial-sized 10-MW plants. The French Government, under the leadership of IFREMER, has conducted OTEC feasibility studies, beginning in 1978, aimed at constructing an experimental facility on the Island of Tahiti. In 1984, site evaluation studies were completed; in 1987, design studies for open and closed cycle systems were completed; and no further work has been conducted since. The Netherlands, in cooperation with several Indonesian companies, completed a feasibility study for a 100-kW closed-cycle plant at a South Pacific site. The governments of Sweeden, Norway, and Jamaica have been cooperating with private companies since 1980 in designing a 1-MW closed-cycle plant to be located near Kingston, Jamaica. Activities on OTEC projects ranged from slow progress to inactive because of the low cost of oil in the 1980s, but recent increases in the Fall of 1990 will likely accelerate interests once again.

The combined production of electricity and freshwater using the principle of Ocean Thermal Energy Converstion (OTEC) is cost effective under certain scenarios defined by the fuel cost of electricity production, with conventional fossil fuel plants, and the production cost of water. At least four scenarios can be envisioned, as summarized in Table 6. To move forward with the development of OTEC, demonstration plants must be built and operated. Demonstration plants should be scaled versions of commercial plants and be operated for at least a couple of years to convince the financial community to invest in OTEC plants (Vega and Trenka, 1989):

Like any offshore or shoreline project, commercial OTEC facilities will affect the marine environment. Construction activities may temporarily disrupt the sea bed, destroying habitats and decreasing subsurface visibility. Platforms and marine subsystems may attract fish and other marine species, and maintenance routines to reduce biofouling may increase the level of toxic substances. Intake pipes can draw marine organisms through the plant and move large amounts of nutrient-rich water up from deep depths. However, OTEC systems can be designed and located to minimize their potential effects on the environment and even enhance the surrounding ocean, as shown by Mini-OTEC, when augmented fish catches were reported near the site off the Kona Coast of the Big Island of Hawaii.

The construction of land-based or shelf-mounted OTEC plants can disturb the sea bed. Deployment of moorings, cables, pipes, piles and anchors may churn up the bottom and increase the number of particles suspended in the water. This type of disturbance can affect areas of special ecological importance, such as coral reefs, seagrass beds, spawning grounds, and commercial fisheries. Short-term disruption of most of these habitats is often reversible, as shown by experience with offshore oil rig construction (SERI 1989). OTEC developers can minimize disruption by locating plants away from critical habitats. Where necessary, cables and pipes can be routed through natural breaks in near-shore reefs.

OTEC plants discharge large quantities of ocean water and could potentially affect natural thermal and salinity gradients and levels of dissolved gases, nutrients, trace metals, carbonates, and turbidity. If cold- and warm-water streams are mixed and discharged at the surface, the density of OTEC plant discharges will be different from that of the surrounding water. Behavior of the discharge plume will respond to initial discharge momentum and to buoyancy forces that result from initial density differences. Within several hundred meters of the discharge point, the plume will be diluted by ambient ocean water, sink (or rise) to reach an equilibrium level, and lose velocity until the difference between its velocity and ambient current velocity is small. OTEC plants can be designed to stabilize the discharge plume below the mixed layer to protect the thermal resource and to minimize potential environmental effects. However, a key point to consider is that, the intelligent management of this discharge could stimulate living marine resources.

An environmental impact of a more serious nature could occur if ammonia, Freon, or some other environmentally-hazardous working fluid was accidentally spilled from a closed-cycle OTEC plant. The effect of ammonia on marine ecosystems would depend on the rate of release and the nature of nearby sea life. Small quantities of ammonia probably would stimulate plant growth downstream. A large ammonia spill would be toxic; for example, a 40 MW plant could release enough ammonia to destroy marine organisms over an area as large as four square kilometers (SERI 1989). This possibility can be minimized by designing the plant for safety, careful operation, and employment of well-trained, attentive personnel. To some degree Japanese developments have steered clear of ammonia because of anticipated objections from the fishing industry.

OTEC facilities release no additional heat and significantly less carbon dioxide than comparably-sized conventional fossil-fueled power plants. These advantages may become increasingly important in the future if predictions concerning global climate change are correct and power plants are required to reduce carbon dioxide production significantly.

It has been projected that circulating and warming large amounts of deep ocean water in any OTEC plant operation could result in outgassing of dissolved carbon dioxide if the discharge is exposed to the atmosphere for sufficient periods. Recently-completed experiments indicate that the immediate carbon dioxide release from an open-cycle OTEC plant would be 15 to 25 times smaller than the emission from a comparably-sized fossil-fueled electric power plant (Oney 1989; Green 1989). The variability of natural outgassing in tropical oceans will greatly exceed any projected OTEC release. The release of carbon dioxide could be ameliorated if the discharge water is used for mariculture or other secondary operations. Most of the potential long-term and immediate releases can be avoided completely by re-injecting any absorbed gas into the sea water discharge (Oney 1989), introducing that discharge below the surface-mixed layer of the ocean, or combining these methods (SERI 1989).

There is an increasing awareness that the multi-product of OTEC plants to provide power, water, food, and refrigeration to remote island communities in an integrated system will stimulate their economic development. Such a prospect appears attractive even in the near-term (Takahashi, and Higgins 1988).

Energy costs have been predicted for an OTEC plant using an ammonia-based closed-cycle system situated on a fixed platform near Kahe Point, Oahu, Hawaii. This site is particularly well-suited to the OTEC concept because of the steep slope of the ocean bottom, and because it is close to an existing 600-MW oil-fired power plant owned by the Hawaiian Electric Company (HECO). The OTEC power plant also benefits by using the warm water being discharged from the oil-fired power plant.

The proposed unit would have a nominal power output of 40 MW, with a peak summer output of 46 MW and a minimum winter output of approximately 33 MW. The temperature of the warm seawater intake of the heat exchangers is increased by approximately 1.6°C(2.8°F), using the warmed cooling water leaving the HECO plant. The temperature difference between the warm and cold water at the design point is 21.4°C(38.5°F). The proposed power system has four 10-MW (net) modules consisting of two evaporators, two condensers, and a turbine-generator set. The four units will be housed in a concrete structure built off-site and floated to Kahe Point. Cold water will be supplied to the facility through a pipe extending approximately 3.2 kilometers (2 miles) seaward to a depth of about 670 meters (2000 feet). In 1985, the predicted installed cost was estimated at $ 558.9 million, giving a unit capital cost of $ 12,200/kW and the cost of electricity produced at 25.5 cents/kWh. A contingency of 30% was included in these estimated costs (Carmichael 1986). In constant 1990 dollars, the capital cost was estimated at $ 15,500/kw and electricity at 32.4 cents/kWh.

