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OCEAN THERMAL AND WIND POWER: ALTERNATIVE ENERGY SOURCES BASED ON NATURAL SOLAR COLLECTION

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INTRODUCTION

There are fundamental reasons why the satisfaction of our energy demands must be transferred to solar energy processes if humankind is to survive on this Earth. Those fundamentals can be summed up as follows:

a) The inability of the ground water resources of the more industrialized nations to provide a heat sink for exponential expansion of combustion and fission heat-engine energy processes.
b) The inability of the atmosphere to accept the effluent and thermal pollution that will accompany the present expansion of combustion and fission heat-engine energy processes.
c) The inability of the world's known or possible fossil fuel and uranium resources to support planned growth in combustion and fission heat-engine processes, particularly the gross inequity in irreversible consumption of finite carbon and hydrocarbon stocks that should be conserved as the feed stock for future generations of the chemical industry.
d) The potential lack of acceptability of the plutonium breeder fuel cycle as a substitute in the future for the uranium fuel cycle.
e) The questionable ability of even the U.S. economy to find and invest the immense amounts of capital required for the large nuclear power plants now planned.

Accepting those fundamental faults with planned growth in combustion and fission, we are faced with two alternative paths. The first is a severe and permanent cut-back in energy usage, with its concomittant permanent cut-back in industrial activity. The second is a reasonable cut-back in energy wastage, the creation of breathing space for the energy industry to reorient itself, and then new growth using solar energy processes in a non-polluting, non-depleting way. The authors contend that the second path is scientifically sound, technically feasible, economically prudent, socially desirable, morally right and politically achievable.

The collection of solar energy for useful energy production can be divided into two categories:[1] "natural collection" and "technological collection." Natural solar collection occurs in the earth's atmosphere, giving rise to wind and rain, and on the earth's land and sea surface, resulting in plant photosynthesis and the creation of temperature differences in the ocean. In technological solar energy collection, man-made structures collect the solar radiation and convert it directly to electricity or heat. This article will discuss the two most important natural solar collection methods for large scale energy production: (1) the collection of solar energy by the earth's atmosphere, which causes the winds, and (2) the natural collection of incoming solar radiation by the oceans, which creates large temperature differences in the ocean waters (See Table 1).

TABLE 1

ENVIRONMENTAL POWER SOURCES—ESTIMATED RESOURCES[2]

Source	Power Potential (watts)
Solar	173,000 x 10^{12}
Incident 30%	
Atmospheric 47%	
Hydrologic cycle 23%	
Earth	
Conducted to surface via rocks	32 x 10^{12}
Convection (hot springs and volcanoes)	0.3 x 10^{12}
Tides, tidal currents	3 x 10^{12}
Wind, waves, convection, currents	370-4000 x 10^{12}
Water Power	3 x 10^{12}

This article will discuss the historical development of systems designed to utilize these renewable energy sources, as well as their potential for making a significant contribution to the energy supply of the United States. Recent research results and technological developments in total power systems and important subsystem components, including those used for the storage of energy, will be discussed. In addition, we will attempt to enumerate the recognized technological and institutional problems standing in the way of their potential implementation.

I. Windpower Systems

A. *History & Description*

Energy conversion devices designed to extract momentum from moving air have been used by the oldest of the world's civilizations. The significance of windpower peaked in the sixteenth century, when the Low Countries used windpower for manufacturing industries and to propel their merchant fleets. In the United States, in 1850, windmills provided about 1.4 billion horsepower hours of work, the energy equivalent of burning 11.8 million tons of coal.[3] Windpower was used to generate electricity very soon after the wire-wound dynamo was invented, and many nations established and maintained national programs aimed toward large scale windpower systems. These large systems never materialized, however. First low-cost coal, then very low-cost petroleum or natural gas fuel plants, and, finally, the optimistic promises of the nuclear power advocates of the 1950-1970 era made the economics of wind-generated electricity noncompetitive.

During the 1920's and 30's, windpower on a small scale in rural America was of great significance, just as it is today in other countries such as Argentina and Australia. The energy budget for a farm, ranch, or even a home, however, grew so rapidly from World War II onward that the single wind generator and storage battery system could no longer reliably and economically supply the increased energy demands. The Rural Electricification Administration played a major role in satisfying that exponential growth in demand,[4] and started the change-over of agriculture in the United States from a man-intensive effort to a fuels-intensive effort with an enormous energy budget.

The largest experiment in wind generation of electricity was conducted on Grandfather's Knob, a 2000-ft. hill near Rutland, Vermont, from 1939 to 1945.[5] This large generator, which developed 1,250 kilowatts of electrical power (kWe), used a 175-ft., two-bladed propeller to drive the generator on top of a 100-ft. tower, and delivered electricity into a sixty cycle power grid. Because this system was conceived solely as a fuel saver, its capital, operation, and maintenance costs had to compete against the differential cost of coal delivered to Vermont. It did not meet that competition; furthermore, it suffered a fatigue failure in one blade, and the test was abondoned.

Since1970, considerable interest in windpower has again been witnessed within the scientific community,[6] primarily for the following three reasons:

1. Several studies[7] have shown that windpower electricity generation systems can be self-contained, with their own storage subsystems, and can deliver electricity on demand at an average revenue per kilowatt-hour (kWh) that is competitive with more conventional systems.
2. It has recently been proposed[8] that large windpower electrical systems be installed offshore on the Atlantic Coast and in the Great Lakes where passage of the winds over about 15 miles of open water is known to intensify their velocity considerably, thus increasing their productivity in momentum exchangers (energy available in the wind varies as the third power of the wind's velocity).
3. A related development involves the concentration of generators in a wind dam or wind barrage, which provides a method for wind generation by reaching up into the air with as dense a population of momentum exchangers as technology will permit.

The influence of these concepts on the development of current windpower systems will be discussed below.

B. *Windpower Resource Availability*

The windpower resources of the world are regionalized, and since power available for extraction varies as the cube of wind speed, it is important to look for the strong and persistent wind fields. Thus, even though the worldwide resource of windpower is huge,[9] with estimates varying from 2×10^{10} kilowatts (kW) to 1×10^{11} megawatts (mW), it is most important to look for sites in regions where the winds are persistently strong if practical and economical windpower systems are to be considered.

The United States "wind belt" includes a strip about 200 miles wide along the northern boundary of the country that is a particularly productive region for conversion of the wind's energy into electrical power. One reason for this is the large generally low pressure cell in the atmosphere over the Atlantic Ocean below Iceland, which acts as a huge suction pump, drawing the winds across the land and out to sea. This natural phenomenon magnifies the value of the windpower resource over the land and continental shelf of North America. With properly designed systems, this "deep ocean" resource can be harvested without venturing too far out into the

Atlantic Ocean.

As shown in Table 2, one recent estimate of the annual energy potential using practical systems in windy regions of the continental U.S., the Aleutian Islands, and the Eastern seaboard is about 1.5 trillion kWh per year. In comparison, it has been estimated[11] that the United States electrical generation load will be 3 trillion kWh per year by 1980, based on the predictions of exponential growth in electricity demand that were so popular a few years ago. It should be noted that the annual capacity at each site was calculated from available wind velocity-duration data at specified heights, using either 200-ft. diameter (2 mW) or 60-ft. diameter (100 kW) wind generators. Other more recent studies[12] using more complex mathematical models have tended to verify and improve those estimates.

