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. For example, if the world population in the year 2000 were to be supplied by energy from SSPPs at the present per capita rate of consumption in the U.S., the surface temperature of the tropical oceans would be lowered by less than one degree Celsius.

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. Table I lists those countries whose coastal waters have the year-round thermal characteristics required by SSPPs and gives the distance, in kilometers, from land to an ocean depth where the water is sufficiently cold (5°C) to be suitable as a heat sink. It is noteworthy that the tropical waters closest to the U.S.—the Caribbean—are unique in having cold deep water within two kilometers of the coast of most of the bordering countries.

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

More than one half the bauxite reserves in the Americas are in Jamaica.[8] Bauxite is mined in Jamaica by all the large U.S. aluminum-producing companies. They ship the ore to the Gulf Coast and there refine it into alumina (aluminum oxide). The alumina is then shipped to all parts of the U.S. where electric power is cheap. Some is even shipped back into the Caribbean, through the Panama Canal, and then up the West Coast of the U.S. to cheap hydroelectric power in the state of Washington. Since Jamaica could enjoy an abundance of cheap electric power generated by SSPPs, a more economical process would be the refining of bauxite into alumina and the electrolytic reduction of alumina into metallic aluminum on the island itself. (For a detailed analysis of costs in producing aluminum, see the editorial box on page 26.)

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. This situation might lead to a third stage in the marketing of electric power from SSPPs with the development of floating metallurgical complexes, as described by Willy Ley.[9]

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-

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

	Distance, km
Countries bordering Indian Ocean (clockwise order):	
Madagascar	32
Mozambique	25
Tanzania	25
Kenya	25
Somali Republic	25
Southern Yemen	32
Muscat and Oman	6
Iran	32
Pakistan	32
India:	
West Coast	120
East Coast	65
Burma	75
Countries bordering Pacific Ocean (clockwise order):	
Hawaii	10
Mexico	25
Guatemala	32
El Salvador	65
Honduras	75
Nicaragua	95
Costa Rica	7
Panama	25
Columbia	25
Ecuador	25
Australia:	
Northeast corner	65
Otherwise	300
New Guinea	5
Java	5
Philippines	5
Vietnam	75
Sumatra	50
Countries bordering Atlantic Ocean (clockwise order):	
Sierra Leone	50
Liberia	50
Côte d'Ivory	50
Ghana	50
Dahomey	50
Cameroun	65
Brazil:	
1° to 20° South	15
Otherwise	100
French Guiana	130
Surinam	130
English Guiana	130
Venezula	3
Columbia	32
Panama	25
Costa Rica	15
Nicaragua	150
Honduras	24
Mexico	7
United States of America:	
Florida	1
Puerto Rico	6
Cuba	2
Jamaica	2
Haiti	2
Dominican Republic	2
Guadeloupe (French)	2
Dominica (British[2])	5
Martinique (French)	2
St. Lucia (British[1])	2
St. Vincent (British[1])	2
Grenada (British[2])	2

[1] Distance to 5°C water at 500 meters.

[2] Freely associated with Britain.

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 Anderson[3] 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.

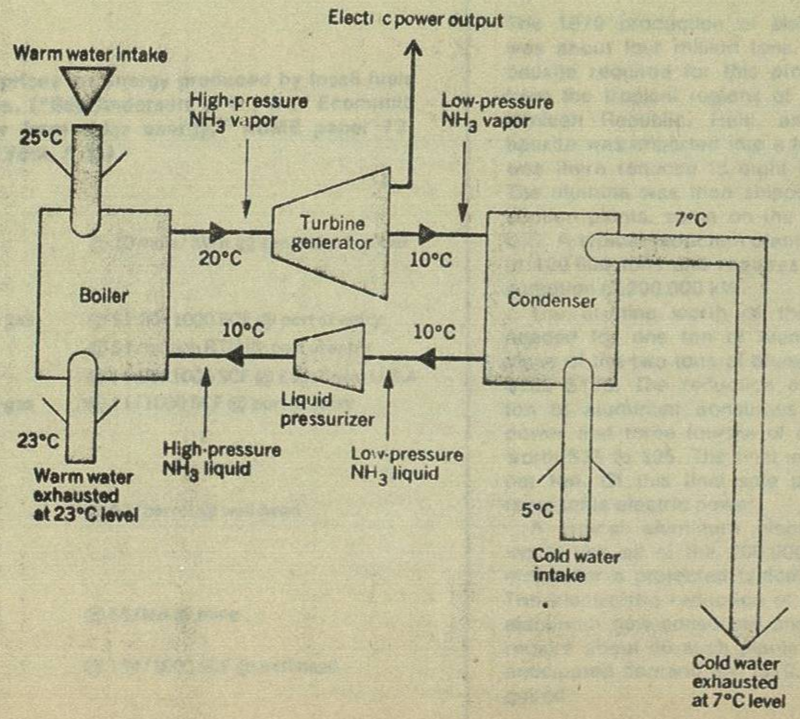
With specially prepared heat transfer surfaces—controlled roughness on the water side, vapor traps on the boiling surface, and vertical corrugation on the condensing surface—heat transfer coefficients as high as 2000 BTU/h·ft²·°F or 12 kW/m²·°C may be obtained. With this technique, boiler plus condenser 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, 1972, p. 1.

