Thermal Power from the Ocean – A Techno-Economic Perspective

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Every day the oceans receive and store vast amounts of direct sunshine energy and are therefore relatively warmer in the surface layers than in the interior. The consequent density difference sustains this thermal gradient, which in the tropics can be as large as 25°C between the surface and a thousand metres below. A typical temperature profile in tropical seas is shown in Fig. 1. Given the magnitude of the oceans and the fact that the surface water temperature is continually maintained by the sun's radiation, this thermal gradient in the aquasphere constitutes a huge and inexhaustible solar thermal resource, which is free from the inconvenient intermittence of direct solar radiation. It is estimated that harvesting even one-thousandth of the total thermal energy of the oceans would suffice to meet wholly the world's future energy needs.

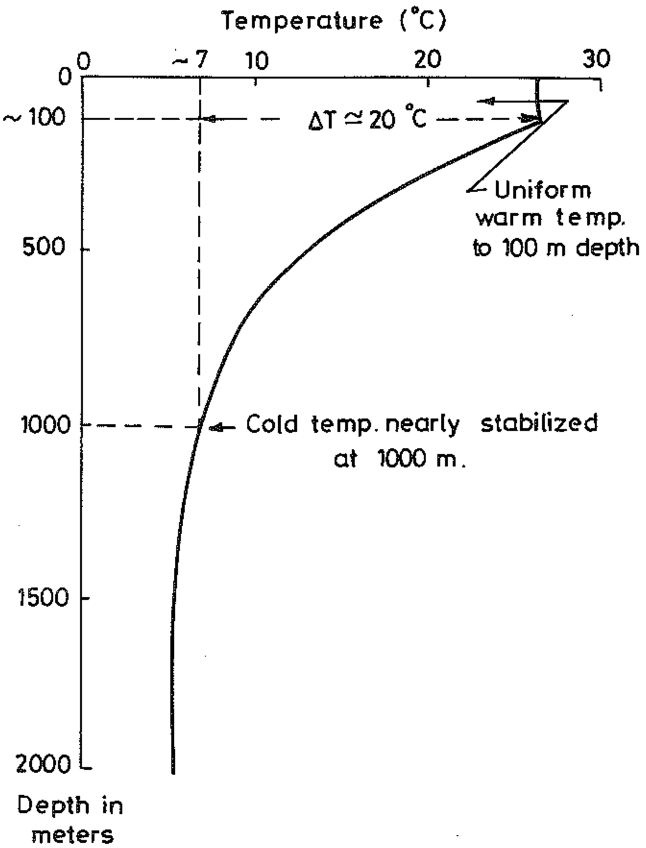

Fig. 1. A typical temperature profile in the tropical seas

Almost exactly a hundred years ago, D'Arsonval (1881) suggested that significant amounts of power could be generated by a heat engine using the warm surface water as the 'heat-source' and cold water pumped from deep below as the 'heat sink'. This, really, was the origin of the ocean thermal energy conversion (OTEC) concept, which was later verified experimentally by Claude (1930) using the waters around Cuba. Using an 'open cycle' plant in which water vapour from flash-evaporated sea water drove a turbine followed by a condenser for the discharge, Claude actually accomplished a conversion; but the power thus generated was hardly sufficient to drive the plant's over-sized pumping system. As a result it consumed more power than it produced.

The proposal was revived more forcefully by Anderson and Anderson Jr. who, in 1964, presented a highly optimistic theoretical study detailing the use of Rankine cycle engines, with propane as the working fluid, for massive power-generation from ocean thermal gradients. They estimated that the existing thermal gradients in the Gulf Stream alone would suffice to generate about 200 TWh (e) annually, which is nearly ten times the estimated total US thermal energy requirement for 1980. The OTEC concept received further support from Zener (1973, 1974) who favoured ammonia as the Rankine engine fluid and also suggested the conversion of the electrical energy produced into hydrogen and oxygen for transmission or transport to the mainland users. OTEC also figured in the proposals of Heronemus (1973, 1974) for ocean-based power plants.

The original dream concept of d'Arsonval has thus matured into a viable scheme for establishing large seabased power plants to convert stored sunshine into useful power, without taking up any land area, causing any hurt to the environment, or needing technological solar collection devices, as the ocean itself serves as a huge thermal reservoir.

THE OTEC TECHNIQUE:

Two types of OTEC plants are possible: the closed cycle Rankine engine and the open cycle Rankine engine.

