

I. Minimum distance from coast to suitable SSPP location for countries that border warm tropical waters

Table with 2 columns: Country/Region and Distance, km. Lists countries bordering the Indian Ocean, Pacific Ocean, and Atlantic Ocean with their respective distances to a suitable SSPP location.

rents. Currents of 0.5 meter/second would prevent appreciable mixing in a 200 000-kW SSPP.

Environmental effects

Solar energy is probably the only pollution-free source of energy. Although its widespread use could lower the surface temperature of the tropical oceans, a tremendous amount of energy would have to be extracted in order to cause a noticeable effect.

Markets for SSPPs

The first market for SSPPs would probably be the local use of electric power in those countries bordering on tropical waters. Although such a market would be small, it would provide the necessary operating experience required for large-scale planning.

The second market for SSPPs would probably be for a power-intensive metallurgical industry which always develops wherever there is cheap electric power.

More than one half the bauxite reserves in the Americas are in Jamaica. Bauxite is mined in Jamaica by all the large U.S. aluminum-producing companies. They ship the ore to the Gulf Coast and then refine it into alumina (aluminum oxide).

Other large reserves of bauxite are also located in countries bordering tropical oceans—Ghana in Africa, Surinam and the Guianas in South America, and Australia. As shown in Table I, these countries are all located a considerable distance from the deep cold water required as a heat sink.

The third market for SSPPs is energy for use in the continental U.S. and in other locations in the temperate zone—Europe, U.S.S.R., and Japan. Since favorable sites for SSPPs are confined to the tropical oceans, how can generated power from SSPPs be used by these countries? A proposed method of transport-

Pure aluminum has the unique characteristic of forming a tightly clinging oxide coating which prevents the metal from contact with water. This is one of the positive electrochemical potentials, pure aluminum will not dissolve in sea water. The Aluminum Company of America has learned how to take advantage of this oxide coating on pure aluminum by bonding a layer of pure aluminum onto a high-strength aluminum alloy. Such a bonded structure is called Alclad. During the last several years, test data have been accumulated demonstrating that Alclad fittings would have a long service life in SSPPs. It should be noted that the tests were conducted at elevated temperatures of up to 80°C where corrosive elements are much more severe than at the ambient temperature of an SSPP.

All surfaces submerged in sea water soon become covered by a film of corrosion. This film would reduce the heat transfer characteristics of boiler surfaces. The Woods Hole Oceanographic Institute has found, however, that an extremely small concentration of chlorine—less than one part in ten million—will prevent such corrosion. Growth and is far below that required to kill marine life.

When chlorine gas is added to sea water, it forms hydrochloric acid which can also be formed directly by electrolysis of sea water. The electric power required for the electrolysis is a small fraction of that generated by an SSPP. This electrolysis could take place in the intake pipes of an SSPP. In fact, such electrolytic equipment has already been developed for use in the intake condenser pipes for power plants located on sea coasts.

The problem of SSPP from adverse weather conditions must be recognized and analyzed as that of an oceanic structure. This is not an easy task, but it is a location in which the SSPP will probably require careful attention so that they can be located in a permanent structure attached to the ocean bottom. Since the power plant will be powered, the structure need not support the weight of the plant. It should merely withstand the drift current. In order to have easy access to the cold ocean water, the site must be selected where the ocean floor slopes away from the plant. When the SSPP is anchored, such ocean-floor conditions are common in the tropical oceans.

Because of the low engine efficiency in an SSPP, immense volumes of water must be processed to generate any appreciable amount of power and it takes power to pump the water—about one-third the gross power generated. Optimization studies have shown that this ratio is independent of the temperature differential between the heat source and heat sink. The important factor is the fuel cost and not plant efficiency. If the water is pumped, the cost is the same. If the water is pumped, the cost is the same. If the water is pumped, the cost is the same.

Even with the boiling problem solved, the SSPP temperature differential might seem to create a cost handicap because it leads to a low efficiency—about 30 percent—compared to nearly 50 percent in a conventional plant. For a given kilowatt output, the SSPP boiler must process more than ten times as much water as the boiler in a conventional plant. In fact, the SSPP boiler tube area must be more than ten times greater than that in a conventional plant. Although this requirement would seem to necessitate excessive cost, two basic physical phenomena enter the picture that tend to offset any cost increase and may even permit a cost decrease.