A small amount of natural chlorine can control biofouling on the warm water side, and roll-bonded aluminum has been developed to replace titanium heat exchangers, reducing costs by up to a factor of five. The major components still undergoing development include open-cycle turbines and flexible cold water pipes using bottom-mounted pumps.

For onshore and shallow water nearshore fixed plants, cable transmission of the electricity from the plant does not represent a technological problem. However, for offshore plants moored in deep water, the technology is being developed in the Hawaii deep ocean transmission cable project where sea floor cables at depths of 7,000 feet are being designed to transmit electricity between islands. Production of energy-intensive secondary products, such as hydrogen, ammonia, or methanol, also has been proposed for moored or drifting OTEC plants which would alleviate the need for such cable technology (details are provided in section 4 of this paper). In the case of a seafloor-mounted cold water pipe, the structural concerns regarding the cold water pipe system, have been somewhat alleviated by the successful deployment and prolonged use of a cold water sub-system at the Sea Coast Test Facility at Keahole Point, Hawaii. The success of this facility has proven the reliability of present cold water pipe technology for small (less than 1-MW) OTEC plants. In the long-term, innovative pipe designs, such as a soft, flexible pipe, will need to be developed for facilities approaching and exceeding 100 MW.

3-2. Tidal Energy

Tidal power is derived from the enormous energy induced in the oceans by the gravitational forces of the sun, moon, and earth. The ebb and flow of the enormously powerful ocean tides are greatly influenced by the tidal swing, volume of water involved, and the inshore geological features. Tidal energy is generated by collecting rising tidal water behind a barrier and then releasing it at ebb tide through turbines to generate electricity. Systems are available to extract energy by relatively conventional hydroelectric turbines and related structures.

The use of conventional technology separates the development of tidal power from other ocean energy sources. Low-head, axial-flow turbines are the modern means of harnessing the relatively small differences in water level in a river system or from a reservoir. Tidal energy extraction requires a strong ocean effect and a natural resonant inshore configuration to make it work most efficiently and economically. The energy is as predictable as the state of the ocean tide at any instant.

Tidal energy extraction appears to be less demanding on advanced technologies than other energy sources; however, it highly depends on natural processes. Just as hydroelectric power depends on natural differences in the terrain elevation, tidal power depends on the natural configuration of inshore geological features. Few coastal areas exist where conditions combine to produce the degree of resonance required. Natural sites and celestial forces appear to favor the development of tidal power systems within latitudes of 50 to 60 degrees. Major tidal power development sites around the world are listed in Table 2 (Warnock 1987).

There are very few tidal energy power stations operating in the world today. The four countries with functioning systems are France, the Soviet Union, China, and Canada. These countries have been the most actively involved in the study of tidal energy conversion. The total power generated by these systems is about 263 MW.

The La Rance tidal power station on the west coast of France, with an installed capacity of 240 MW, is the world's largest. Construction began in 1961 and was com-

Table 2.— Major Tidal Power Developments

Country	Location	Mean Tide Range (M)	Output (MW)	Initial Operation
China	Shashan	5.1	0.04	1959
France	La Rance	8.5	240.0	1966
USSR	Kislayan Gulf	3.9	0.4	1968
China	Jingang Creek	5.1	0.165	1970
China	Yuepu		0.15	1971
China	Ganzhutan		5.0	1974
China	Haishan		0.15	1975
China	Liuhe		0.15	1976
China	Beisakou		0.96	1978
China	Jiangxia Creek	5.1	3.2	1980
Japan	Kurushima		0.002	1983
Canada	Annapolis Royal	7.1	19.1	1984
China	Xingfuyang	5.1	1.28	1989
Canada	Bay of Fundy	15.2	1428.0	Proposed
Canada	Minas Basin	15.2	5338.0	Proposed
USA	Maine-Cobscook	5.4	300.0	Proposed
USA	Alaska-Cook Inlet	9.4	1440.0	Proposed
UK	Severn Barrage	11.0	7200	Proposed
UK	Mersey Barrage	6.5	620	Proposed
India	Gujurat	12.4	1100.0	Proposed
Korea	Garolim-Inchon	4.8	480.0	Proposed
USSR	Mezenskaya	20.0	15,000.0	Proposed
Argentina	Puerto Gallegos	7.7	400.0	Proposed
Australia	Walcott Inlet	12.0	1300.0	Proposed

pleted by 1968. The powerhouse is 390 meters long, housing 24 10-MW turbine units. The plant has been operational since 1968 with an outstanding 95% availability.

In 1968, the Soviet Union put into operation a 400-kW pilot plant in Kislayan Gulf, called the Kislogubskaya pilot plant; it pioneered floating construction techniques. In 1985, the Soviet Union announced plans to build a tidal plant on the White Sea coast with a generating capacity of 15,000 MW. Called the Mezenskaya plant, it is still in the preliminary stages of development.

In the People's Republic of China, tidal energy was first reported in 1959 with the installation of a 40-kW plant located in Shashan. A 165-kW tidal plant was later built in 1970 in the Shandong Province on the Jingang Creek. In May 1980, China's first twoway tidal plant, rated at 500 kW, began operating on the Jiangxia Creek near the Zhousan Islands. This plant was later expanded to 3.2 MW in 1986.

The Canadian tidal power project is the 20-MW plant at Annapolis Royal, Nova Scotia. This plant was built by the Nova Scotia Power Corporation. Located on the Annapolis River near its outlet at the Bay of Fundy, the plant contains a single "Straflo" hydropower turbine and has been operational since 1984. Presently, Canada is investigating the potential of such turbines for larger scale installations in the Bay of Fundy, and for low-head run-of-the-river developments.

Both positive and negative environmental effects can be expected from the development of tidal power plants. While potential effects would be very site-specific, they may be grouped into several categories based on the physical changes brought about by construction and operation of the plant. These include the physical presence of the dam, changes in water level, changes in flow patterns and current velocities, and changes in sediment patterns.