The closed cycle OTEC power system closely resembles a refrigeration system working in the reverse. The temperatures encountered in a OTEC power plant are relatively low, and the pressures far below those employed in most power plants.

A schematic diagram of the outfit proposed by the Andersons to generate 100 MW(e) and the Rankine-cycle engine that is part of it, are shown in Figures 2 and 3 respectively.

The main components of an OTEC plant are the two heat exchangers (evaporator and condenser), the turbine and power-cycle components, the cold water pipe, the hull or platform on which the power-plant is erected, and its mooring or positioning arrangements.

For the working fluid, any refrigerant which can be vaporized at the available warm water temperature and condensed at the available cold water temperature can be used, provided it satisfies the criteria of overall power system economics, safety to personnel, and environmental considerations. Among the few refrigerant fluids available presently, anhydrous ammonia scores over others because of its low cost, good heat transfer characteristics, high latent heat of vaporization, low explosivity, and minimal adverse effects in the event of a major leak into the ocean.

Warm surface water is pumped through the evaporator (boiler) to generate ammonia vapour at *ca.* 10 atmospheres pressure. Cold water is pumped from a depth of *ca.* 1000 metres through the condenser to condense the ammonia vapour. The high pressure vapour from the evaporator flows through a liquid separator and then expands to condenser pressure in a turbine. In the