The first phenomenon is that the vapor pressure in a working medium rises rapidly as its temperature increases. The pressure increase must be offset by a corresponding increase in thickness of the boiler tubes. Since in an SSPP the maximum pressure is reported to be only about 150 psi (about one million W/gal compared to 2500 psi (about 25 million W/gal) in conventional steam boilers, much thinner boiler tubes can be used.

The second phenomenon is the decrease in strength of metals with a rise in temperature. In a conventional boiler, must be offset by an increased wall thickness or by the use of expensive alloys. Again, an SSPP benefits because the temperature in the boiler is small compared to those in conventional plants. The increase in cost of boiler tubes because of the use of these phenomena—or both—in conventional plants can be nearly catastrophic. For example, in the mid 1960s, the Edgewater power station was constructed in Philadelphia with a cost to peak temperature of 600°C. The drastically increased cost of the station required by the higher temperature was the main show for plants above 500°C.

Because of the electric conductivity of sea water, metallic structures submerged in the ocean suffer electrolytic corrosion. A quantitative measure of the tendency of a metal to dissolve in water is its electrochemical potential. These metals with a positive potential will dissolve spontaneously with the evolution of hydrogen. Those with a negative potential will not. Inexpensive metals such as iron have a positive potential while only expensive metals such as copper, silver, and gold have negative potentials.

ing energy from SSPPs is tied in with the so-called hydrogen economy.

The hydrogen economy

While electric power can be useful in many ways, an all electric economy is not feasible for several reasons. First, the cost of transmission is too high. On a BTU or kWh basis, it costs more to transmit electric energy over a long distance than to ship fuel through a pipeline. Second, electric energy cannot be stored

as efficiently as fuel. Third, there are many applications—notably, transportation and industrial processes—where fuel is irreplaceable. These observations have led to the concept of the hydrogen economy.¹⁰

The basic idea in a hydrogen economy is to generate electricity by ringing the U.S. shores with floating nuclear power plants. Since a large percentage of the U.S. population is located within 150 kilometers of water fronts, all electric energy needs could then be

How a solar sea plant works and what it costs

The basic components of a solar sea power plant are shown in the accompanying illustration. Operation of the plant is as follows:

Warm water is pumped into the boiler to boil the working fluid—a fluid that boils at ambient temperature under moderately high pressure. Ammonia is indicated in the illustration as the working fluid. It meets most of the requirements for a low-temperature-difference cycle. But ammonia does present other problems that might preclude its use in favor of freon, propane, or a number of other substances.

The ammonia gas under "high pressure" is fed into a turbine-generator and is discharged at "low pressure" into the condenser, which also receives cold water from the deep ocean. Ammonia liquid at low pressure from the condenser is then pressurized and pumped to the boiler. The cycle is then repeated.

The total temperature difference between warm and cold water is about 20°C. It must be allocated optimally among the boiler, the turbine-generator, and the condenser. In the boiler, heat must flow from the water to the boiler tubes and then to the working fluid. A similar heat flow takes place in the condenser.

The manner in which the available 20°C is divided among the boiler, turbine-generator, and condenser influences the overall cost of a power plant. If, for example, 10°C is allocated to the heat exchangers in the boiler and in the condenser, the Carnot efficiency is only 3.3 percent. With such low efficiency, the boiler and condenser must process enormous volumes of water. If conventional heat-exchange technology had to be used, the cost would be prohibitive. By being able to install the boiler and condenser underwater at convenient depths where water pressure on the outside can equalize internal pressures, construction can be relatively "flimsy" with thin tubes throughout. This construction has the double advantage of enhancing heat conduction on the one hand and drastically reducing cost on the other. Anderson and Anderson³ have proposed such an installation where the boiler is placed below the condenser by a few hundred feet so as to equalize the pressure on each unit. In a practical design, one must weigh the economy versus

the resultant increase in water pumping and overall system complexities.