During construction, dredging operations (including disposal), blasting, and placement of rock fill or concrete structures will impact benthic habitats, increase turbidity (thus affecting organisms within the water column), and may restrict navigation. These impacts would be short-term and local, and would vary depending on whether float-in or cofferdam construction were employed. Once constructed, the physical presence of the dam represents permanent changes which could affect recreational use of the water and impoundment, navigation, and fish passage and habitat. Locks can be used to assist navigation and, in some cases, navigation within the basin could be improved by higher average water levels. The opportunity to build a road accross the dam would be a major positive benefit, especially at large sites. The generally smaller tidal ranges, as discussed below, would offer increased opportunity for recreational boating. Because of the large volumes of water involved, entrainment of fish in plant turbines could be a problem. For example, shad migrate through the Bay of Fundy and concern over their entrainment has been cited in regards to potential Bay of Fundy tidal power projects (Carmichael 1986).

The United Kingdom conducted a design study of a tidal plant at Langstone Harbor, Hampshire that had a 3-meter mean annual tidal range generating 24.3 MW on the ebb tide cycle. Construction cost was estimated at $ 2813/KW and electricity produced at 16.2 cents/kWh in 1986 dollars. In constant 1990 dollars, this equates to about $ 3511/KW and electricity cost at 19.7 cents/kWh.

Compared to other ocean energy technologies, tidal power is relatively well developed. However, there are three areas in which research and development could enhance the performance and reduce the costs of tidal power: sluice gate design, development of float-in construction techniques including construction of a pilot plant, and improved turbine design. Construction experience with the Delta Works, a system of tidal barrages and sluices along the Dutch coast, should prove useful in guiding development of float-in construction techniques. Recent experience with the Straflo turbine operation at Annapolis Royal should be useful in evaluating potential improvements in turbine technology (Carmichael 1986).

3-3. Wave Energy

Ocean wave energy conversion technologies utilize the kinetic energy of ocean waves to produce power. Wave energy is a potential environmentally benign and renewable energy resource. The general approaches to converting wave energy into electricity can be broadly categorized by means of deployment and means of energy extraction and conversion. Means of deployment include floating deep-water technologies and shallow-water, fixed-bottom technologies. Means of energy extraction and conversion include mechanical cams, gears, and levers; hydraulic pumps; pneumatic turbines; oscillating water columns; and funnelling devices. Table 3 describes the size, location, and technology of a number of active or proposed wave energy facilities (Hay 1990 and SEASUN Power Systems 1990). At present, five wave energy systems generate a total of 535 KW of power, and two more commercial systems will be operating by 1992.

The Japanese government has had a very active wave energy research and development program for many years. Applications under investigation range from wave power generators for lighthouses and light buoys to wave pump systems, ship propulsion, and energy for road heating, heat recovery systems, and fish farming. Several technologies have been examined by both government and industry under the Japanese wave energy program. These include floating terminator-type wave devices, fixed coastal-type wave power extractors, and applications of oscillating water column turbines. The most well known project, supported by the International Energy Agency, was the KAIMEI, a 500-ton barge-like platform containing

Table 3.— Major Wave Energy Developments

Country	Location	Wave Power (KW/M)	Technology*	Rating (KW)	Comments
Norway	Toftestallen	7.0	Mutiresonant OWC	500	Operated ('85-89)
Norway	Toftestallen	7.0	Tapered Channel	350	Operating ('86)
Norway	Java	20-25	Tapered Channel	1,500	Operation ('92)
Norway	Tasmania	30-32	Tapered Channel	1,500	Operation ('92)
Denmark	Hanstholm	9.0	Heaving Buoy	45	Tested 1990
UK	Islay	5-15	Shore-based OWC	75	Operation ('91)
UK	Mauritius		Shore-based OWC	500	Proposed (Inactive)
India (UK)	Madras		Offshore OWC	5,000	Proposed (Inactive)
India	Southwest Coast		Offshore Caisson OWC	150	Pending
Japan	Yura		KAIMEI, Barge-mounted OWC	125	Operated ('78-80 & '85-86)
Japan	Sanze		Shore-based OWC	40	Operated ('83-84)
Japan	Sakata Port		Breakwater OWC	60	Operating ('89)
Japan	Kujukuri		Shore-based OWC	30	Operating ('88)
Japan	Mashike		Breakwater Pivoting Flap	20	Operating ('83)
Sweeden	Gottenberg		Heaving Buoy	30	Tested 1989
Spain (Sweeden)	Atlantic Coast		Heaving Buoy	1,000	Proposed (Inactive)
Portugal	Azores		Shore-based OWC	300	Proposed
USSR	Makhachkala		Heaving Buoy	50	Tested
China	Dawan Island		Shore-based OWC	8	Constructing
USA	Puerto Rico		Heaving Buoy Desalination Project	350 (GPD)	Operating ('89)

* OWC = Oscillating Water Column

about ten oscillating water columns. Wave action produces oscillations of the water column that produce pneumatic power which is converted to electrical power via air turbo-generators.

The Indian government has investigated the potential of oscillating water column plants and studied the feasibility of building a 5 MW plant in a new harbor breakwater near Madras. Presently, a 150 kW demonstration plant using a Wells turbine-generator is under construction at a fishing harbor near the port of Trivandrum.

The United Kingdom wave energy program was initiated in 1974. Ongoing development projects include wave-powered desalination and pumping, investigation of the use of a Wells turbine in naturally-formed rock gullies, construction of a 75-kW prototype wave power plant on the Scottish Island of Islay, production of wave-powered turbine generators for navigational buoys in Northern Ireland, and development and model testing of a small-scale Sea Clam wave energy converter at Loch Ness by Coventry Polytechnic.

Norway has conducted an extensive wave power program since 1975. In the 1980s, these efforts included the installation by Kvaerner Brug A. S. of a 500-kW prototype wave power system, called the multiresonant oscillating water column (MOWC), on the west coast of Norway. Operational since November 1985, the plant was swept off its foundation and destroyed during a severe storm in January 1989. In 1986, the Norwegian firm NORWAVE A.S. installed a new system called TAPCHAN, a tapered channel wave power plant in Bergen, Norway, that produces 350 KW of power. Typically, a tapered channel is carved out of a rocky coastal area, using shaped charges, if necessary. The taper can handle a wide spectrum of wave lengths efficiently. As a wave passes through the tapered channel, its wave height is gradually increased as the channel narrows. The wave then spills over into a reservoir where it is stored and subsequently passes through a low-head Kaplan water turbine to generate electricity. NORWAVE A.S. is developing two commercial TAPCHAN systems: one to be installed in Java and the other in Tasmania. Each system will produce about 1.5 MW of power. The construction costs range from about $ 2000/KW in Java to $ 3550/KW in Tasmania and the systems are expected to produce power at rates of about 5 to 10 cents per kilowatt hour (Vadus 1991).