TABLE 2

WINDPOWER ENERGY PRODUCTION OF SELECTED AREAS OF THE UNITED STATES[10]

Site	Annual Power Production (10^9 Kilowatt hours)
Offshore New England	360
Offshore Eastern Seaboard	283
Great Lakes	133
Great Plains	210
Offshore Texas Gulf Coast	190
Along Aleutian Island Chain	402
Total Resource	1578

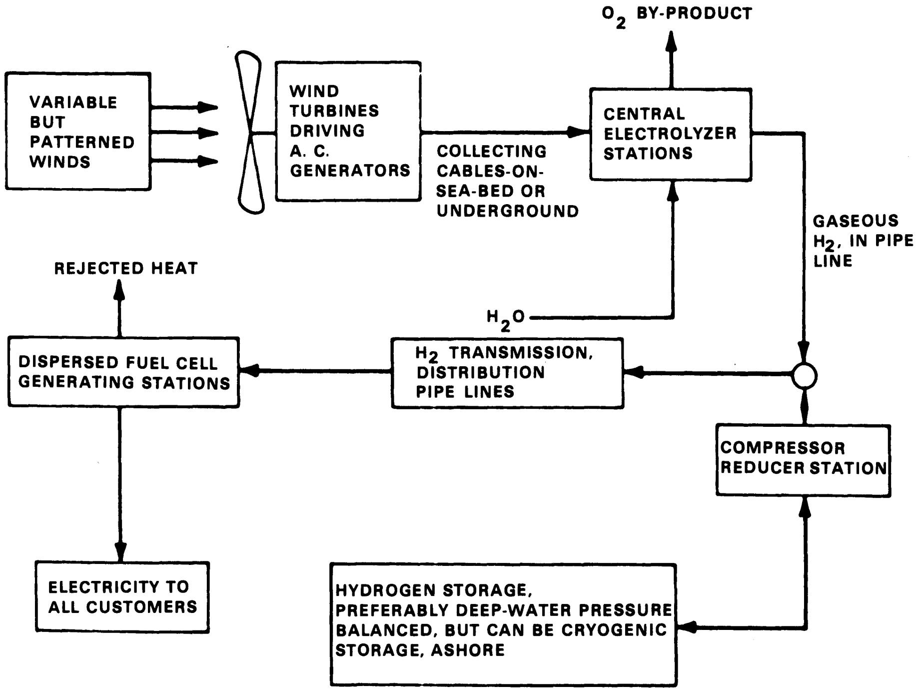
C. *Typical Windpower Systems Design*

In this section, examples of state-of-the-art designs for windpower electrical generating systems will be discussed. As previously noted, the choice of power plant location can have a significant effect on the design and overall performance of one of these natural collection systems, an effect which siting seldom exerts on conventional power system performance. An important consideration to remember is that an energy storage subsystem is a major part of a windpower system.

The key components of a windpower system are shown schematically in Figure 1: (1) a wind resource in a specified area; (2) a support system for placing large numbers of generators up into the wind; (3) the wind generators; (4) an energy collection system that delivers electricity into a regional distribution center or a transmission line; (5) an energy storage subsystem; and (6) an energy delivery system. All of the above depend on "the energy product" to be sold, which need not be restricted to electricity.

FIGURE 1

BLOCK DIAGRAM OF ONE PROPOSED WIND CONVERSION SYSTEM[13]



The question of site selection has been discussed briefly in the previous section, and its importance is again emphasized. For example, as shown in Table 3, a single 32-foot diameter, 20 kW rated machine would capture about 40,000 kWh per year if located at Milwaukee, Wisconsin, but would capture about 100,000 kWh per year if located out on Georges Shoals, about 80 miles to the east of Cape Cod, where Texas Tower II was sited. For each of those sites, the available energy imput to the system was determined with the use of monthly wind velocity-duration data, in conjunction with an analytical model of a specified wind generator.

Many support subsystem designs are available, ranging from a simple pole reaching to as high as 100 feet above the ground to a number of very tall multiple-rotating unit supports, a carousel billboard array (either land or sea based)[15] or to a single or double banked king post and wire rope suspension system.[16] The latter

TABLE 3

EFFECT OF SITE SELECTION ON WINDPOWER GENERATION[a] [14]

Site	Power Output (Kilowatt hours/year)
Madison, Wisconsin	40,000
Squantum, Massachusetts	46,000
Fargo, North Dakota	54,000
Lake Superior	70,000
Lake Huron	85,000
Georges Shoals	98,000

[a] Based on one 32 ft. diameter machine, 20 kW generator, atop a 100 ft. pole.

system is best described as a wind bridge or wind dam, and is held up in the sky by supports located at half-mile intervals. Those supports carry a 4-rope or 6-rope cable suspension system in which lattice frameworks containing numbers of relatively small wind generators are suspended.

Wind generators can today be built from proven designs of various researchers[17] or can be projected from new more efficient or novel concepts.[18] A choice must be made between a small number of larger, more economical (capital cost per kW of capacity) machines which are limited to higher wind velocities (as represented by their cut-in speed), and a multitude of smaller diameter machines with lower cut-in speeds. In many cases, however, the smaller machines prove more economical to operate since they run more often, requiring smaller energy storage. They also may prove more economical to manufacture.

The energy collector system could be a mechanical system (used for pumping, to run compressors, etc.), a power cable system, or a hydrogen gas pipeline if the electrical power is converted to hydrogen and oxygen gas by an electrolyzer subcomponent. Various storage systems have been considered, such as compressed air,[19] flywheels, electric storage batteries, pumped hydro storage, or a hydrogen gas storage system in which electrolyzers are used.[20] For an ocean-based system the use of pressure-balanced[21] hydrogen storage in conjunction with electrolyzers is an attractive possibility.

If electricity is to be delivered directly from the system, the power can be delivered to the consumer via conventional electrical transmission systems (land-based plants) or underwater electric cables (ocean-based plants). The most economical system is one that delivers the largest possible portion of its production directly into a central power grid as electricity. If hydrogen storage is used, the hydrogen can be pumped directly to the consumer for use as a synthetic fuel, or it can be converted to electricity by fuel cells or a conventional thermal-electrical power plant which will burn the hydrogen. The use of hydrogen as our major energy fuel, the so-called "hydrogen economy," has been under considerable research and development in recent times.[22] The "hydrogen economy" concept seems to be the way to use solar energy to fuel most of our energy producing combustion processes, including internal combustion engines used for transportation.

The general methodology for simulating the performance and estimating the cost of a windpower system has recently been published.[23] For purposes of illustration, a system designed for operation off the New England Coast will be discussed. This large windpower system, proposed for location in the relatively shallow waters of the Gulf of Maine and over the Banks, is estimated to have an annual productivity of as large as 360 billion kilowatt hours per year. That number can be placed in perspective by noting that the entire electricity demand of all six New England states was about 45 billion kilowatt hours in 1974.[24] Such a system not only offers the opportunity to convert all present petroleum and coal fueled heating processes either to electricity or hydrogen combustion, but could also provide synethetic fuel (hydrogen) to road, rail and air transport. The size of the proposed system would enable all existing New England central power plants to be retired gracefully as they reach the end of useful life.

The system has been conceived as self-contained, with the ability to supply electricity or hydrogen fuel on demand. The conception is one of a major energy supply system that can grow gradually, with relatively small increments of generating capacity being added daily, weekly or monthly. The parts are all amenable to steady state production in efficient factory settings with a steady cash flow, rather than the lengthy tie-ups of great sums of capital now required to add nuclear power generating capacity to the system.

When the windpower system was first designed and costed in 1971,[25] the capital cost estimates were kept conservative, but several optimistic assumptions were made: (a) that certain developments in electrolyzers and hydrogen fuel cells would be funded and would yield the improvements in efficiency and concurrent cost reductions thought to be reasonable by experts in those areas; and, (b) that all wind generator components would be assembly-line built and would therefore be considerably less expensive per unit of power than were the few "hand-built" wind generators available in the market at that time. When the entire system was costed and the required average revenue per unit power delivered was calculated, it appeared that a kWh of electricity would have to cost an average price of 32 mills (3.2 cents). In 1971 that average revenue was considerably higher than the 28 mills per kWh then required in New England. By November 1974, however, that 28 mills had risen to 48 mills and was still climbing.

In 1973 Dambolena[26] improved upon the original 1971 concept, and was able to show that if certain achievable improvements in hydrogen system hardware were realized the average revenue per kWh delivered by the offshore windpower system could fall to the low 20 mill region. Thus, in late 1973 there was good reason to project that electricity from offshore windpower systems would be selling in all of New England at prices 50% lower than the going price for electricity from the fossil and nuclear fueled plants. In three short years this idea moved from a noncompetitive to a clearly superior competitive position. The greatest advantage of the windpower concept, besides being totally pollution-free, is that it has a technological future rather than a past. The opportunity for improving the hardware components, increasing their efficiencies and reducing their costs, is a real one, whereas the combustion and fission competitor technologies may not offer the same advantages.