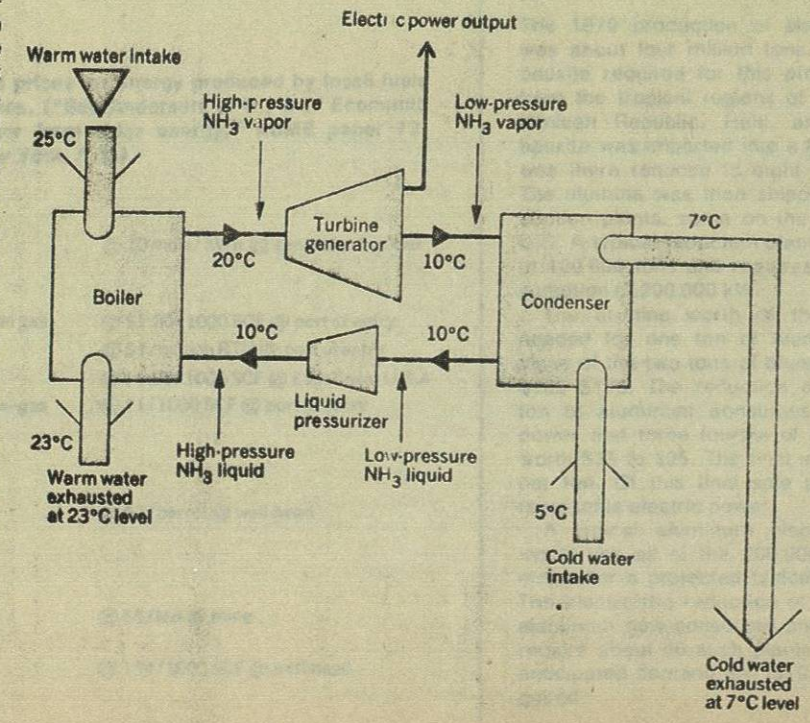
With specially prepared heat transfer surfaces—controlled roughness on the water side, vapor traps on the boiling surface, and vertical corrugation on the condensing surface—heat transfer coefficients as high as 2000 BTU/h-ft²·°F or 12 kW/m²·°C may be obtained. With this technique, boiler plus condenser costs should not exceed \$30 per kilowatt.

A complete breakdown of power-plant costs beyond the early experimental units has been detailed by Anderson. The accompanying table compares the generation costs of SSPP with conventional and nuclear power plants.

Generation cost comparison

Energy Source	Capital (\$/kW)	Fuel (mills/kWh)	Total (mills/kWh)
SSPP*	165	0	3
Fossil fuel	300-360	4	10-11
Nuclear	500**	2	12**
Breeder	500	1	11

*These figures appear optimistic and require close reexamination.
**Latest figures according to NUS Corp. See *The New York Times*, Nov. 26, 1977, p. 1.



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The total temperature differential between warm and cold water is about 20°C. It must be allocated optimally among the boiler, the turbine-generator, and the condenser. In the boiler, the low boiling liquid is heated to the boiling point and then to the working fluid. A smaller heat exchanger is placed in the condenser.

The manner in which the working fluid is divided among the boiler, turbine-generator, and condenser determines the overall cost of a power plant. If, for example, 10°C is allocated to the heat exchanger in the boiler and in the condenser, the Carnot efficiency is only 3.3 percent. With such low efficiency, the boiler and condenser must process enormous volumes of water. If conventional heat-exchange technology is used, the cost would be prohibitive. By using a low boiling liquid, the boiler and condenser can be made much smaller and the cost of the heat exchangers can be reduced. This is the advantage of using a low boiling liquid.

Construction of the plant is a major task and directly impacts the cost of the plant. Anderson and Anderson have proposed a modular design for the plant. Each module is a self-contained unit that can be installed in a body of water. The modules are connected to a common power line and can be expanded or reduced in size as needed.