In Sweeden, use of a heaving buoy as a wave energy converter has been extensively studied. Field tests of a 30-kW prototype hose-pump device have recently been completed off Sweeden's west coast and there was a proposal for a 1-MW pilot plant to be installed off the Atlantic coast of Spain. Pharos Marine in United Kingdom has developed a wave-powered navigation buoy using the same concept. In the Soviet Union, testing is underway for a 3-KW wave power plant and a 50-KW inertial wave power unit at Makhachkala in the Caspian Sea. In the United States, wave energy activity has included research and development of the McCormack pneumatic turbine; prototype testing of a heaving and pitching circular float, tandem-flap system, and contouring raft device; and research on a heaving buoy type, wave-powered desalination system in Puerto Rico.

The impact on the environment of wave energy conversion is strongly dependent on the scale of the activity. When a modest project is proposed, where the average power delivered to the grid is 40-100 MW, the impacts are likely to be small. However, there will be community resistance should recreational sites be compromised. If a large scheme delivering several thousand megawatts is proposed, the impacts are obviously expected to be larger, and may not be benign.

The conversion of wave energy to electricity may be expected to influence the coastal wave and current climate, the populations of fish and marine mammals, the navigation of ships, and the visual environment. A large wave power conversion system would modify the local wave climate. A reduction in the wave energy arriving at the shores can change the density and balance of species of organisms around the coast, and may modify the deposition of sand on the beaches. The wave energy conversion devices might be expected to have an influence on the populations of fish and marine mammals. Bottom feeding fish and shellfish, such as lobster and crab, are likely to be unaffected. Fish and marine mammals that spend much of their life near the surface require more consideration. Salmon, members of the herring family, and even sea lions have been mentioned as species that will have to be evaluated when impacts of large-scale wave energy conversion systems are considered.

Wave energy converters placed in or near shipping lanes would present a hazard to shipping because their relatively low profile would make them less visible to sight and radar. The devices would have to be properly marked, and navigation channels would have to be provided through large arrays of the converters. Mooring failures resulting in drifting of the floating devices would provide an additional hazard to navigation and shoreline structures.

The visual effects of wave energy will depend on the site selected, size of the floating platforms, the length of the array, distance offshore, and method of cable transmission. Shore-based systems such as TAPCHAN may be blended into the coast and require a relatively low-profile reservoir ashore to provide the necessary head of water. Depending on the power, the profile of an array can be barge-like (e.g. the KAIMEI Project) and could require a long line of such structures. The visual effect will depend on how far offshore and the impact is difficult to generalize because each configuration and installation plan will differ from one location to another.

A wave energy system designed for Lewis, Outer Hebrides Islands, is used as a base case in Table 5. The wave source is estimated at 48 KW/M mean annual power. The system is based on the SEA CLAM design in a circular-spine configuration to produce 2.5 MW. 1990 construction cost is estimated at $ 1500/KW with the cost of electricity produced at 12.6 cents/kWh. Wave energy conversion devices can provide additional benefits such as: providing calm seas behind by the breakwater effect; and cogeneration of freshwater by forcing seawater through a semi-permeable membrane.

New configurations of wave energy conversion devices are continually being designed at various research centers throughout the world. At the present time, it is very difficult for companies to obtain an accurate assessment of the performance and energy cost of such devices. There is a need to support field-test facilities that are equipped to evaluate various wave conversion devices and their performance claims.

Considerable wave data has been collected but not evaluated. Wave climate data is needed in a form suitable for the designers of wave energy systems, for potential sites. Methods exist for extrapolating and interpolating data collected at particular locations to provide wave climate information. Such a data base would be invaluable not only to the designers of wave energy devices, but to the entire ocean engineering community. There is also a need to provide the technology for reliable and cost effective moorings and riser cables for floating wave energy devices. This problem exists for all types of ocean engineering projects that use floating, moored platforms.

3-4. Current Energy

The kinetic energy of river currents has been used from medieval times to produce power using simple water turbines. There are many old prints that show mechanical power produced from mills at bridges to pump river water to the adjacent communities. The proposed application of current turbines in the oceans is a comparatively recent development, and has been prompted by the observations of mariners and oceanographers of the swiftly-flowing current in some regions of the world. The Gulf Stream, or more specifically, the Florida Current, is of particular interest because of the high current velocity and its proximity to large centers of population on the Florida coast. The Florida Current is particularly strong off the city of Miami, and ocean current turbines have been proposed to exploit this resource.

The performance of an ocean current turbine is similar to the performance of a wind turbine. The ocean or wind turbine transforms a proportion of the kinetic energy of the flow into mechanical power. A small ocean turbine was demonstrated in 1985 in the Florida Current. The unit was suspended from a research vessel at a depth of 50 meters and developed approximately 2 kW. The project was privately funded, and a proposal made to design and test 100-kW and 1 to 2-MW units of a similar design (Carmichael 1986).

In addition, a 20-kW prototype turbine, designed by UEK Corporation, is under research and development, for which testing is planned in New York City's tidal East River. Since 1979, Canadian researchers at Nova Energy Ltd. have been developing large Darrieus-type vertical axis turbines for hydropower applications and are presently completing testing of a 5-kW prototype. Australian current energy conversion units designed by Tyson Turbines Ltd. are small to medium size modular devices capable of producing an energy output of more than 670 kW depending on depth and stream velocity. These units are commercially available for a variety of applications and have been demonstrated in many countries including Australia, the Philippines, Mexico, the United States, and Canada (Saris 1989).

The Gulf Stream carries 30 million cubic meters of water per second, more than 50 times the total flow in all of the world's freshwater rivers; the surface velocity sometimes exceeds 2.5 meters per second. The extractable power is about 2,000 watts per square meter and would, therefore, require extremely large, slow-rotating blade turbines operating like windmills. The total energy of this Florida current is estimated to be about 25,000 MWs.

In 1979, the Aeroenvironment Company conducted a conceptual design study (Coriolis Project) based on installing very large diameter turbines (referred to as coriolis turbines) in the Gulf Stream. Energy calculations indicated that an array of 242 large turbines, each about 170 meters in diameter, moored in the Gulf Stream in an array occupying an area of 30 kilometers cross-steam and 60 kilometers downstream would produce about 10,000 MW. This is the energy equivalent of about 130 million barrels of oil per year. Cost estimates indicated that each unit could be built and installed at about $ 1,200/kw in 1978 dollars. Including capital, operating, maintenance, and fuel costs, power is delivered at about $ 0.040/kWh in 1978 dollars. These figures assumed a plant factor of 57%, which is computed in a way similar to that used for wind turbines, by considering the seasonal variation in the current, plus a two-week annual maintenance shutdown. The Coriolis system is an environmentally benign, cost-efficient method of extracting energy from a renewable source (Lissaman 1979).