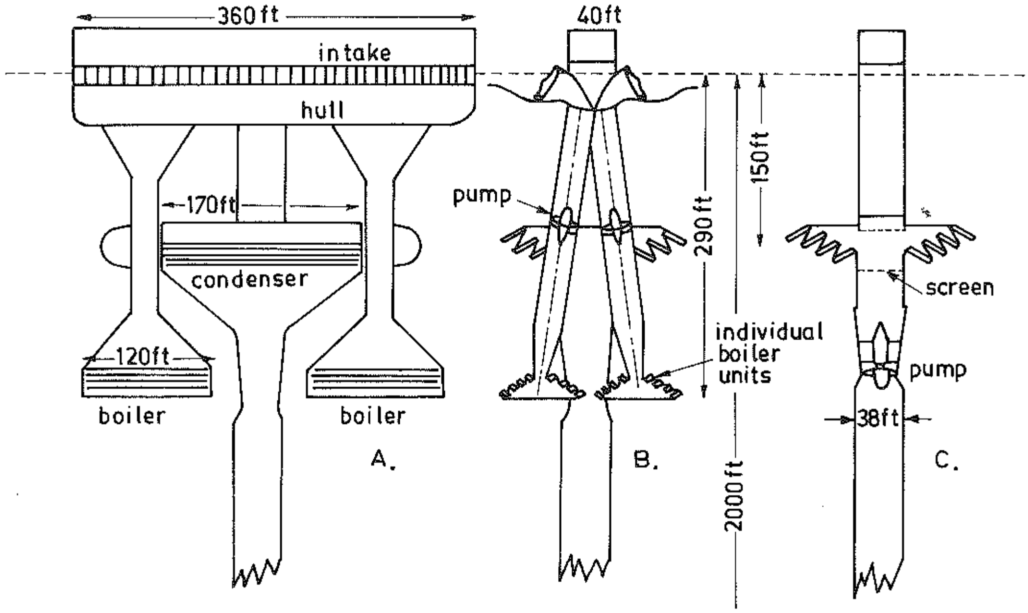

Fig. 2. Schematic diagram of the Andersons' OTEC plant

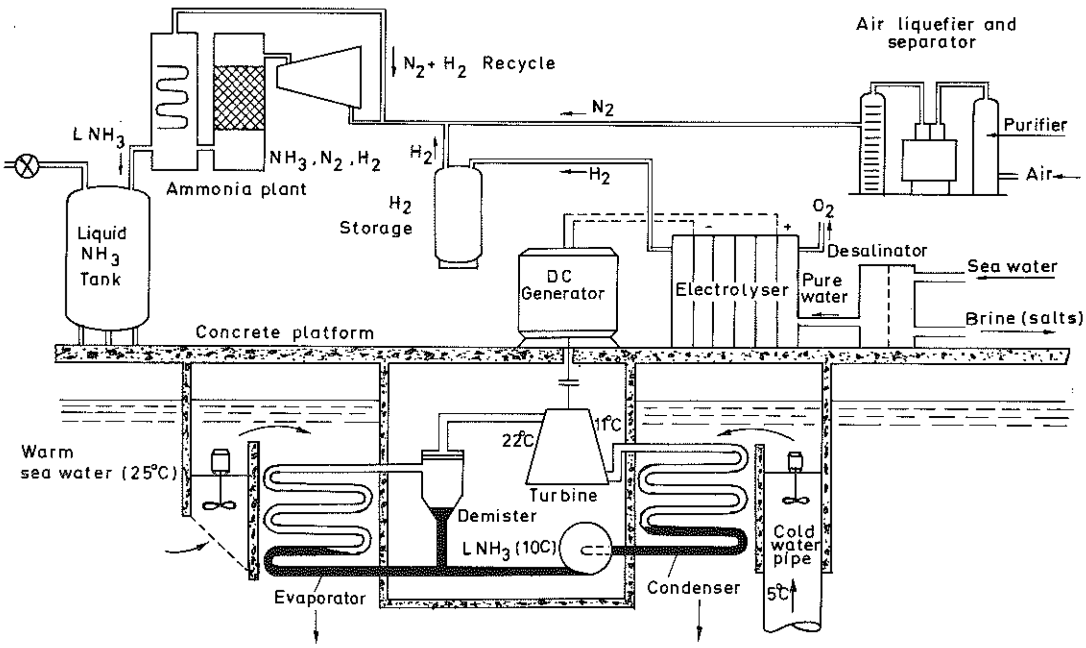

Fig. 3. The OTEC power plant with integrated ammonia plant

process, the enthalpy of the vapor is converted into mechanical energy by the intervening turbine. The low pressure vapour from the turbine is condensed in the condenser. The condensate is pressurized and returned to the boiler to close the cycle. A recycle pump is used to recycle the liquid ammonia from the liquid separator into the system. The pumps are all actuated by vapour turbines located within the pumphubs. The entire system is bouyant with internal and ambient pressure differentials of about 1 atmosphere.

The upper part of Figure 3 depicts a self-contained integrated plant for the production of ammonia, which is one of the alternative modes of transmission of OTEC power. This is discussed later.

It is claimed that in a well designed unit, the thermal-to-mechanical energy conversion can be accomplished with an efficiency approaching the theoretical Carnot efficiency (6 to 7.5%) depending on the respective warm and cold water temperatures – the main efficiency eroding factor being the inevitable temperature drops occurring in the heat exchangers. Nearly a third of the energy produced is internally consumed in running the pumps and other ancillary accessories, leaving a net surplus conversion efficiency of 2-2.5 %, i.e. roughly one-third of the theoretical Carnot efficiency. Though this is indeed very low compared with the 30-35 % efficiency routinely available with fossil/nuclear fueled power plants, the compensating feature of OTEC is that its fuel is free of cost and unlimited.

While most OTEC development efforts currently in progress focus on the closed Rankine cycle, just described, there is at least one serious effort to revive the old open cycle concept of Claude, and this is from Westinghouse of USA (Coleman, in Lavi, 1980). Here, warm sea water is drawn into a flash evaporator and the steam generated therein drives the turbine-generator and passes on to the condenser where the vapour is condensed by the cold seawater drawn from down below. Non-condensable gases (mainly air and carbon dioxide dissolved in the seawater) released