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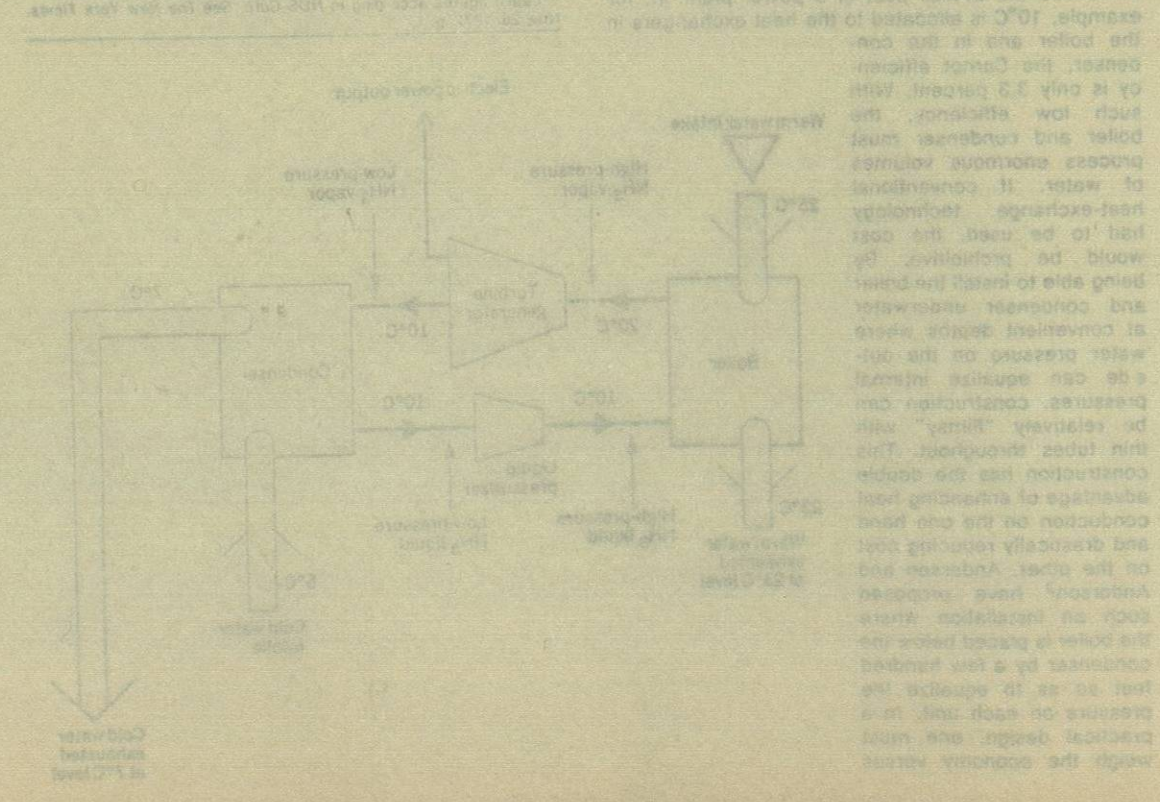
The manner in which the working fluid is divided among the boiler, turbine-generator, and condenser determines the overall cost of a power plant. If, for example, 10°C is allocated to the heat exchanger in the boiler and in the condenser, the Carnot efficiency is only 3.3 percent. With such low efficiency, the boiler and condenser must process enormous volumes of water. If conventional heat-exchange technology is used, the cost would be prohibitive. By using a low boiling liquid, the boiler and condenser can be made much smaller and the cost of the heat exchangers can be reduced. This is the advantage of using a low boiling liquid.

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Cost Source	Capital (\$/kW)	Fuel (mills/kWh)	Total (mills/kWh)
GSP*	100	0	100
Fossil fuel	300-500	2-4	300-500
Nuclear	500*	2	500*
Hydro	500	11	500

*Based on a 10% discount rate and a 20-year life.



met directly. Furthermore, by using electric current to electrolyze desalinated sea water, hydrogen could be produced and shipped or piped inland for various uses. (It might be necessary to produce and ship liquid ammonia which would then be separated into hydrogen and nitrogen before use as a fuel.)

If a hydrogen economy is indeed desirable and economically feasible, then why not use solar energy to produce the hydrogen? Figure 2 illustrates how it could be done. It is estimated that the cost of producing hydrogen by solar sea power would be \$1.28 per million BTU.

Hydrogen may be the most desirable form of fuel for electric power generation, residential and commercial heating, industry, and transportation—the four main uses for fuel.

In electric power generation within metropolitan areas, the use of hydrogen and oxygen in place of fossil fuels could reduce the cost of electric power by at least 50 percent. If hydrogen and oxygen are already pressurized, it is more efficient and economical to use an open-cycle process rather than a closed one. By burning pressurized hydrogen and oxygen in a com-