The environmental effect of an array of Coriolis ocean turbines on the Florida Gulf Stream current has been investigated for several models. The results showed that for an annual average extraction of 10,000 megawatts, the reduction in speed of the Gulf Stream is estimated at about 1.2 percent, much less than its natural fluctuation. Further calculations indicated that any heating effects resulting from turbulence in the wake of the turbines would be very small (Lissaman, 1979). A 1-meter diameter turbine with compliant blades and rim-driven system was constructed and demonstrated in a water flume. No further research and development was conducted. However, more research is needed to provide greater confidence in technical and economic feasibility in constructing, installing, and mooring very large turbines of the size proposed. Current energy systems do not appear to be ready for commercial application at this time.

3-5. Salinity Gradient Energy

A large unused source of energy exists at the interface between freshwater and saltwater, and the extent of energy depends on the salinity gradient. In extracting this salinity gradient energy, the heart of most systems is a semi-permeable membrane that allows water, but not dissolved solids, to pass through the membrane. With freshwater on one side and saltwater on the other side of the membrane, the force of the freshwater through the membrane creates an osmotic pressure difference. As freshwater permeates through the membrane, a head of water is developed with respect to the saltwater, and a turbine can be used to extract energy from the water flow.

The energy difference that exists between fresh water and salt water depends on the salinity gradient and is represented thermodynamically as the difference in the free energy at the temperature of the two flows of water. The power that could be produced from any salinity gradient device increases with salinity difference and would be particularly effective when the salt water is a dense brine. Power may be generated from the free energy difference in various ways: in a hydraulic system using the difference of osmotic pressure between freshwater and seawater; as electrical energy in a reverse electrodialysis cell; or in a vapor turbine utilizing the difference in vapor pressure between fresh water and sea water. An additional method of using the free energy in a salinity gradient has been devised utilizing the extension and contraction of special fibers induced by changes in salinity (Carmichael 1986).

The potential energy available from major sources of salinity gradients throughout the world is shown in Table 4. To place this in perspective, the projected U.S. energy consumption for the year 2000 is about $6x10^{11}$ watts. Note that Table 4 does not include the potential for producing power by mixing fresh water or sea water with salt marshes or other major salt deposits. The extent and distribution of these resources have not been addressed. Also, there may be considerable potential for producing power with small units using evaporation ponds. Although energy from salinity gradients cannot by itself provide energy independence, it has the potential for ultimately making a substantial contribution, depending on its economic competitiveness.

The application of energy from salinity gradients should be relatively simple once the power has been generated. The most promising concept for energy conversion would use the osmotic pressure head to drive turbines which would produce electrical power in the same manner as the production of power from existing hydroelectric systems. This technology is well developed, and the conversion efficiency of a hydroturbine-electric generator system is about 90%. If sea water were used in a salinity gradient power system, the power would likely be generated in coastal zones. These zones are generally the most heavily populated and the electricity produced could be tied directly into existing power supply grids (Monney 1977).

The development of candidate systems for the production of power from salinity gradients has not progressed far enough to provide an accurate economic assessment of system types and configurations. However, general considerations can be presented which point to one concept which may be promising if the salinity gradient is very large, such as where the Jordan River flows into the Dead Sea. An analysis and prelimi-

Table 4.— Potential Power from Salinity Gradients

Source	Country	Flow Rate (10^4 m/sec)	Pressure (atm)	Power (10^6 kW)
Run-Off	Global	110.0	24.0	2,600.0
Run-Off	USA	5.3	24.0	130.0
Amazon River	Brazil	20.0	24.0	470.0
La Plata-Parana River	Argentina	8.0	24.0	190.0
Congo River	Congo/Angola	5.7	24.0	130.0
Yangtze River	China	2.2	24.0	52.0
Ganges River	Bangladesh	2.0	24.0	47.0
Mississippi River	USA	1.8	24.0	42.0
Salt Lake	USA	0.0125	300.0	1.8
Dead Sea	Israel/Jordan	0.0038	300.0	1.8
Wastewater to Ocean	USA	0.05	22.5	1.1

nary experiments for a 100-MW plant at the mouth of the Jordan River indicate that power could be produced at a cost of $ 0.072/kWh in 1976 dollars (Monney 1977).

Although this cost is more than double the cost of electricity from a coal-fired power plant, dramatic improvements may be possible for the salinity gradient power plant with improvements in semipermeable membranes. A brine such as that which exists at the Dead Sea or Great Salt Lake can be used to produce a greater salinity gradient. Another difficulty is that geographical areas with naturally occurring bodies of high salinity brine are usually deficient in the fresh water needed to provide the salinity gradient. However, it may be possible to use sea water or other brackish water as the low salinity permeate. It may even be feasible to create a renewable energy resource by using sea water in evaporating ponds in a coastal area to produce the high salinity brines which would be mixed with the low salinity sea water permeate.

In an evaluation of the subsystems and components which would comprise a salinity gradient power plant, it becomes apparent that the semi-permeable membrane is the major technical problem. In all other respects, the plant would draw upon well established technical capabilities which have little potential for marked improvements.

The membrane, however, has a very significant potential for improvement in terms of cost and performance and, at the same time, is the major controlling factor in determining the power output of a plant operating with a specified salinity gradient. The major problems with respect to semi-permeable membrane development are flux, fouling, salt rejection, life expectancy, and cost. The production of power from the salinity gradient between fresh water and sea water will not be economically feasible unless the membrane flux can be improved by an order of magnitude and the requirement for pre-treatment of the water can be virtually eliminated.

3-6. Wind Energy

The winds of the earth are caused primarily by unequal heating of the earth's surface by the sun. During the day, the air over the oceans and lakes remains relatively cool, since much of the sun's energy is consumed in evaporating water, or is absorbed by the water itself. Over land, the air is heated more during the day since the land absorbs less sunlight than the water, and evaporation is less. The heated air over land expands, becomes lighter, and rises. The cooler, heavier air from over the water moves in to replace it. In this way, local breezes on a shoreline are created. During the night, these local seashore breezes reverse themselves, since the land cools more rapidly than the water, and so does the air above it. The cool air blows seaward to replace the warm air that rises from the surface of the water. Similar local breezes occur on mountainsides during the day as heated air rises along the warm slopes heated by the sun. During the night, the relatively cool, heavy air on the slopes flows down into the valleys.