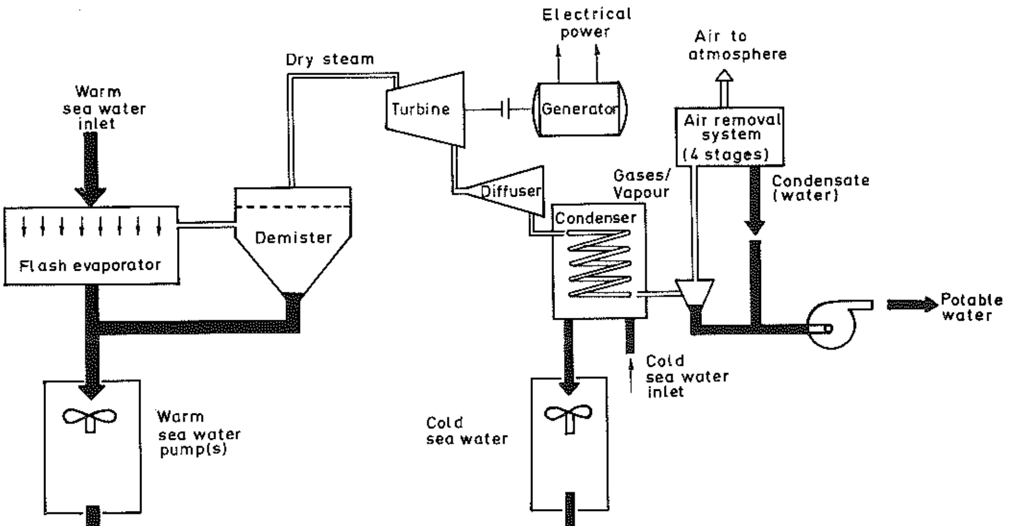

Fig. 4. Open cycle OTEC (schematic)

in the evaporator, are also entrained with the steam and ultimately discharged through the condenser to maintain low pressure of operation. In such open cycle systems, expansion takes place typically from a pressure of 0.03 atm. to 0.02 atm. At these low pressures, the specific volume of vapour is quite large. This gives rise to an enormous size of the turbine-generator, working at low speeds, and for the flash evaporator. These, in turn, require a large platform structure. Fig. 4 gives a schematic presentation of the Westinghouse open cycle OTEC plant which has now advanced through the conceptual design stage.

Because of the low-quality heat content of the warm water (heat source), an ocean thermal power plant will need huge quantities of sea-water to be circulated through it to get the required amount of heat input. It amounts to nearly 80 m^3 per second for a 100 MW(e) plant, which is several times the cooling water flow-rates required for land based fossil-fueled thermal power plants of equal capacity. This is a major engineering challenge. Except for this item (which no doubt is very important), the technology required for OTEC is relatively low-level. That is, no major scientific or technological breakthroughs are called for (although some are expected); and the basic technology is presently intrinsically available to enable the construction of commercial size ocean thermal power plants, though undoubtedly current technologies and materials will require modification and upgrading in a number of areas to suit the particular requirements of OTEC plants.

The major engineering challenges of OTEC technology are mainly in the following areas:

1. *The heat exchangers:* The heat exchangers constitute the heart of the 'OTEC' plant and represent ¼ to ½ of total plant costs. The mean temperature differences ΔT_m, between the sea water and working fluid are quite small (about 4 to 5°C) and therefore large areas of heat transfer $A = Q/U \cdot \Delta T_m$. are required (typically, of the order of 5-8 m^2/kWe net). The overall heat transfer coefficient, U, is given by the expression

$$\frac{1}{UA} = \frac{1}{h_r A_r} + \frac{x}{K A_m} + R_f + \frac{1}{h_w A_w},$$

where

h_r	=	heat transfer coefficient of the working fluid
x	=	tube wall thickness
r_o	=	outer radius of the tube
r_i	=	inner radius of the tube
A	=	reference area
A_r	=	area on the refrigerant side
A_w	=	area on the water side
A_m	=	mean area of the tube perpendicular to heat flow
K	=	thermal conductivity of the tube
R_f	=	$1/h_f A_w$ = resistance due to biofouling or scale on the sea water side (This probably can be limited to 4×10^{-5} m^2 °C/W by suitable cleaning methods).

Each term indicates the effective resistance to heat transfer by convection or conduction. The relative magnitudes of these terms decide whether the overall heat transfer coefficient is governed by the working fluid or by the seawater. They also determine whether an increase of the heat transfer area by using finned surfaces will have any effect at all on the overall heat transfer coefficient. For example, the heat transfer coefficients (boiling or condensation) for ammonia are quite high compared to those of Freon-12. Therefore, finned surfaces may be advantageous only in the case of Freon-12 heat exchangers.

In the closed cycle OTEC, the design of heat exchangers is constrained by three factors, namely (i) the cost (ii) operating problems due to biofouling and (iii) the associated maintenance problems. The open-cycle OTEC heat exchangers, though devoid of these problems have other constraints – for example, operation under negative pressures. This raises problems like leakage and degasification. At these low pressures, the vapour specific volume is large. This requires the size of the flash evaporator to be large, thereby necessitating a large platform structure.

An ideal OTEC plant heat exchanger should satisfy the following requirements:

(a) the heat exchanger should be able to transmit heat efficiently across small temperature differences, so that the available thermal potential of the cycle is better utilised.