Table 4 summarizes size and estimated "economics" of five different applications of windpower systems thought to be technically feasible for deployment in the near future. The largest of the systems could be on station delivering product at the end of four years.

TABLE 4

TECHNICAL SUMMARY: WINDPOWER SYSTEMS

Proposed System	Size of System	Economics
1. Residence-sized, self-contained windpower systems available today; with electric storage battery, for the supply of modest amounts of electricity on demand.	1 kW-6 kW, 200 kWh to 1000 kWh per month, depending upon region. (Most hardware is imported.)	Very expensive electricity: 100 to 200 mills per kWh of electricity.[a] Particularly attractive where bringing in new power lines would be very costly. Considerable savings can be made by using home-built hardware.

[a] The electricity rates in New York City, for the smallest block of consumption, have reached over 100 mills per kWh, Nov. 1974. (New York Times, Nov. 13, 1974)

Proposed System	Size of System	Economics
2. Heating of buildings with one of the versions of "The Wind Furnace" now being developed.	27,000 to 65,000 kWh during a nine month heating season, provided by a 32 ft. diameter wind machine atop a 60 to 100 ft. tall pole. (57,000 kWh keeps a standard well-insulated house at 75 ° F in Syracuse, N.Y. during the heating season.)	Thought to have an excellent chance of competing against 40 cent per gallon fuel oil where wind speeds average at least 12 mph at 100 ft. height above ground; assuming 20 year mortgage, 1973 rates. As mortgage rates drop, economics becomes much more attractive. Excellent opportunity for tax incentives to promote fuel oil savings, state or national level.
3. Generation and sale of electricity-on-demand, Wisconsin Market.	A system capable of generating an additional 65 billion kilowatt hours per year of electricity by 1990, to provide a total of 91 billion kilowatt hours of electricity per year.[b]	The average kWh of electricity would have to bring a revenue of 32 mills, assuming a 15.5% fixed charge rate and a 10 mill per kWh distribution charge.

[b] The authors in no way endorse this unrealistic, "planned," growth in electricity consumption!

Proposed System	Size of System	Economics
4. Generation and sale of electricity when-the-wind blows, to the Taconite Industry in the Masabi Range of Minnesota.	A system capable of delivering 19 million kilowatt hours per year, a system owned by the Taconite Industry.	A cost of 9 mills per kWh, delivered, assuming a 15.5 % fixed charge rate, but no general and administrative expenses or profit charged thereon.

5. Generation and sale of electricity, on-demand, for the six-state New England region, or, some combination of electricity-on-demand plus hydrogen gas sold as a synthetic fuel for use on-demand.	A system providing as many as 360 billion kWh per year, distributed and sold at uniform prices throughout all of New England.	The average kWh of electricity would have to bring a revenue between 33 mills and 23 mills, delivered on demand, at fixed charge rate of 15.5% and a 10 mill per kWh distribution charge.

II. Ocean Thermal Power Systems

A. *Description and History of the Concept*

A fundamental law of the science of thermodynamics states that it is always possible to place a heat engine between two different temperature sources to generate useful power. It is this law that provides the driving force for our conventional "Rankine cycle" vapor power systems. For this type of system the working fluid occurs in both liquid and gas (vapor) states; steam electrical power generating plants are the most common example. In the simplest system, liquid enters a pump and is compressed and fed to a boiler. Combustion supplies the energy for a change of phase from liquid to gas in the boiler, and the vapor is fed to a turbine. In the turbine, which connects to an electrical generator, the flow is accelerated to high velocity in nozzles; then the high-speed jets of gas flow against the turbine blades, which extract kinetic energy from the flow stream. The vapor then passes out of the turbine and, in the "closed cycle," is condensed (by river water, cooling towers, etc.) to the liquid state and returned to the pump.

This vapor cycle is the basis for the ocean thermal differences power plant concept. The warm ocean surface (about 25 degrees Celsius in the tropics) acts as a natural solar collector to sustain the high temperature source, while the underlying cold water (about 4 degrees Celsius), at depths greater than 1000 feet, acts as the cold sink. More precisely, the surface temperature of the ocean stays at the high temperature (about 25 degrees Celsius) because thermal equilibrium is established between the radiation from the sun and such heat losses as those associated with evaporation and convection. The cold water at the ocean depths, on the other hand, is caused by melting ice at the polar caps, subsequent sinking of the heavier cold water, and the movement of that water toward the tropical parts of the world. Thus, both the source and sink are renewed continually by solar energy processes.

The idea of exploiting this natural energy source originated in the 1880's with the French physicist D'Arsonval[27] and was later carried to analytical design and experimental work by Claude[28] in the 1920's. Claude's system, installed on land near Matanzas, Cuba, used water as the working fluid and featured a low pressure flash evaporator to produce steam, a power turbine, and a direct contact condenser using cold sea water pumped from the ocean's depths. His system, which delivered 22 kW of turbine power, was plagued with technical difficulties, but failed chiefly for two reasons[29]: (1) Water itself was used as the working fluid; although the heat transfer properties of water are superior to those of other working fluids, the corrosiveness of seawater, the requirement of extremely large turbine sizes, and the need for a high vacuum and water deaeration caused formidable technical problems. (2) The land-based plant required extremely long cold water lines (2 kilometers long), which were destroyed during testing and whose great length permitted excessive heat flow losses. Further work on a similar design was carried out by the French Government[30] in the 40's and 50's for a 7000 kW system off the Ivory Coast, but a working power system was never completed. The thermal cycle used by Claude is called an open Rankine cycle, since the working fluid is not returned to the pumps supplying the evaporator.

In more recent times, a potential improvement over the open Rankine cycle concept of Claude has been proposed and conceptually designed by Anderson and Anderson.[31] Their initial design featured a closed cycle (propane as the working fluid), driven by the temperature difference in the Caribbean. In this type of system the working fluid is vaporized by heat energy taken from the warm water in an evaporator, expanded through a turbine to generate power, and then condensed at lower temperatures by the cold water source. The condensed fluid is then recirculated back to the evaporator where the cycle repeats itself with the same fluid; thus the name, "closed cycle." Other key parts of this system, in addition to the four Rankine cycle components (evaporator, turbine, condenser, and working fluid pump), are the hot and cold water delivery systems. Large ocean water pumping systems for both the hot water and the cold water are needed to keep the system operative. Starting from many of the Andersons' ideas, recent ocean thermal power system studies have been carried out at Carnegie Mellon University[32] and the University of Massachusetts.[33] A review of 1973 state-of-the-art technology for ocean thermal power plants has recently been published[34] as a result of an NSF sponsored workshop on the subject. As will be discussed below, at least one comprehensive study has yielded thermal design and ocean hull configurations as well as the conceptual design of total power systems based on this concept.

B. *Resources for Ocean Thermal Power*

The most productive use of the ocean's thermal power potential would occur at sites with maximum temperature differences, a resource which is also regionalized, and is most abundant in tropical climates or where tropical currents exist.[35] In places where there are no extensive ocean currents (such as the Gulf of Mexico), plants would be required[36] to "graze" from the stagnant hot surface water. One optimistic estimate[37] of the world's resources for ocean thermal power concludes that in the year 2000 the tropical oceans could supply the world with a per capita level of energy consumption equal to the per capita rate consumed in the United States in 1970. (The tropical seas receive almost half of all the solar energy showered upon the Earth at any time).