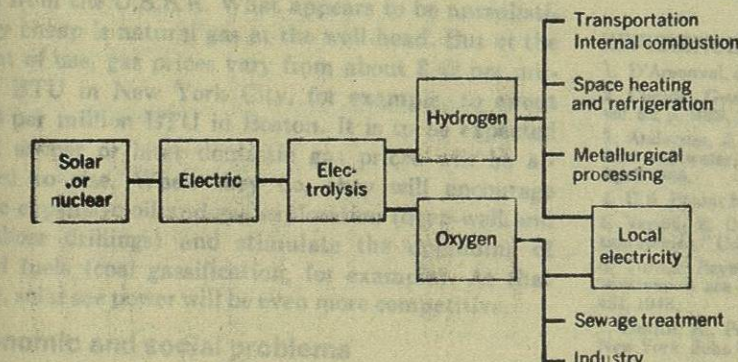
bustion chamber rather than in a boiler, high-pressure superheated steam is generated and fed directly into the turbine. This technique eliminates one half the capital cost of a power station and results in no chemical pollutants. Therefore, power stations could be located in the vicinity of residential and commercial loads with the result that most of the power transmission costs would be eliminated. Another advantage of locating the power plants within a city would be that the rejected heat, in the form of exhaust superheated steam, could be distributed to heat residential and commercial buildings. Heating of these buildings using natural gas, petroleum, and coal constitutes 18 percent of the total fuel consumption in the U.S.

The fact that hydrogen burns cleanly, and reacts completely with oxygen to produce water, makes it a more desirable fuel than fossil fuels for most industrial processes. One example is the direct reduction of iron ores by hydrogen rather than by coal in a blast furnace.

Hydrogen also has many attractive features as a fuel for internal combustion engines for transportation. Its light weight compared to kerosene or other aircraft fuels would enable aircraft to have from two to three times their present range. And the absence of pollution when hydrogen is burned would provide an answer to the problem of eliminating automobile pollution.

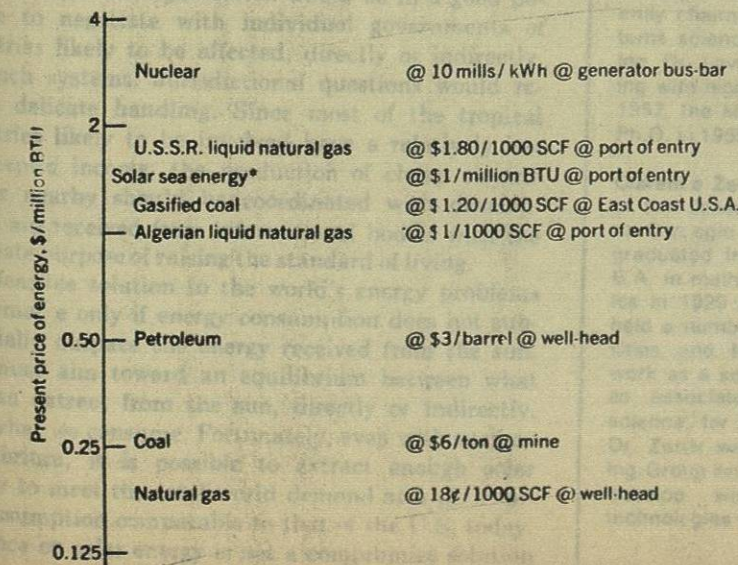
What about comparative costs?

It is interesting to compare costs of the various common energy sources with that of solar sea power as is done in Fig. 3. Costs vary from \$1.18 per million BTU for natural gas at the well-head to \$3 per million BTU for nuclear energy at the generator bus bar.



[2] Basic elements of a hydrogen economy system.

[3] Comparative prices for energy produced by fossil fuels and other sources. (*See Anderson, J. H., Jr., "Economic power and water from solar energy," ASME paper 72-WA/SOL-2, New York, N.Y.)



Electric power and the production of aluminum

The 1970 production of aluminum within the U.S. was about four million tons. The 16 million tons of bauxite required for this production came primarily from the tropical regions of Jamaica, Surinam, Dominican Republic, Haiti, and British Guiana. The bauxite was imported into a few Gulf Coast ports and was there reduced to eight million tons of alumina. The alumina was then shipped to 30 electrolytic reduction plants, some on the Northwest coast of the U.S. A typical reduction plant has an annual capacity of 100 000 tons and requires an electric power consumption of 200 000 kW.

The at-mine worth of the four tons of bauxite needed for one ton of aluminum is \$20-\$30. The value of the two tons of alumina derived therefrom is \$100-\$130. The reduction of this alumina into one ton of aluminum consumes \$90 worth of electric power and three fourths of one ton of pure carbon worth \$35 to \$95. The final ingot sells for about \$520 per ton. Of this final sale price, about 17 percent represents electric power.