Likewise, circulating planetary winds are caused by the greater heating of the earth's surface near the equator than near the poles. This causes cold surface winds to blow from the poles to the equator to replace the hot air that rises in the tropics and moves in the upper atmosphere toward the poles. The rotation of the earth also affects these planetary winds. The inertia in the cold air moving near the surface toward the equator tends to twist it to the west, while the warm air moving in the upper atmosphere toward the poles tends to be turned to the east. This causes a large counterclockwise circulation of the air toward low pressure areas in the northern hemisphere and clockwise circulation in the southern hemisphere. Since the earth's axis of rotation is inclined at an angle of 23,5° to the plane in which it moves around the sun, seasonal variations in the heat received from the sun result in seasonal changes in the strength and direction of the winds at any given location on the earth's surface (Gordon 1977).

The wind at many ocean sites is both strong and persistent. Such sites may be suitable for placing arrays of wind turbines to generate electricity. Some studies of ocean wind turbines have been conducted in the United States and in other countries. Also, there is international cooperation in the development of the technology of ocean wind turbines, through the International Energy Agency. As part of that program, some European turbine systems are being designed and it is intended that the offshore support structures will be evaluated using computer analyses developed in the United States.

Probably, the most detailed engineering evaluation of ocean wind turbines was conducted in the U. K. for a large array of turbines designed for an annual mean wind speed of 8.5 meters/second at a site about 20 miles off the east coast of England. The proposed wind turbines were 100 meters in diameter and the designs were based on a conventional wind turbine 60 meters in diameter. An array of 320 wind turbines were to be placed on individual towers, which were 86.5 meters tall, in water 20 meters deep. The predicted energy costs for the British study, in 1984, were 5-9 p/kWh, or about 7.5 to 13.5 cents per kWh. The cost of electrical energy from offshore wind turbines was predicted to be twice that of onshore wind turbines (Carmichael 1986). Wind farms located in offshore waters would increase the capital cost of construction by adding the cost of larger seaworthy towers and foundations. The cost for offshore maintenance would also be higher.

As of May 1989, the American Wind Energy Association (AWEA) estimated that there were more than 1,600 MWs of wind power on line in the U.S. Over 90 percent of the machines are at three California sites (Altamount Pass, Tehachapi, and Palm Springs), with 16,000 wind machines generating about 2 billion kWh of electricity in 1988, an energy equivalent of 3.5 million barrels of oil. Hawaii ranks second, with about 34 MWs of wind power on line. Hawaii also has the world's largest operating wind machine, the 3.2 MW U.S. Department of Energy/ Boeing MOD-5B (3.2 MW); 15 Westinghouse 600 kW wind turbine generators; 37 Mitsubishi 250 kW wind turbine generators; 320 Jacobs 17 kW machines; four Carter 25 kW machines; and many small wind machines. The greater capacity of wind power produced in California is mainly attributed to state tax credits (since abolished). Economic factors make the difference (Neill & Takahashi 1989).

The cost per kWh is dropping rapidly (as low as 7 to 10 cents/kWh) and the projected cost with the advanced midsize wind turbine generator is 4 to 6 cents/kWh. Improved reliability (95% or better availability factor), better materials, and other improvements to newer machines have resulted in further reducing operating and maintenance costs to under 0.5 cents/kWh and a capital cost per kW of less than $1,000. These costs are in 1989 dollars. Due to the variability of the wind source, utilities must limit the dependency on wind power applied to the power grid. In the future, wind energy-related energy storage systems such as flywheels, batteries, pumped-storage hydroelectric, hydrogen, compressed air, and so forth coupled with computer control system(s) and advanced power electronics will diminish variability (Neill & Takahashi 1989).

AWEA's newsletter (July 10, 1989) pointed out that: "A typical 100 kW wind electric turbine by U.S. Windpower weighs about 7 tons, and if it offsets coal-fired electric generation, would prevent nearly two and a half times its own weight each month in emissions of carbon dioxide (CO_2), the primary gas implicator of global warming." The article also pointed out that California's 16,000 wind machines offset 11 million pounds of air pollutants per year (Neill & Takahashi 1989).

Public acceptance of wind energy conversion systems is an important consideration in planning for the widespread application of wind energy. Studies have shown that the environmental impact of such systems is relatively small compared to conventional electric power systems. Wind-powered systems do not require the flooding of large land areas or the alteration of the natural ecology, as for hydroelectric systems. Furthermore, they produce no waste products or thermal or chemical effluents, as fossil-fueled and nuclear-fuelued systems do. A wind farm of many rotor blades could have some impact on the local bird population (Gloria, 1990).

Conventional wind turbine systems that generate several megawatts of power require large exposed rotors on the order of

60 meters in diameter, located on high towers. The rotors of such systems; being passive, are practically noiseless. However, special precautions will be necessary to prevent them from causing interference with nearby TV or radio receivers, and some safety measures may be required to prevent damage or injury from possible mishaps in cases where there is danger that the rotors might break or shed ice.

The only other concerns with conventional wind machines are those of aesthetics. Large numbers of units and interconnecting transmission lines will be required in the future if such systems are to have any significant impact on U. S. energy demands. Particular attention is being given, therefore, to the development of attractive designs for the towers, rotors, and nacelles of these conventional systems to avoid "visual pollution" (Gordon 1977). Depending on the location and proximity to living and recreation spaces, large fields of towers and rotors may be visually offensive.

There appear to be important advantages to using wind-derived energy in combination with energy derived from other sources, such as conventional fuels, sunlight, ocean thermal differences, bioconversion fuels, etc. Since the wind blows intermittently in most locations, there may be a need to store wind energy over long periods of time, perhaps up to 10 days or more, if the energy is being used for isolated applications requiring continuous power. The cost of providing sufficient storage capacity for such applications can be reduced if the wind-derived power is interconnected with other sources of power. Because in most locations the wind often blows when the sun is not shining, and vice versa, a system using wind energy collectors and sun energy collectors (solar photovoltaic arrays or other solar thermal collectors), in combination, can be expected to require less energy storage capacity than systems that use these types of collectors singly.