The most abundant source of ocean thermal power for the United States is contained in the waters of the Gulf Stream. Assuming a Gulf Stream flow rate of 33 x 10^6 m^3/sec and a one degree reduction in temperature,[38] a heat energy input equivalent to 690 trillion kWh per year is available for an ocean thermal power system. If a two per cent overall energy conversion efficiency is assumed,[39] an assumption which includes theoretical thermodynamic as well as real component limitations, plus a 75 per cent load factor, the available power from the Gulf Stream is equal to 10 trillion kWh per year. Siting limitations, assuming the need to restrict the power plant array to one line of 400 mW plants placed one mile apart along 550 miles of the Gulf Stream, would reduce the available power to 1.4 trillion kWh per year, still a significant value. Since the Gulf Stream is about 15 miles wide, however, there is adequate space for up to fifteen parallel lines, one mile apart, without unacceptable interference with navigation. Furthermore, oceanographic data[40] indicate that this supply is reasonably constant throughout the year, eliminating the need for the large energy storage subsystems common to windpower (and those solar energy conversion processes which stop producing when the sun sets). The ocean thermal power plants sited in the Gulf Stream are therefore able to serve as base load, intermediate and peaking load power plants, with very small storage subsystems added thereto.

C. *Ocean Thermal Power Systems Design*

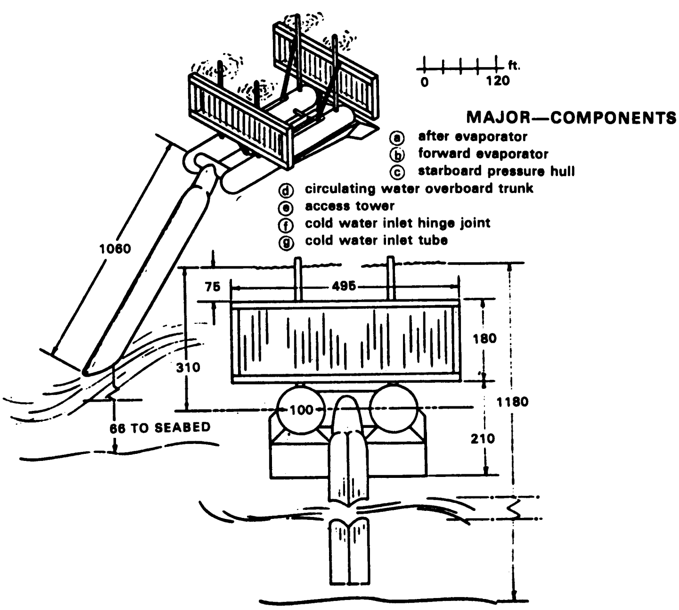
The design of an ocean thermal power system is similar to that for a wind power system in that the site conditions strongly determine performance. In contrast to windpower systems, however, the near-constant ocean temperature difference allows the power plant to be designed as a base load or total load system, with a minimal amount of energy storage capability to accommodate both small seasonal fluctuations in the resource and the daily customer demand load curve. As previously discussed, the best power cycle suited to utilize the ocean temperature difference is a simple closed boiling and condensing Rankine cycle. Although there are many potentially feasible component choices and arrangements for ocean thermal power systems[41] the system that will be discussed in detail is the result of recent research[42] at the University of Massachusetts, supported by the National Science Foundation RANN (Research Applied to National Needs) program. This work has as its goal the creation of an initial systems layout plus the preliminary design of all components of the thermal power cycle, the external seawater delivery system, and all other subsystems required to make up a total power plant delivering an energy product to a specified market.

The site selected for this power system is in the Gulf Stream, approximately 25 kilometers from the University of Miami in Florida.[43] Oceanographic variables[44] influencing this choice were depth and seasonal current and temperature profiles. The initial system design, as shown in Figure 2, is that of a 400 mWe power plant, the largest size thought to be feasible, feasibility being determined primarily by heat exchanger and cold water supply tube size limitations.

In the power plant shown, the warm surface water of the Gulf Stream flows naturally across the tubes of the evaporators and changes the working fluid (propane) inside those tubes into vapor under pressure. More recent designs[45] have replaced these tall evaporators with much shorter more compact heat exchangers, which use pumps to assist the flowing Gulf Stream in feeding the warm surface water. This power plant configuration uses a catamaran submarine hull, each reinforced concrete cylinder of which is approximately 100 ft. in diameter and 600 ft. long. The evaporators are placed on top of the hull cylinders. The single large diameter cold water inlet pipe, of streamlined cross section with an 80 ft. minor diameter and a length of about 1100 ft, supplies the condensers inside the hulls with cooling water and also serves as a part of the mooring system.

Vertical access trucks reach from the hull top up through the ocean surface. The hulls are fitted with the equivalent of a variable ballast system, which will accommodate the expected fluctuations in the Gulf Stream current by ballast changes and thus changes in the static balance of the system.[46] Inside the hulls the vaporized working fluid is passed through 16 separate turbines (there are 16 separate turbine-condenser-working fluid pumps forming independent power packages). A major part of each hull interior is a cold water distribution system that supplies the 16 different condenser packages.

FIGURE 2
ONE DESIGN OF AN OCEAN THERMAL POWER SYSTEM



Each turbine drives a generator. In one design, the generated electricity is rectified to direct current and sent ashore via a large cable that passes out of the hulls, down the mooring to a sea bed anchor and cable connection point, then across the sea bed to the shore. In another design, the electricity is consumed in the power plant itself in electrolyzers to produce hydrogen gas from distilled water. The hydrogen gas is then pumped via hose and pipeline out of the power plant, down the mooring to the sea bed, then via in-sea-bed pipeline to the on-shore market. Very long hydrogen pipeline energy umbilicals are being studied: one would deliver hydrogen generated off South Carolina and Georgia all the way to Narragansett Bay, or up the Hudson River to upper New York State and

Vermont. If direct-current electricity is sent ashore, it must be reconditioned into the correct type of alternating current, and fed into the synchronized net or grid. If hydrogen is sent ashore, it may either be sold as a synthetic fuel for direct use or converted into electricity by means of a generator driven by any one of a number of different thermal power cycles. However, the most desirable way to convert the electrolytically pure hydrogen to electricity would be via a hydrogen-air fuel cell, in which hydrogen and oxygen are caused to combine back into water, releasing a flow of electrons in the process.

Table 5, giving some preliminary cost estimates for a 400 mW system,[47] shows that the two large heat exchanger components, evaporator and condenser, are the most costly parts of the system. On the basis of economic, material, and volume constraints, the best current design calls for plate-fin type heat exchangers (similar in construction to conventional automotive radiators) for both the evaporator and condenser components. Although others[48] have proposed the use of very thin walled, ocean water and working fluid pressure-balanced heat exchangers, designs based on thicker, pressure proof components appear to be more practical. Regardless of the type of exchanger construction, because of the small differences in temperature which must be exploited in this process, studies have shown[49] the need for highly detailed analytical models of these components and of the entire thermal cycle. Also, the current design calls for inherently corrosion-proof and fouling resistant materials (cooper-nickel alloys), together with reasonably high water velocities, to assist in the prevention of fouling.

The structural configuration of the cold water delivery system and the hull are major design problems of an ocean thermal power system. The configuration previously described uses a cold water inlet pipe which is essentially a long, deep, "open-ended" ship's hull, designed and fabricated to be neutrally buoyant, not to vibrate due to the passage of the Gulf Stream across it, and to possess enough axial strength to serve as a major portion of the mooring system. The hulls, having the characteristics of pressure proof submarine hulls, are presently conceived as very large diameter horizontal axis cylinders made from reinforced concrete. The internal compartmentation bulkheads will also be cast in concrete, and the main ballast tanks may be either reinforced concrete or steel. Analogies for all of this work are taken from the rapidly expanding semi-submerged hull technology of the offshore oil industry.

TABLE 5

PRELIMINARY COST ESTIMATE FOR A 400 MW OCEAN THERMAL POWER PLANT[47]

Component Description	Cost ($/kW) Low	High
Hull and Concrete Components	13.5	39.0
Cold Water Inlet Pipe	45.0	63.0
Machinery	136.0	179.0
Heat Exchangers	140.0	340.0
Electrical and Transmission	44.0	82.0
Command and Control	0.5	0.5
Auxiliary/Life Support	5.0	5.0
Outfit and Furnishings	3.1	3.1
Sub-total	387.1	711.6
Present Value of Construction with Interest and Escalation	433.6	797.0[a]

[a] At a fixed charge rate of 15.5% and a plant factor of 0.93, Fixed Charges, Generation for an $800 per kW plant would be of the order of 15 mills per kWh. If a very high (relatively speaking) 2 mills per kWh were added to that for Operation and Maintenance, electricity would cost 17 mills per kWh at the terminal on the shore. It would probably have to sell for 27 mills per kWh to break even.