(b) the size of the heat exchangers should not be unmanageably large.

(c) it should be possible to keep the effects of biofouling to a minimum. In other words, the heat exchangers should lend themselves to easier cleaning methods.

The evaporator of a 100 MWe OTEC plant may comprise approximately 250,000 tubes of 5 cm o.d. x 15 cm long each, housed in a shell of approximately 35 m diameter.

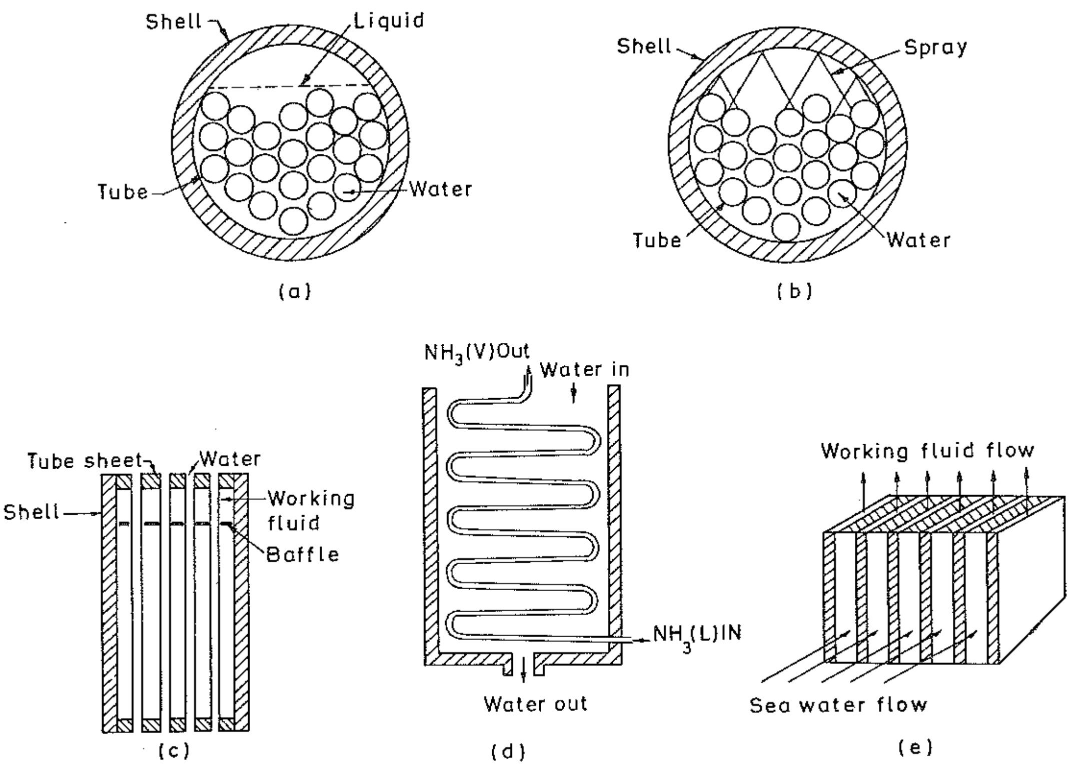

Fig. 5. Schematics of heat exchanger concepts: (a) pool boiling (b) spray film (c) vertical falling film (d) folded pipe 'trombone' (e) plate 'compact'

The corrosiveness of a sea-water environment poses a serious materials problem. Titanium, which is the preferred heat-exchanger material because of its corrosion resistance, is expensive, especially since the quantity involved will be very large – approximately 1,500 tons for a typical 100 MWe plant. Among the alternative candidate materials being researched, aluminium seems promising.

Cost and producibility are the two major issues to be addressed in the development of OTEC heat exchangers. The dimensions mentioned above for a 100 MWe plant are beyond the presently known manufacturing capability of even technologically advanced countries like the U.S.A. Such large heat exchangers create additional problems for the designers to ensure uniform water feed to all tubes and to avoid excessive liquid ammonia heads. Modular construction involving smaller units has therefore to be resorted to at least initially, to gain operational experience. To reduce the cost, there are basically three approaches: (1) enhance the heat-transfer rate so as to reduce the heat-transfer area per kW output, (2) use less expensive material (e.g. aluminium alloys), taking care to see that they can resist corrosion in the marine environment, and (3) search designs that are simpler to fabricate and to mass-produce. Heat exchangers of the shell-and-tube type, the vertical tube and falling film type, and the shell-less type have been found to be suited to the OTEC requirements. Schematics of some of these heat exchanger concepts are shown in Fig. 5. Some evaporator designs that are currently being performance-tested in the USA are discussed by Lavi (1980).