4. FUELS AND ENERGY-ENHANCED PRODUCTS FROM THE SEA

While considerable solar energy is stored within tropical oceans, these regions generally are not centers of industrial development, nor significant energy markets. Thus, for offshore ocean power production to prove useful and competitive in the world energy market, it is necessary to formulate efficient and economical means to redistribute the energy generated by these technologies from areas rich in ocean energy resources to areas of high energy consumption. This need has sparked interest in the development of transportable fuels and other products which take advantage of power produced by ocean energy conversion systems in manufacturing processes. The U. S. Department of Energy's recent review of the concept provides a concise assertion: "The greatest potential for OTEC is to supply a significant fraction of the world's fuel needs using large plantships to produce hydrogen, ammonia, or methanol". (*The Potential of Renewable Energy: An Interlaboratory White Paper,* Idaho National Engineering Laboratory, Los Alamos National Laboratory, Oak Ridge National Laboratory, Sandia National Laboratory, Solar Energy Research Institute, March 1990).

Substantial effort has been expended thus far to improve isolated ocean energy conversion technologies, yet very few have reached the commercial stage. One major reason for their lack of commercial success is that the isolated technologies have not capitalized on ancillary products or on inputs that might synergistically integrate these isolated technologies into complete systems, as depicted in Figure 1. It is this integration that will make the development of ocean resources economically viable in the future (Vadus 1982).

If the ocean is ever to develop into a major supplier of energy fuels, multi-product systems will be the primary inducement. Many tens of thousands of ocean energy megawatt equivalents can someday power floating cities and industrial platforms for strategic metals, transportation fuels, chemicals, and other products. The commercial success of these enterprises will almost surely depend on total system integration. For example, a grazing platform which harvests and processes seabed ores, using OTEC electricity, and returning wastes to the ocean floor, could well turn out to be the only acceptable option for strategic metal production. Likewise, a marine biomass plantation encircling a floating methanol production facility in the open ocean, utilizing upwelled deep ocean water, creating new fisheries, while perhaps enhancing the atmosphere by utilizing carbon dioxide, could be much more efficient and economical than non-integrated ocean or land-based enterprises.

During the next decade, much of the research required to advance the science and engineering relating to production of fuels and energy-enhanced products from the sea can be performed at land-based facilities such as at the Natural Energy Laboratory of Hawaii and the Shikoku Laboratory of the Japan Marine Science and Technology Center, both of which feature pipes that bring deep, cold water to the surface. However, prototype experiments will also need to be performed on the open ocean to test concepts and gain the confidence of the financial sector.

The National Science Foundation sponsored a workshop in 1989 on "The Ocean Enterprise." Recommended was a series of OTEC-related projects leading to a 500 MW ocean mineral platform combining OTEC and seabed ore processing by the year 2000, and a 1000 MW Pan American complex featuring multinational cooperation and a full range of co-products at a cost of $ 10 billion by 2010. If global warming becomes a serious matter, nuclear power plants continue to face societal acceptance problems, mineral shortages occur, and the commercial equivalent of the National Aerospace Plane —which will be powered by liquid hydrogen— flies, OTEC should be in a prime position to provide fuels from the sea by year 2020.

5. INTERCOMPARISON OF OCEAN ENERGY CONVERSION SYSTEMS AND FOSSIL-FUELED POWER PLANTS.

Table 5 provides a comparison of small-scale ocean energy systems for coastal and island communities in the United Kingdom. This comparison shows that the capital costs for construction in 1990 constant dollars range from about $ 1500 to $ 3285 per KW for the small-scale wave, wind, and tidal power, but the cost of electricity produced is about the same for wind and wave and almost double for tidal. However, at this relatively early stage of development, these differences are not very great.

By 1992, over 3.5 MW of wave power will be on-line with energy utilization costs that are economically competitive, especially for the island market. Most of this wave power will be derived from the TAPCHAN System developed and commercialized by NORWAVE A.S. The oscillating water column and the heaving buoy are competing systems. Wave power capital costs range between $ 1500/KW to $ 3550/KW and cost of electricity produced from about 7 to 13 cents/kWh. Environmental impacts of wave energy differ based on their location, e.g., the shore-based TAPCHAN involves coastal land use for the funneling system and reservior, but has minimum impact on marine life and nearby coastal activities; the near-shore caisson-contained line of wave energy converters can create calm seas behind and affect sediment transport and associated marine life; and the far offshore line of wave energy converters can create an obstacle for commercial fishermen, and also require navigation markers for marine transportation.

Wind farms on land, as demonstrated by over 1600 MW on-line in the U. S. in California and Hawaii, have proven economic competitiveness and have coupled into the commercial electric power grid. The construction capital costs in the U.S. were about $ 1000/KW and energy costs about 7 to 10 cents per kWh and this is fairly close to the U.K. example in Table 5. Wind farms offshore are expected to cost more for installation and for offshore maintenance cost, but the cost of electricity produced would be close to costs on land. Environmental impact pertains mainly to use of large expanses of coastal land for a field of vertical towers, which may not be visually attractive from some perspectives.

Tidal power has been on-line for over two decades using conventional technology and has proven economic viability with energy costs varying, depending on the physical characteristics of the selected site. Environmental impacts will also vary from site-to-

Table 5.— Comparison of Small-Scale Ocean Energy Systems for Coastal and Island Communities in the United Kingdom

	Wind	Wave	Tide
Location:	Brennan Hill, Ayrshire	Lewis, Outer Hebrides Islands	Langstone Harbor, Hampshire
Resource:	10m/sec mean annual wind speed	48 kW/m mean annual wave power	3.13m mean annual tidal range
Technology:	horizontal axis, twin-blade	SEA Clam (circular-spine)	single-effect ebb-generation
Plant Dimensions:	60m rotor diameter, 45m high tower	60m diameter waterplane area 6.25m draft	550m long barrage 19 million sp. m reservoir
Plant Capacity (MWe):	3.7	2.5	24.3
Capacity Factor:	29%	22%	25%
Construction Cost ($/kW):	1,585	1,500	2,813
Cost of Energy (¢/kWh):	9.0	12.6	16.2
Year of Estimate:	1986	1990	1986

site depending on: the extent of alteration of the marine ecology by the controlled diurnal movement of water flowing through the turbines; and the extent of disruption to the multi-users and nearby inhabitants of the body of water involved.

As noted in Table 2, a considerable effort has been expended in advancing research and development of OTEC. Based on the available information, the construction capital costs (constant 1990 dollars) for OTEC range from about $ 16,260/KW for the 46-MW closed-cycle plant proposed for Hawaii to $22,570 for a small scale 1.15-MW open-cycle plant proposed for a Pacific Island. The cost of electricity in 1990 constant dollars is about the same. These costs do not reflect the potential of providing coproducts such as freshwater and nutrients for aquaculture to offset these costs.