Although this work has shown the initial feasibility of a sea-based power system, the scale of such a system requires a carefully sequenced major development program to move from drawing board through subsystems, thence to test vehicles, and finally to a demonstration prototype. Also, the potential environmental impact of such systems must be considered, particularly if grand scale deployment is contemplated. Some of these problems will be discussed in more detail in the next section.

III. Major Technological, Environmental, and Legal Problems

A. *Technological*

1. *Windpower*

Wind energy conversion machines have worked for centuries. At one time the technology of the wind machine and the supporting skills and tools of the millwright were at the pinnacle of technology within society. There has been a continuing interest in the most subtle scientific aspects of fluid mechanics underlying wind machine operations, and the most noted of fluid mechanicians have made serious contributions to the science and to the art. What is still needed is the development of the manufacturing processes associated with wind machines, the applications of materials, and the technological stability that comes with competitive manufacture of large quantities of a product to satisfy an eager market. In short, there is a need for application of modern industrial know-how to large scale manufacture of wind machines.

There is a need for imaginative support or suspension systems, structures that will fling large numbers of these machines across the winds in a satisfactory if not eye-pleasing way. An excellent, sophisticated technology base from which to develop a large windpower industry exists, but that development has not yet started. It is possible for wind system components to be priced like assembly-line automobiles. The individual components of wind systems lend themselves to assembly-line production, and here they could have a clear advantage over any of the fossil fuel or fission energy devices, except for the gas turbine units which are comparably susceptible to factory production. Without such assembly-line production, windpower systems will remain quite expensive.

The storage subsystem of greatest interest today is that which prepares, stores and then consumes hydrogen gas. The hydrogen industry is a well-established industry today, and has shown considerable growth in the recent past. There are excellent opportunities for imagination and invention and plain development to increase the efficiencies of the hydrogen devices used for reconversion, *i.e.*, electrolyzers and, preferably, hydrogen-air fuel cells. This part of the technology development program is particularly exciting because neither the electrolyzer nor the fuel cell is limited by the relatively low efficiency of conventional power cycles caused by fundamental thermodynamic limitations. It is desirable to have electrolyzers and fuel cells that are inexpensive, very efficient, made from minimal quantities of relatively abundant materials, and capable of at least 25 years full-service operation. Although such goals are said by those in the industry to be achievable, to date no one has been willing to underwrite the required effort.

2. *Ocean Thermal Power*

The work carried on by the University of Massachusetts has been an elaboration of the earlier work by the Andersons and by the later French investigators, particularly Daric.[50] As the research has progressed, and as the design of the baseline configuration has developed, the major "problem areas" become ever clearer. It is the opinion of those at work in this project that each such problem area has at least one practical and economic solution. The problems have been discussed in some degree previously and will be summarized again here.

First, there are two overriding problem areas which must be totally conquered, or the concept will fail:

1. Corrosion: These power plants must survive in an ocean environment. They must exhibit larger maintenance-free life than have most ocean systems in the past. They simply must be free from corrosion opportunities! That can be achieved, and at reasonable cost.

2. Biofouling: The warm water which these plants are to use will contain populations of fouling organisms. The cold water from near the sea bed will probably be free from such populations. But in both cases, the heat exchanger surfaces simply cannot accept biofouling encrustation: such growth will effectively stop the power plant. Nor can the hull or other exposed parts of the power plant accommodate excessive marine growth. Therefore, positive and continuing measures, such as continuous or batch chlorination, that will prevent marine growths must be taken. This can be done, at some real cost, but economically.

Second, the controlling technological problems for which steadily improved solutions must be sought are listed as follows:

1. The turbines must achieve component efficiencies of at least 90 per cent. It is thought that this can be done, particularly if power package size is dictated by optimum turbine size.

2. The heat exchangers must be configured to achieve high rates of heat transfer at the least possible cost in invested material. The necessary heat exchanger theory seems to be well in hand though a "breakthrough" in heat transfer augmentation would give the economics of the process a most wonderful boost. Low cost fabrication techniques for desired heat exchangers must be demonstrated.

3. The supply of both hot water and cold water at a site without disruptions of the material thermal layering of the ocean at that site must be assumed.

4. The structure required to convey the required huge quantities of cold water with a minimum of hydraulic losses in the process appears to be a major design problem.

5. The mooring and anchor system for power plants located in swift currents, such as found in the Gulf Stream, will be larger and heavier than any previously used and therefore must be developed carefully. Many competitive concepts should be developed. The probable motions and acceleration of these power plants in an ocean excited by wind-waves and currents must be understood prior to hull design.

6. These power plants offer an opportunity for large-scale use of steel reinforced concrete in the ocean, particularly for submerged pressure hulls. The use of concrete in the oceans involves a new technology, and development must keep pace with planned usage.

7. The energy umbilicals will be large and possibly expensive, regardless of whether electricity, hydrogen, ammonia, or some other energy product flows through them. The creation of hydrogen in the far reaches of the tropical high seas and the return of that product as cryogenic hydrogen in tank ships is almost a fact from a purely technological viewpoint, but the economics of that kind of an umbilical must be understood far better than they are now, and considerable development may be in order before such a system can be called practical.

B. *Environmental*

A recently sponsored EPA report[51] has summarized the direct and indirect environmental consequences which must be considered in the development of advanced or alternative energy sources. With reference to the costs of energy production, the report notes that both windpower and ocean power systems, even if assumed to be pollution free, require substantial amounts of materials, which could cause considerable off-site pollution during production.

Other major environmental questions involving windpower are concerned with climate or weather modification.[52] For land based sites, it is possible, but highly improbable, that an array of windmills would offer sufficient resistance to the flow of wind to cause it to shift and affect the local or regional ground climate. It is also possible that the use of extensive windpower installations might be significantly affected by, or have a significant effect on, large scale weather modifications. These two questions should form the basis of extensive future research. Those who have pondered the question to date have done so in a preliminary way, and have concluded that man could never erect enough wind machines at any place to modify weather. More study, however, is appropriate.

Environmental problems posed by the extensive use of ocean thermal power systems range from questions dealing with the biological and ecological aspects[53] of antifouling agents, primarily used for the evaporators, and exchanger erosion to those dealing with the ecological and environmental impacts due to changes in salinity and thermal redistribution on biota, mixing processes, density structure and climate.[54] In addition, large scale global effects, such as those on Europe caused by the slight lowering of the Gulf Stream's temperature, must be evaluated. A positive effect which some authors[55] have postulated is that the movement of vast quantities of water from the nutrient rich cold waters could be used for large scale food production. Again, as for the windpower systems, once potential sites for ocean thermal power systems are chosen, large deployment of these plants should be preceeded by detailed environment impact studies.

C. *Legal*

The key legal problems of both windpower and ocean thermal power systems stem from the potential deployment of large scale ocean-based systems. The law of the sea allows anyone to anchor to the sea bed, and to lay a cable or pipeline in the sea bed, provided his anchor, cable or pipeline does not foul one that is already there. The concept of "the beneficial use of the seas" has favorable implications for large ships and platforms, fishing factory ships, or oil drilling platforms, in use for commercial exploitation of the natural resources of the sea. So, it is postulated that these systems, whether moored to the sea bed or afloat on the high seas, should be welcome, provided they do not trespass upon some other ocean system that is already there. This hypothesis is, of course, open to much discussion.

Another legal concern is related to risk and incentive. The federal government saw fit to remove all but a small portion of liability insurance requirements from public utilities in order to give nuclear power a boost. What kind of similar or even more significant boost could the federal government give to ocean thermal power plants, thus accelerating demonstration of the process and acquisition of these systems?

IV. Potential Systems: Implementation and Costs

A. *Potential Systems: What Could be Implemented?*

As previously discussed, the size of these natural energy conversion systems could range from a few kilowatts for individual household windpower systems to large scale 400 mW ocean thermal difference power plants. Such a size range presents obvious differences in future implementation of such systems.