2. *The cold water pipe:* The need to pick up cold water at 4-5°C for the condensers translates into the use of very long pipes or shafts reaching down to depths of 800-1,000 m. The diameter varies according to the quantity of water pumped up, from about 10 m for a 50 MW(e) plant to about 30 m for a 400 MW(e) plant. In the earlier designs the fabrication of such huge structures was conceived with reinforced concrete. The practical difficulties foreseen with this material (weight, corrosion-proneness, surface-roughness) have led to consideration of alternatives such as fibre-reinforced plastics, frame-supported elastomers, etc., which are more amenable to prefabrication procedures.

The nature of the cold pipe design problem is becoming better understood. The success of a CWP design depends on the ability to predict the effects of hydrodynamic loads from waves and currents and the effects of platform coupling. Motion and dynamic force decouplers can be used to split the problem into two major domains – the upper portion and the lower portion. A compliant coupling between the two sections would make the unusual length of the cold water pipe less of a problem than it initially presents. A parametric design approach to study the behaviour of the CWP has indicated that the elastic properties of the pipe and the introduction of hinges or compliant joints have very significant effects on the bending moments. CWPs that are naturally compliant (plastic, rubber etc.)) or those that are made compliant by the introduction of hinges or joints tend to reduce material stresses. This approach to CWP design and construction results in a structure that is intrinsically effective in shedding the hydrodynamic forces and utilises proven concepts of concrete pipe fabrication.

3. *The platform or hull:* Though shore-based OTEC plants may be workable in selected island situations with limited power requirements, large plants will necessarily have to be erected on seabased floating platforms, which may be circular, rectangular or ship-shaped. The choice of design is made on considerations of seaworthiness at the site in question, fabrication costs, overall reliability and the mode of utilization or disposal of the energy that is generated. While ship hulls for housing smaller OTEC plants of up to 50 MWe can be constructed from steel or reinforced concrete with currently available ship-building technology, the design-data and technology for the construction of platforms/hulls for large (250-400 MWe) OTEC plants are yet to be deve-

loped. These would, perhaps, be as huge as 500,000 ton ocean tankers, and their design and fabrication could become more complicated if they have to be moved about for grazing.

4. *Marine biofouling and corrosion-products deposits:* These factors could seriously impair heat transfer efficiency and fluid pumping rates. Both mechanical brushing and chemical cleaning with on-line chlorine generators have been proposed to combat this hazard.

CRITERIA FOR OTEC SITE-SELECTION

Dugger and Francis (1976) have enumerated the following oceanographic criteria to be satisfied by sites considered for the location of OTEC plant-ships:

1. Surface currents of approximately 0.5 knots or less and no substantial sub-surface currents; deep currents of 0.2 knots or less.
2. Deep bathymetry, which ensures that there is no possibility of encountering an under-ocean peak extending up to half a mile below the surface.
3. Available water temperature differences between the surface and the deep cold water exceeding 20°C (36°F); surface temperature of 25°C or greater.
4. Normal winds of Beaufort force 3 to 4 (7-16 knots).
5. Normal sea states $\leqslant 5$ (wave-height $\leqslant$ 12ft or 4m).

ECONOMICS OF OTEC

Although ocean thermal energy represents an enormous potential to meet the world's energy demand, the development of this resource is severely limited by cost considerations and capital availability.

Since OTEC is a fuel-free system and its operation and maintenance costs are low, the bus-bar cost of OTEC power is determined largely by the initial capital cost of the plant. The low source-sink temperature difference of an OTEC plant (*ca.*20°C) translates into inherently poor cycle efficiency, enormous fluid flow rates and huge equipment. As a result, the capital cost of OTEC is substantially higher than that of conventional thermal power systems operating with a temperature difference of a few hundred degrees. The components which dominate OTEC plant cost are the heat exchangers (evaporator and condenser), the platform and cold water pipe, and the energy delivery sub-system. To illustrate the significance of low temperature differential, a good OTEC system design requires a heat transfer surface of $8m^2$/kW(e), which could cost as much as US$900/kW(e).