A typical aluminum electrolytic reduction plant would use all of the 200 000-kW anticipated power output for a projected typical solar sea power plant. The electrolytic reduction of the four million tons of aluminum now consumed annually in the U.S. would require about 40 such plants. In order to supply the anticipated demand for 1970, 80 plants would be required.

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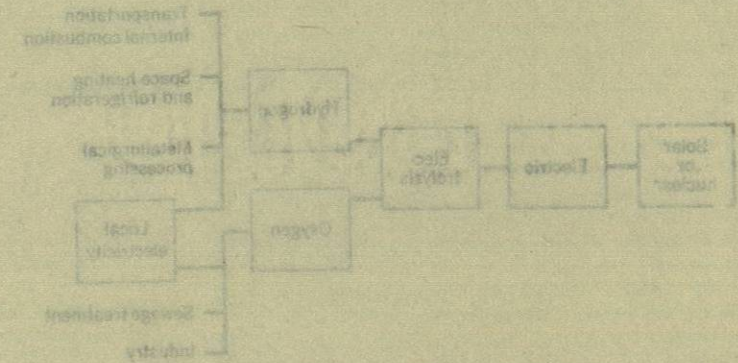
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most directly. Furthermore, by using electric current to electrolyze sea water, hydrogen could be produced and shipped or piped inland for various uses. It might be necessary to produce and ship liquid hydrogen which would then be separated into hydrogen and nitrogen before use as a fuel.

If a hydrogen economy is indeed desirable and economically feasible, then why not use solar energy to produce the hydrogen? Figure 3 illustrates how it could be done. It is estimated that the cost of producing hydrogen by solar sea power would be \$2.35 per million BTU.

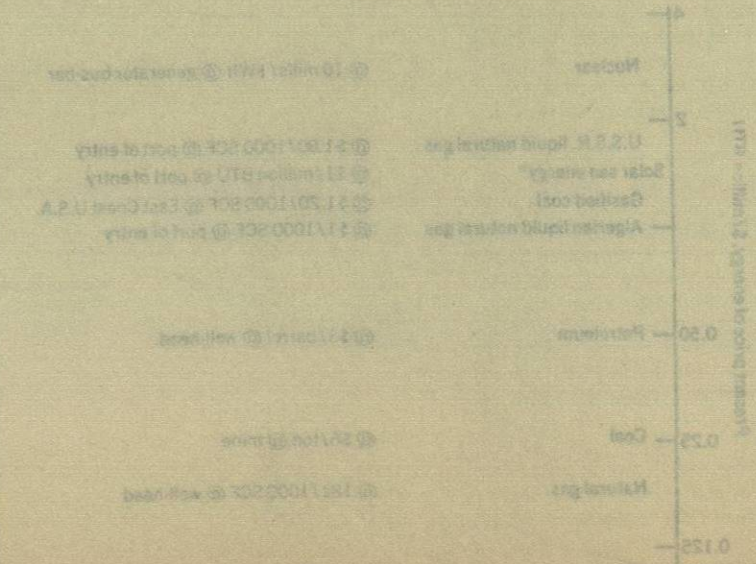
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The 1950 production of aluminum within the U.S. was about four million tons. The 16 million tons of bauxite required for the production of aluminum comes from the tropical regions of Jamaica, Surinam, Guyana, French Guiana, and other countries. The bauxite was shipped to the Gulf Coast ports and was then refined to high-purity alumina. The alumina was then shipped to West Virginia for electrolysis. Some of the electrolytic cells in the U.S. A typical electrolytic plant has an annual capacity of 100,000 tons and requires an electric power consumption of 200,000 kW.

The alumina yield of the last two years of alumina needed for one ton of aluminum is 2.5-3.0 tons. The value of the alumina is about \$100 per ton. The reduction of alumina into one ton of aluminum consumes 250,000 kWh of electric power and three tons of one ton of pure carbon worth \$50 to \$60. The last two years of alumina per ton of aluminum cost about 15 percent of the cost of electric power.

A typical aluminum electrolytic reduction plant would use all of the 200,000-KW anticipated power output for a projected typical solar sea power plant. The electrolytic reduction of the two million tons of alumina now consumed annually in the U.S. would require about 40 such plants. In order to supply the anticipated demand for 1970, 80 plants would be required.