The existing windpower technology base is seeing small but significant improvement currently. A windpower research and development program has also been administered by the National Science Foundation (NSF)[56] for two years; a sizeable portion of those resources have been entrusted to NASA for both in-house and controlled development. Work is underway in certain areas of windpower technology where the results of previous researchers were thought to be capable of amplification and improvement. There is not yet a major industrial or utility commitment to the use of windpower. Significant, self-contained, windpower systems for the generation of electricity or the preparation of a synthetic fuel, however, could start operation in as few as four years with the right backing.

The existing ocean thermal differences process technology is not as well developed as that of windpower. The ocean thermal differences process was demonstrated in real hardware in 1928; but it was the open cycle that was demonstrated, and the preponderance of present thinking favors the closed cycle process. As shown by recent NSF programs,[57] there is a small, but significant, research program in ocean thermal power systems development at the federal government research and development level which may ultimately lead to a proof-of-concept experiment. A national commitment properly organized, funded, and managed, however, could see a prototype ocean thermal power plant in operation within six to ten years. This task probably will have to be executed by a federal agency, but there is an increasing possibility that a private group might assume the responsibility if shielded from loss hazard as were the so-called private nuclear pioneers. This program would have to start with existing limited technology and move boldly through component, subsystem, and system evaluations. A number of candidates would have to be entered into competition at each level, exactly as was done in the U.S. Navy's POLARIS program, for example. Indeed this ocean-flavored task might profitably be assigned to the U.S. Navy, whose vast resources, including shipyard, heavy power plant fabrication and assembly capabilities, as well as ocean related science and engineering capabilities, could be applied to almost all facets of the program.

The ocean thermal differences process has world-wide implications: the abundance of this naturally collected resource makes this process potentially the largest of all solar energy processes; furthermore, the resource is available to all nations, both rich and poor. It has recently been calculated,[58] for example, that all of the nitrogenous fertilizer used in 1973 on crops in Thailand could have been produced from air and seawater alone, using one 400 mWe ocean thermal power plant and an adjoining ammonia fixation plant at costs less than one-fourth those paid for the fertilizer actually consumed. The world-wide implications of freeing the food supply of the world from the need for petroleum based fertilizer should certainly receive attention.

There are small-scale windpower systems which could eventually supply a significant part of the world's energy needs. In fact, wind generated electricity might be the only kind of energy that the majority of the world's population ever knows. The majority must now find a way to bypass a petroleum based fuel economy, because the world's petroleum supply will have been consumed by the minority of the world's population. Electrical energy supplied by small-scale windpower may play a role in the lives of the most hungry and least affluent. For those living in the Western World where cooking by electricity is still thought to be a luxury, it may be difficult to conceive of less developed populations, totally lacking cooking fuel, using electricity to prepare food.

Small scale ocean thermal differences plants do not seem to be as likely. With the closed cycle there is a minimum sized power plant which provides the required efficiency, probably no smaller than 10 mWe to 25 mWe. As such plants require considerable capitalization they will never be an artifact of the village or small city.

B. *Comparative Economics: Windpower and Ocean Thermal Differences Systems versus Proposed Fossil Fuel or Fission Plants*

It is not easy to make both brief and equitable comparisons of the economics of proposed energy systems. One of the methods used today involves construction of a small table purporting to compare the elements of cost of future electricity produced by several competitive systems. The table is intended to leave the reader with the clear-cut impression that the future consumer will save money if he selects "System X." This method has been used by nuclear power proponents in an attempt to elicit popular support for huge new nuclear power plants. One of several inadequacies associated with this method is that the presentations take full advantage of supposed "economies-of-scale" associated with the large plants, without mentioning any of the real diseconomies-of-scale. The authors have concluded, after some years of research on this subject, that more complex comparisons are necessary. It is therefore proposed to compare possible costs of electricity to be produced by several different electricity generating systems, in the year 1981 or thereabouts. Each system is to produce electricity in accordance with a projected load-demand-curve pattern, electricity available on consumer demand.

Today, consumers purchase electricity via a large number of different rate structures, etc., but they purchase it on demand, in accordance with a rather well established load-demand curve, with a very high degree of reliability assured for them by the rules of the Federal Power Commission. The price paid per kilowatt hour can usually be distributed amongst these categories:

1. Fixed charges, Generation (cost of "owning" generating plant).
2. Operation and Maintenance Charges, Generation (which includes fuel costs).
3. Fixed Charges, Transmission (cost of "owning" transmission plant).
4. Operation and Maintenance Charges, Transmission.
5. A rather large add-on which covers all the distribution plant, customer billing, advertising and other public relations activities, the overhead of all the supporting staff, and profit.

The sum of these figures is that number which, when multiplied times all the kilowatt hours sold that year, gives the total revenue required to offset exactly the total annual expense. This figure is referred to as "the average revenue per kWh delivered." The sum of (1) through (4) may be called the "bus bar plus transmission cost of an average kilowatt hour."

When one calculates and compares "the average revenue per kWh delivered" for a number of competitive systems, then one can perhaps see with some clarity why one electricity producing system could be economically superior to another system. An attempt has been made to make such a comparison for four different electricity systems, each of 25,000 megawatt size, coming on line in 1981 (see Table 6).

TABLE 6

COMPARISON OF FOUR DIFFERENT ELECTRICITY GENERATING SYSTEMS, EACH CAPABLE OF PROVIDING ELECTRICITY ON DEMAND TO A MARKET WHOSE TOTAL DEMAND IS 25,000 MWE

System Type	Projected 1981 Average Revenue per kWh Delivered on Demand
1. System 1: A mixture of 1000 mWe Pressured Water Reactor (PWR) nuclear plants capable of 75% plant availability, no earthquake standard, no missile protection, relatively inexpensive cooling water, gas turbine intermediate and peaking plants.	Total cost at bus bar = 29 mills/kWh. Add 10 mills/kWh for Distribution, Profit = 39 mills/kWh.[a]

[a]*Source*: September 1973, U. Mass (Amherst) study made by Norman and Heronemus in preparation for testimony at a State of Connecticut hearing on licensing of Millstone #3, using the New England Power Port Planning Manual Method (1969) with updated 1973 capital cost and fuel data (Arthur D. Little Report to Northeast Utilities).

2. System 2: A mixture of various sizes of coal burning plants, each fitted with expensive and very complete effluent clean-up systems, inexpensive cooling water and gas turbine peaking plants.	Total cost at bus bar = 29 mills/kWh. Add 10 mills/kWh for Distribution, G & A, Profit = 39 mills/kWh.[b]

[b]*Source:* Norman and Heronemus study, *supra* note *a*.

3. System 3: An offshore windpower system complete with hydrogen storage subsystem, delivering electricity on demand to any existing New England customer. Fitted with adequate subsystem redundancy to meet all FPC reliability requirements.	Total cost at bus bar = 13 to 25 mills/kWh, depending upon success of electrolyzer and fuel cell development programs. Add 10 mills/kWh for Distribution, G &A and profit = 23 to 35 mills/kWh.[c]

[c]*Source:* Heronemus, W.E., *Power from the Offshore Winds,* PROCEEDINGS OF THE 8TH ANNUAL MARINE TECHNOLOGY SOCIETY CONFERENCE (1972); Dambolena, I., *A Planning Methodology for the Analysis and Design of Windpower Systems,* Ph.D. Dissertation, Univ. of Mass. (Jan. 1974).

4. System 4: An Ocean Solar Power Plant complete with a small hydrogen storage subsystem capable of delivering electricity on demand to Miami Beach. The hydrogen storage is used to meet FPC reliability requirements.	Total cost at bus bar = 19 mills/kWh. Add 10 mills/kWh for Distribution, G & A and Profit = 29 mills/kWh.[d]

[d]*Source*: Progress Report NSF/RANN/SE/GI-34979/PR/74/4 (Feb. 1975); *See also* O. Griffin, *Energy from the Ocean: An Appraisal,* NAVAL RESEARCH LABORATORY MEMORANDUM REPORT 2803, at 28 (1974).