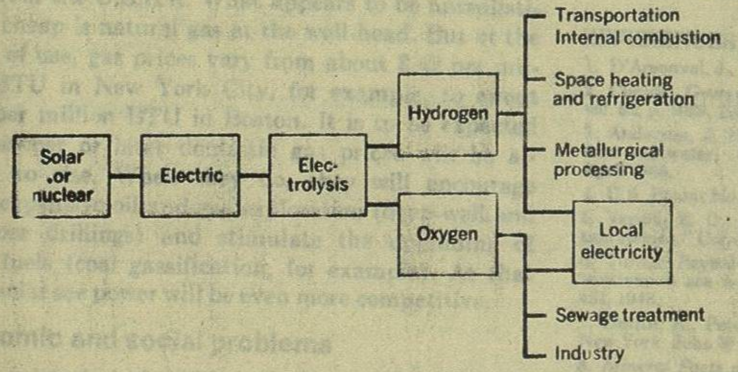


met directly. Furthermore, by using electric current to electrolyze desalinated sea water, hydrogen could be produced and shipped or piped inland for various uses. (It might be necessary to produce and ship liquid ammonia which would then be separated into hydrogen and nitrogen before use as a fuel.)

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 combustion 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.



[2] Basic elements of a hydrogen economy system.

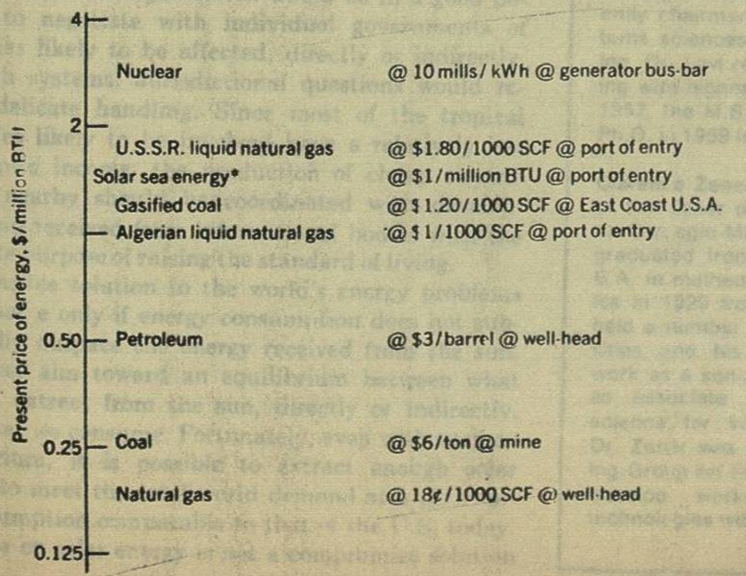
The fact that hydrogen burns cleanly, and reacts completely with oxygen to produce water, makes it a more desirable fuel than fossil fuels for most industrial processes. One example is the direct reduction of iron ores by hydrogen rather than by coal in a blast furnace.

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 $.18 per million BTU for natural gas at the well-head to $3 per million BTU for nuclear energy at the generator bus bar.

[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.

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 gassification, 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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