A perspective on solar sea power

With the many alternatives to conventional power sources under consideration, it is interesting to attempt to find where solar sea power fits into the scheme of things. One strong clue is the National Science Foundation. It is active in a number of energy programs and has more than one half of its total energy funds devoted to terrestrial solar energy programs during FY1973 and FY1974.

Five-year goals and plans have been formulated by NSF for each of the following application areas: solar energy for buildings, solar thermal conversion, photovoltaic conversion, conversion of organic materials, photosynthetic production, wind energy conversion, and ocean thermal difference conversion. In FY 1973 wind energy conversion and ocean thermal conversion research received about \$200,000 each out of a total budget of \$3.8 million. The budget estimate for FY 1974 funding is \$600,000 for ocean thermal energy conversion out of a total solar energy budget estimate of \$12.2 million.

The five-year goal for solar sea power is component and subsystem proof-of-concept experiments under simulated or actual sea conditions. There will

be systems studies and optimizations to identify the most economical systems. A system definition and component and system preliminary design project on ocean temperature differences is presently sponsored by NSF/RANN at the University of Massachusetts. This project also includes cooperation of the firm of J. Hilbert Anderson and the United Aircraft Research Laboratories. Another project has been initiated at Carnegie-Mellon University to develop computer-based analytic models for technical and economic analyses of components and subsystems of the most important approaches to solar sea power systems.

At a conference on solar sea power at Carnegie-Mellon University in late June of this year, sponsored by NSF and organized by Professor Lavi, several technical sessions and workshop sessions were held. The workshop on power-plant siting recommended that either the Island of Hawaii or St. Croix in the Caribbean be used as the site for a small prototype solar sea power plant (1 to 10 MW) to prove the concept. The next move is up to NSF.—

R. K. Jurgen

Based on these estimates, solar sea power appears to be competitive with liquefied natural gas from Algeria and from the U.S.S.R. What appears to be unrealistically cheap is natural gas at the well-head. But at the point of use, gas prices vary from about \$.42 per million BTU in New York City, for example, to about \$.70 per million BTU in Boston. It is to be expected that sooner or later domestic gas prices will be allowed to rise. When they do, they will encourage more expensive oil and gas exploration (deep-well and off-shore drillings) and stimulate the upgrading of fossil fuels (coal gasification, for example). At that time, solar sea power will be even more competitive.

Economic and social problems

The nontechnical problems in implementing a solar sea power system—ranging from financing to international relations—deserve even a higher priority than design, testing, and manufacturing.

It seems desirable to have a Government organization sponsor the development of solar sea power systems. Government-backed financing might also be needed. Such an organization would be in a good position to negotiate with individual governments of countries likely to be affected, directly or indirectly, by such systems. Jurisdictional questions would require delicate handling. Since most of the tropical countries likely to be involved have a relatively low per capita income, the production of cheap electric power nearby should be coordinated with development aid received from international bodies with the ultimate purpose of raising the standard of living.

A feasible solution to the world's energy problems will emerge only if energy consumption does not substantially outpace the energy received from the sun. We must aim toward an equilibrium between what we can extract from the sun, directly or indirectly, and what we consume. Fortunately, even with such an equilibrium, it is possible to extract enough solar energy to meet the total world demand at a per capita consumption comparable to that of the U.S. today. Reliance on solar energy is not a compromise solution

but a sound objective to be pursued in earnest. It deserves far more attention that it has thus far received.

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Abraham Lavi has been a member of the faculty of Carnegie-Mellon University since 1959. He is presently chairman of a university-wide program on systems sciences and professor of electrical engineering. Dr. Lavi received the B.S. in electrical engineering with highest distinction from Purdue University in 1957, the M.S. in 1958 from that university, and the Ph.D. in 1959 from Carnegie Institute of Technology.

Clarence Zener, perhaps best known as the inventor of the Zener diode, has been a university professor at Carnegie-Mellon University since 1968. He was graduated from Stanford University in 1926 with a B.A. in mathematics and received his Ph.D. in physics in 1929 from Harvard University. Dr. Zener has held a number of faculty positions at various universities and his nonacademic career has included work as a senior physicist at Watertown Arsenal and as associate director, director, and director of science for Westinghouse Research Laboratories. Dr. Zener was appointed recently to the U.S. Working Group on Solar Energy which has been set up to develop working relationships in solar-energy technologies with the U.S.S.R.