The economic competitiveness of ocean energy conversion systems versus fossil-fuel power plants is shown in Tables 6 and 7. Table 6 shows a comparison of a wave energy system versus a coal-fired plant in California. In 1990 constant dollars, the construction capital costs are about the same and cost of electricity is fairly close, considering the wave energy system is in its early stages of development. Table 6 also compares OTEC with a coal-fired plant, showing that construction capital costs and cost of electricity produced are about six times greater for OTEC, exclusive of the benefits of by-products. Table 8 illustrates dramatically the advantages of producing freshwater as an OTEC by-product.

Table 7 is a comparison of wave energy and OTEC versus an oil-fired plant in South Pacific Island sites. In the case of wave power for Tasmania, construction capital costs are much higher than the oil-fired plant in New Zealand; however, the cost of electricity produced is less than half the

Table 6.— Comparison of Ocean Energy with Coal
California & Hawaii

	California		Hawaii	
	Coal	Wave	Coal	OTEC
Technology	Pulverized Coal	Heaving Buoy	Fluidized Bed	Closed Cycle
Fuel Cost ($\$/10^6$BTU):	2.05	N/A	2.05	N/A
Plant Capacity (MWe):	275	30	180	46
Capacity Factor (%):	70	29	85	
Construction Cost ($/kWe):	1940	2098	2131	12,203
Service Life (yrs):	30	30	40	35
Cost of Energy (¢/kWh):	6.9	13.1	5.9	25.5
Year of Estimate:	1987	1990	1990	1985

cost. The cost of OTEC construction capital costs are about 50 times greater and cost of electricity produced about two times greater than that of the oil-fired plant.

OTEC plants that discharge large quantities of cold water could affect: the natural thermal and salinity gradients; levels of dissolved gases; composition of nutrients and trace metals; and water turbidity; and thus affecting the marine ecosystem. The effect on marine life will depend on the care taken to stabilize the discharge plume below the mixed layer to protect the thermal resource and reduce environmental effects. A more serious impact could occur in the event of an accidental spill of OTEC working fluids such as ammonia, freon, or some other environmentally hazardous fluid. Also, the use of chlorine as a cleaning fluid to reduce buildup of any organic film on the heat exchangers could be a problem. Research experiments have shown that the amount of chlorine needed for cleaning is diluted with seawater to safe levels before discharge.

6. CONCLUSION

As energy demands continue to increase in support of burgeoning populations and industry demands, a growing concern exists about the impact of: fossil fuel combustion causing global warming and air pollution; extracting oil and gas, and oil spills; and dwindling supplies of oil and gas which may be exhausted by the middle of the 21st Century. One hundred percent safe nuclear power would be an alternative, but society has not been receptive because of potential catastrophic failures and problems of disposing spent radioactive fuel elements. Relative to fossil fuels and nuclear power, ocean energy conversion systems provide an inexhaustible, nonpolluting source that has great potential as an alternate energy source to contribute to present and future needs with relatively minor impacts on the marine environment. Ocean energy can be extracted by: converting the dynamic motion (Kinetic energy) of wind, waves, and currents induced by solar winds; converting

Table 7.— Comparison of Ocean Energy with Oil South Pacific Island Sites

	Wave	Oil	OTEC
Location:	King Island Tasmania, Australia	Stewart Island New Zealand	Design Study
Technology:	TAPCHAN	Power Plant	Open Cycle
Fuel Source:	N/A	Bulk Diesel	N/A
Plant Capacity (MWe):	1.5	0.9	1.15
Capacity Factor (%):	68	34	80
Construction ($/kWe):	3550	449	22,570
Service Life (yrs):	40	20	30
Cost of Energy (¢/kWh):	6.7	13.6	33.1
Year of Estimate:	1990	1985	1989

Table 8.— OTEC Market Penetration Scenarios (Vega & Trenka 1989)

Nominal Net Power (NWe)	Type	Scenario Reqts	Scenario Availability
1	Land-Based OC-OTEC with 2nd-Stage additional Water Production	. \$45/barrel of diesel .\$1.6M^{3}water	South Pacific Island Nations by Year 1995
10	Land-Based (as above)	.\$25/barrel of fuel oil .\$0.85/m^{3}water -or- .\$30/barrel with .\$0.8m^{3}water	American Island Territories and other Pacific Islands by Year 2000
40	Land-Based Hybrid (ammonia power cycle w/Flash Evaporator downstream)	.\$44/barrel of fuel oil .\$0.4/m^{3}water -or- .\$22/barrel .\$0.8/m^{3}water	Hawaii, if fuel or water cost doubles by Year 2000
40	.Closed-Cycle Land-based .Closed-Cycle Plantship	.\$36/barrel .\$23/barrel	 By Year 2005

. OC-OTEC limited by turbine technology to 2.5 MW modules or 10 MW plant (with four modules)
. OC-OTEC or Hybrid (water production downstream of closed-cycle with flash evaporator)

ocean thermal and salinity gradients; and converting biomass energy derived through photosynthesis. Technical feasibility, economic competitiveness with the cost of energy, and environmental impacts are the major determinants in realizing commercialization.

The intercomparison of ocean energy conversion systems and fossil-fuel plants discussed in Section 5 indicate that energy derived from wind power, wave power, OTEC, and tidal power are economically competitive to fossil-fueled systems, considering their early phase of development and the potential by-products that can offset costs for OTEC and wave power.

It is fortunate that an initial need exists for small-scale ocean energy plants to satisfy the island market by providing a degree of energy independence, as well as some valuable by-products. As experience is gained and further cost reduction achieved, the systems can grow in capacity to satisfy an even larger market, eventually leading to the coastal mainland. Design studies have shown that costs will be further reduced by economies of scale.

The selection of which form of ocean energy conversion is most suitable will depend mainly on: the particular needs of a region, the available ocean energy resource, and the geographical and geological characteristics of the site. Once that is determined and the technical requirements formulated, the system can be financed in many ways. To stimulate early commercialization and share in any risks, a public/private partnership between, for example, state/local government, local utility, and the constructing firm would be a good way to increase probability of success.

Ocean energy will provide much needed energy diversity in an environmentally acceptable manner to: phase in the replacement of dwindling supplies of oil and gas that could be severely depleted in three decades; and to reduce oil and gas usage due to its impact on global warming and air pollution.

The rationale for continued commercialization of ocean energy conversion systems is very compelling and essential to help meet societal needs in the 21st Century.

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8. DISCLAIMER

The concepts and ideas presented in this paper are the views shared by the authors and do not necessarily represent the views of any organizations that they are affiliated with.

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