Lavi and Trimble (1978) have discussed the influence of the temperature differential (ΔT) and the generation capacity of the OTEC plant on its capital cost. The plant cost is inversely proportional to $(\Delta T)^{2\text{-}2.5}$, and is thus highly sensitive to the design ΔT. Thus, a large design ΔT would mean a greatly reduced capital cost. The design ΔT should, of course, be matched to the thermal characteristics of the site and the latter should take into account seasonal variations. The overall economic considerations seem to favour designing the plant for a ΔT lower than the annual average ΔT at the proposed site.

Regarding the dependence of plant cost on plant size, there is a definite economy of scale with OTEC plants. In terms of 1978 US dollars, the following cost-estimates have been suggested by Lavi (1979) for OTEC plants of various size ranges, designed for $\Delta T = 22°C$:

250-400MW(e) = \$2000/kW(e)
40-100MW(e) = \$2500/kW(e)
10-40MW(e) = \$4000-5000/kW(e)

As mentioned earlier, the major cost-ingredient is the heat-transfer sub-system (8 m^2/kWe) costing roughly \$900 per kW(e) output.

The estimates given above are near-term costs applicable to one-of-a-kind construction exercises and therefore include the initial "learning costs". It is believed that the costs may come down substantially as more plants are made and the technology matures. Avery (1980) has developed an estimate of US\$1200/kW(e) for the construction of the 8th commercial size plant.

The cost of electricity from OTEC plants is composed mainly of capital-dependent factors, such as the interest rate, amortization, insurance, taxes and other recurring expenses. It is also dependent on the overall capacity factor, which is the ratio:

$$\frac{\text{Total kilowatt hours produced per year}}{\text{Kilowatt rating of plant x 8760 (hrs/yr)}}$$

For an assumed total investment cost of US\$1,775 and a capacity factor of 0.9, Lavi and Trimble (1978) have estimated a tax-free busbar cost of 29.3 mils/kWh, which is indeed very high compared to the *present* cost in the United States, but competitive with the projected 1985 costs (US\$3.50/10^6 Btu = 40 mils/kWh).

The economic aspects of OTEC, with cost projections, have also been discussed from different angles in several papers contributed to *Energy,* Vol. 5, No. 6 (special issue on OTEC, June 1980, edited by A. Lavi). From these projections, it seems almost certain that OTEC will become cost-competitive with coal and nuclear utilities – particularly at island sites – provided steps to develop the technology are taken up in earnest without further delay or hesitation. Until the status of OTEC matures to the stage of construction and performance – the testing of a 50-100 MWe prototype – it would be futile to discuss the commercialization issues that could arise in the dissemination of OTEC energy.

The Department of Energy (DOE) of the USA Govt. has planned to install and test two experimental OTEC facilities, designated OTEC-1 (for 1 MW capacity) and OTEC-5 (for 5 MW). OTEC-1, targeted for the early 1980's, will not generate electrical power, but will focus primarily on the evaluation of pumping and heat exchange sub-systems. OTEC-5 which is expected to include the complete system and will, naturally, derive from the lessons of OTEC-1, may be installed in the 1985-1990 time-frame.

The basic targets of the DOE-OTEC program are –

Installed capital cost: US\$1,000-1,600/kW(e).
Bus power cost: 23-25 mils/kWh.
Heat exchange coefficients at the above costs: 700-1,000 Btu/ft^2 hr.

ENVIRONMENTAL EFFECTS OF OTEC

For a complete assessment of the OTEC programme one must consider, in addition to the direct costs in monetary terms, the possible environmental consequences of large-scale development of OTEC. No one doubts that a major worldwide development of OTEC can have a profound effect on atmospheric temperature and carbon dioxide concentrations because of the very large amounts of cold ocean water (roughly 1,000 gallons/sec per MW(e) of OTEC power output) that will be pumped to the surface from depths of 2,000 to 4,000 feet. The question is whether these effects will on the whole be benign, or adverse, or inconsequential.