Each system of 25,000 mWe capacity is to be made up of some mix of individual power plants. The large base load nuclear plants are to be joined by some near-optimum numbers of intermediate fossil-fuel (clean coal) plants and gas turbine peaking plants. The proposed windpower system uses nothing but wind generators plus gaseous hydrogen storage. The proposed sea-thermal power plants use relatively modest gaseous hydrogen storage to match the daily load demand curve and small seasonal variation. The nuclear power plant used for comparison here is a 1000 mWe sized Pressurized Water Reactor (PWR) plant which is designed for siting where earthquakes are never expected, which will sit above ground without any significant protection against missiles of any kind, accidental or otherwise, and which will be able to use large quantities of water in evaporative cooling towers at relatively low cost. This is assumed to be the lowest-cost reactor plant. Factors which could add to cost are: (a) construction to a specified earthquake survival code, (b) undergrounding, (c) ballistic protection against inadvertent or intended "missile" attack, (d) requirement that dry cooling towers be used instead of once-through cooling or evaporative cooling.

The fossil fuel system is a 25,000 mWe system equipped to burn just coal, with total stack-gas clean-up for base and intermediate load installed in various plant sizes. To that mix is added enough gas turbine power plant to take care of peaking, and as much as is optimum to satisfy overall system "spinning-reserve"[59] requirements dictated by the Federal Power Commission.

The estimates, which were calculated about two years ago, may not reflect increased costs due to severe inflation, *e.g.*, fossil fuel costs, construction costs, energy costs for mining and enrichment of uranium fuel, costs of transporting nuclear wastes from any part of the country to the single waste repository now in operation.

Several major items of expense were left out when calculations were made for the nuclear competitor in the table:

a) No capital cost of increase in fixed charge rate to provide for disassembly and safe storage of the spent and poisoned plant at the end of its useful life was provided. At least one estimate by a credible engineering firm has said that restoration of a nuclear power plant site to human access will cost more than the initial total plant construction cost. This forseeable expense is in no way covered in any of the nuclear power plant financial arrangments made to date.

b) The expanding cost for armed surveillance over all aspects of the uranium fuel cycle and the nuclear power plants themselves has not been added.

c) The expanding costs for training and education of the technical people required to administer and operate an expanding nuclear power plant system has not been included.

When all resources required for continuation of combustion and fission, indeed for the expansion of combustion and fission, are clearly identified and even some small attempt made to cost them out, the economics of any proliferation of such fission processes take on very different hues from those they wore prior to, say, 1972. Table 6 suggests that the two solar energy alternatives are economically desirable and promise to supply large quantities of energy at lower dollar energy costs. Furthermore, this may be achieved without any of the undesirable side effects, economic or otherwise, predicted for combustion and fission. Indeed, if earlier computations for wind or ocean thermal power systems costs are in error by factors of 2 to 4, those systems would still be a hard-cash bargain.

VI. Summary and Conclusions

This discussion has only scratched the surface of the possibilities of solar energy for the future. These two processes, based on natural collection, can be combined with each other[60] or with a number of other solar energy processes[61] to take over gradually the task of supplying energy for the United States. From a national viewpoint we have everything to gain from solar energy process developments and early implementation. Solar energy dependence is the proper substitute in this country for imported oil dependence, and the sooner we accept that concept the happier we all will be. Solar energy is the only energy alternative that offers any chance for additional growth in our industry, in our economy, and in our standard of living.

Outside the United States the challenge is even more clear. Officials in the United Nations Environmental Program are now convinced that over half of the human population of the earth will never benefit from fossil-fueled or fission-fueled energy systems.[62] These people must make a rapid and vast commitment to solar energy or accept that they will have only their own muscles and a few draught animals to help increase their energy supply.

We have all witnessed what can be done by the poorest of nations when entrusted with a "peaceful" nuclear power plant,[63] and we certainly should rethink the provisions of any act which encourages sales of such devices to any and all foreign countries. Can solar energy help the rest of the world; can either windpower or the ocean thermal differences process help the energy needs of all nations? The answer must be "yes". Most of the less developed countries border on tropical seas. Most of these countries lack petroleum, coal, and fertilizer; many lack water, and all lack electricity. Whether or not water or electricity from ocean thermal difference power plants could ever be distributed widely enough in these countries to do any good for the bulk of the population, the peasant farmer, is not clear. Fertilizer, however, could be manufactured and distributed. Up to a point, one pound of nitrogenous fertilizer added to rice culture, the agriculture that feeds half of the world, will add eight pounds of grain to the harvest. Air plus 8,000 to 10,000 kilowatt hours of electricity plus sea water, when fed into the proper machinery, will produce ammonia. Ammonia plus distilled sea water is one of the best of the nitrogenous fertilizers. If ammonia nitrate is preferred, it too can be made with electricity, water and air. The manufacture of adequate fertilizer in the future could be separated totally from the supply of oil or gas, if adequate capital were invested in fertilizer factories powered by ocean thermal difference power plants. Or, in the windy latitudes known as the Roaring Forties, drifting fertilizer factories extracting energy from those strong winds could aid in this task. Those factories and power plants must probably be the product of the industrialized nations, and they may even have to be, to a large extent, gifts from the wealthy to the poor. They could do a job that needs to be done. Their product could cost a small fraction of what nitrogenous fertilizer is costing in 1974. Their product could cost much less than that coming from a factory whose input energy is based on either enriched uranium or bred plutonium fuel. The international implications of large-scale proliferation of ocean thermal power plants and windy-seas windpower plants are numerous.

In conclusion, the following important points concerning both windpower and ocean thermal systems should be re-emphasized:

1. Both systems make use of a renewable resource, energy from the sun, and therefore only their construction and maintenance draw upon the world's nonrenewable resources.

2. Both systems are based on current technology and proven engineering feasibility, although major efforts in product and manufacturing development must be expended before either wind or ocean thermal power systems can be placed into large scale operation.

3. Either of these systems provides an alternative or competitor to conventional fuel, nuclear fission, or fusion processes. The need

for a well-balanced energy resource program is clear.

4. The need for improved methods of energy storage is apparent for both systems. Work on hydrogen or other energy storage and delivery systems should be given a high national priority.

5. The environmental impact of both systems should be determined before any large-scale implementation. Such problems as potential weather modification, changes in ocean environment and visual pollution should be considered in detail.

6. At the present time, capital cost estimates for each of these systems, especially the ocean thermal power system, are not of the level of reliability needed before commitments are made. However, those estimates that have been made clearly suggest an excellent competitive position for these processes, even without consideration of externalities.

Both windpower and ocean thermal systems can form an important base for a group of long-term pollution-free solar based energy systems. These two processes should be developed as the first real step in solving the global energy problem.

FOOTNOTES

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[1] NSF/NASA Solar Energy Panel, AN ASSESSMENT OF SOLAR ENERGY AS A NATIONAL ENERGY RESOURCE, at 46 (University of Maryland, Mechanical Engineering Department, 1972).

[2] O. Griffin, *Energy from the Ocean: An Appraisal*, NAVAL RESEARCH LABORATORY MEMORANDUM REPORT 2803, at 28 (1974).

[3] W. Clark, *Interest in Wind is Picking Up as Fuels Dwindle*, SMITHSONIAN, 71 (Nov. 1973).

[4] BUREAU OF POWER, FEDERAL POWER COMMISSION, STAFF REPORT ON WIND POWER, at 4 (Sept. 1973).

[5] *See* P.C. Putnam, POWER FROM THE WIND, (1948).

[6] *See* NSF/NASA WORKSHOP PROCEEDINGS *Wind Energy Conversion Systems*, (June 1973); SCIENCE, 184: 1055-58 (June 7, 1974).

[7] *See* W.E. Heronemus, *Power from the Offshore Winds*, PROCEEDINGS OF THE 8TH ANNUAL MARINE TECHNOLOGY SOCIETY CONFERENCE (1972); I.G. Dambolena, F.C. Kaminsky, and R.F. Rikkers, *A Planning Methodology for the Analysis and Design of Windpower Systems*, PROCEEDINGS OF 9TH INTERSOCIETY ENERGY CONVERSION ENGINEERING CONFERENCE, at 281 (1974) [hereinafter cited as

Damolena]; R.K. Swanson, C.C. Johnson, and R.T. Smith, *Windpower Development in the United States*, SOUTHWEST RESEARCH INSTITUTE SPECIAL REPORT (Feb. 17, 1974) [hereinafter cited as Johnson].

[8] Heronemus, *supra* note 7.

[9] World Meteorological Organization, *Energy from the Wind*, TECHNICAL NOTE No. 4 (Geneva, Switzerland, 1954); Heronemus, *supra* note 7, at 6.

[10] NSF/NASA Solar Energy Panel, *supra* note 1, at 69.

[11] W.G. Dupree, and J.A. West, UNITED STATES ENERGY NEEDS THROUGH THE YEAR 2000, (Department of the Interior, Dec. 1972).

[12] Dambolena, *supra* note 7.

[13] W.E. Heronemus, *Windpower: Look Backward, Then Move Forward Confidently*, IEEE WINTER ANNUAL MEETING PAPER, at 4 (Jan. 1974).

[14] W.E. Heronemus, *Oceanic and Atmospheric Energy Sources*, IEEE/WAS/WSE SOLAR ENERGY LECTURE VI, at 11 (April 18, 1974).

[15] Heronemus, *supra* note 7.

[16] W.E. Heronemus, *Windpower: Near-Term Partial Solution to Energy Crisis*, IEEE EASCON Meeting (Washington, D.C., Sept. 18, 1973).

[17] *See*, NYU COLLEGE OF ENGINEERING REPORT WPD 144, FINAL WIND TURBINE REPORT, NTIS PB25370 (1946); R.E., Chilcott, *The Design, Development and Testing of a Low-Cost 10 H.P. Windmill Prime Mover*, BRACE INSTITUTE PUBLICATION NO. MT7 (June 1970).

[18] NSF/NASA WORKSHOP PROCEEDINGS, *supra* note 6.

[19] Johnson, *supra* note 7.

[20] *See* Heronemus, *supra* note 7; Dambolena, *supra* note 7.

[21] The term "pressure balanced" means simply that the pressure on the volume of gas in storage is balanced exactly by the pressure of surrounding sea water. Thus costly containment vessels, such as steel gas cylinders, are avoided, being replaced by thin membranes.

[22] *The Hydrogen Economy - Miami Energy (THEME) Conference*, CONFERENCE PROCEEDINGS, (University of Miami, March 1974).

[23] I. Dambolena, *A Planning Methodology for the Analysis and Design of Windpower System*, Ph.D. Dissertation, University of Massachusetts (Jan. 1974).

[24] Personal Communication from the New England Energy Policy Staff, Boston, Massachusetts.

[25] Heronemus, *supra* note 7.

[26] Dambolena, *supra* note 23.

[27] A. D'ARSONVAL, L'REVUE SCIENTIFIQUE, at 370-372 (Sept. 17, 1881).

[28] G. Claude, *Power from the Tropical Seas*, 52 MECHANICAL ENGINEERING 1939 (Dec. 1930).

[29] Griffin, *supra* note 2, at 13.

[30] C. Beau and M.A. Nizery, 4 TRANSACTIONS OF THE FOURTH WORLD POWER CONFERENCE 2525 (1952); M.A. Nizery, BULLETIN DE L'INSTITUTE OCEANOGRAPHIQUE, No. 506 (Dec. 1946).

[31] J.H. Anderson, and J.H. Anderson, Jr., TECHNICAL REPORT NSF/RANN/SE/GI 34979/TR/73/5 (University of Massachusetts, March 1973); J.H. Anderson, and J.H. Anderson, Jr., *Large-Scale Sea Thermal Power*, AMERICAN SOCIETY OF MECHANICAL ENGINEERS PAPER No. 65-WA/SOL-6 (Dec. 1966).

[32] *See*, C. Zener, *Solar Sea Power*, PHYSICS TODAY (Jan. 1973); Zener, *et al.*, *Solar Sea Power*, NTIS PB228068, (Jan. 1974).

[33] *See*, J.G. McGowan, *et al.*, *Ocean Thermal Difference Power Plant Design*, AMERICAN SOCIETY OF MECHANICAL ENGINEERS PAPER No. 73-WA/OCT-5, (1973); Heronemus, *et al.*, *Research Applied to Ocean Sited Power Plants*, NTIS PB228070 (Jan. 1974).

[34] *Solar Sea Power Plant Conference and Workshop*, NSF WORKSHOP PROCEEDINGS, NTIS PB228066, (Sept. 1973).

[35] A. Lavi, and C. Zener, *Plumbing the Ocean Depths: A New Source of Power*, IEEE SPECTRUM, at 24 (Oct. 1973).

[36] Anderson and Anderson, *supra* note 31, at 14.

[37] Zener, *supra* note 32, at 52.

[38] W.J. Schmitz, and W.S. Richardson, *On The Transport of the Florida Current*, TRANSACTIONS OF THE AMERICAN GEOPHYSICAL UNION, (April 16, 1967).

[39] McGowan, *et al.*, *supra* note 34.

[40] W.J. Schmitz, and W.S. Richardson, *Data Report A Preliminary Report on Operation Strait Jacket*, Institute of Marine Sciences, University of Miami, NTIS AD802262 (1966).

[41] NSF WORKSHOP PROCEEDINGS, *supra* note 34.

[42] *See* McGowan, *supra* note 33; Heronemus, *supra* note 33.

[43] McGowan, *supra* note 33, at 1.

[44] Schmitz, *supra* note 40.

[45] J.G. McGowan, and J.W. Connell, *Heat Exchanger Design for Ocean Thermal Difference Power Plants*, AMERICAN SOCIETY OF MECHANICAL ENGINEERS PAPER No. 74-WA/OCT-4 (1974).

[46] "Static balance" is the condition existing when the weight of the system acting downward, the force of the displaced sea water

acting upward, the current-induced drag on the system acting in the direction of the current, and the opposing pull of the anchor, are all in equilibrium.

[47] McGowan, *supra* note 45, at 1.

[48] Anderson and Anderson, *supra* note 31.

[49] McGowan, *supra* note 33.

[50] G. Daric, *Schema de fonctionnement d'une centrale sous-marine equipression a fluide auxiliarire*, QUATRIEMES JOURNEES DE L'HYDRAULIQUE 694 (June 1956).

[51] E. Hughes, E. Dickson and R. Schmidt, *Control of Environmental Impacts from Advanced Energy Sources*, STANFORD RESEARCH INSTITUTE REPORT EPA-600/2-74-002 (March 1974).

[52] *Id.* at 153.

[53] *Id.* at 148.

[54] National Science Foundation Program Solicitation, *Ocean Thermal Energy Conversion,* at 5. (March 1974).

[55] *See*, D. Othmer, and O. Roels, *Power, Fresh Water, and Food from Cold, Deep Sea Water*, SCIENCE, 182: 121-25 (Oct. 12, 1973); H. Davitian, and W. McLean, *Power, Fresh Water, and Food from the Sea,* SCIENCE 184: 938 (May 31, 1974).

[56] National Science Foundation Program Solicitation, *Research on Wind Energy Conversion Systems* (1974).

[57] National Science Foundation Program Solicitation, *Ocean Thermal Energy Conversion* (1974).

[58] W.E. Heronemus, unpublished report to U.S. State Department, (Nov. 1974).

[59] One of the techniques used to protect consumers against loss of power should a portion of the on-line generating capacity suddenly become inoperative is to require that other standby or idling generators be kept "spinning", *i.e.*, up to speed, ready to take over that capacity before the load is lost.

[60] W.J.D. Escher, and J.A. Hanson, *Ocean Based Solar-to-Hydrogen Energy Conversion Macro System*, ETA PT-33 *Escher Technology Associates, Nov. 1973.*

[61] R. Ramakumar, H.J. Allison, and W.L. Hughes, *Prospects for Tapping Solar Energy on a Large Scale*, SOLAR ENERGY 16, No.2, at 107-115 (October 1974).

[62] Personal Communication, Dr. Ousmani, UNEP (Nov. 1974).

[63] Gillette, R., SCIENCE 184: 1053 (June 7, 1974).