Climatic and environmental consequences of various alternative energy sources have been studied recently by the National Center for Atmospheric Research in the United States and the International Institute of Applied Systems Analysis in Austria and the results are summarized in a recent paper by J. Williams of NCAR (1979). With specific regard to OTEC, it has been estimated that by siting OTEC plants all through the ocean in the tropical waters between 20°N and 20°S latitudes, a total of 60 TW(e) could be generated and that this could result in a persistent 1°C decrease in the ocean surface temperature over this zone. While this will no doubt decrease the thermodynamic efficiency of OTEC, it may provide an important means of ameliorating the effect of man-made heat additions on atmospheric temperature by using the oceans as a heat-sink. Studies with atmospheric models and observational data have shown that OTEC-induced sea-surface temperature anomalies can cause significant climatic anomalies.

Deep sea-water is rich in CO_2 and plant-nutrients. The transfer of huge quantities of this water to the surface may, through upwelling, discharge considerable quantities of CO_2 into the atmosphere and also stimulate phytoplankton growth, thereby causing widespread changes in the albedo of the sea-surface. It has been estimated, however, that the amount of CO_2 released by an OTEC operation is only about one-third of that emanating from a fossil-fuel plant of equivalent energy production. Nonetheless, OTEC-produced CO_2-addition may acquire significance should the CO_2-building-up from continued use of fossil fuels eventually pose an unacceptable climatic risk.

The quantitative long-term climatic impacts of large-scale OTEC development are still unclear. Potentially, they are important and warrant careful study over a protracted period of time. It is expected that experiments with OTEC-demonstration plants, now under construction in the USA, will address this issue.

DELIVERY OF OCEAN THERMAL ENERGY:

In the foregoing sections, a favourable case has been presented for the exploitation of ocean thermal gradients for the production of useful energy – specifically electrical power – on a massive scale. However, the fact that OTEC plants, if built, would be stationed at sea, 4 to 100 miles (or even more) off-shore, raises the question of how, and perhaps in what form, the energy produced by these plants will be made available to the user markets on land, since wholly Neptunic uses for this energy are rather limited. The link between the OTEC plant and the land-based energy markets is an important part of the total system, as the overall credibility of the OTEC concept will depend upon the availability and economics of the transmission system.

Power generated by OTEC plants moored less than 25 km off-shore may be transmitted through submarine cable as high-voltage A.C. (~150 kV). For longer distances, up to 200 km, high voltage D.C. ($\geqslant$250 kV) transmission has to be resorted to. Underwater bulk-power transmission at depths (1 to 2 km) and distances characteristic of OTEC conditions has not been attempted so far This is bound to pose numerous engineering problems, particularly with regard to platform positioning and cable-design and installation. The D.C. cable will have to be in one piece since no splices or joints are permissible in lengths exceeding 100 km. No such cable has been manufactured. Creation of new cable manufacturing capacity will entail additional capital deployment on the OTEC account, which is already overburdened with plant and siting costs. Transmission adds to cost and increases the system's vulnerability to loss and reliability-erosion factors – all of which will tend to escalate the final (delivered) cost of electricity on shore.

For OTEC plants which are more remotely sited than a few tens of kilometers from the coast, as will generally be the case, both engineering and economic considerations seem to favour strongly the conversion of the primary OTEC electrical energy to hydrogen by electrolysis of de-ionised sea water. The hydrogen thus produced could be transmitted as gas ($H_2(g)$) through sub-marine pipes if the distance is not large, or else converted in the OTEC plant itself to liquid hydrogen ($H_2(1)$) or liquid ammonia ($NH_3(1)$), which could be shipped in special containers or tankers to the land-terminals. The latter alternatives offer greater operational flexibility in the disposal of the energy product.

Dugger and Francis (1976) developed a baseline design of an OTEC plant-ship to produce ammonia, liquid hydrogen, and electricity. They estimated that the ammonia production cost would be US$1,975 for a 500 MW(e) (Net), 1,697 short-ton/day, commercial OTEC ammonia plant ship, and reported a plant investment of US$383 million and ammonia cost of US$90/ton. The product costs provide a 50% return on sales at the 1975 USA price level of US$180/ton.

The cost estimates (1975 US$) for a 500 MW(e) OTEC ($H_2(l)$ plant ship) have been reported as follows:

For the year 1985, the plant investment will be US$487 million and the $H_2(l)$ delivered cost will be US$815/short ton or US$6.70/million Btu (based on the HHV of hydrogen). The possible costs for the 1990's will be US$362 million plant investment and US$558/short-ton or US$4.6/106 Btu.

The possible 1990 costs (based on 1975 US$) for generating power with fuel cells on shore, using $H_2(l)$ from OTEC plants, are estimated as 27.3 mils/kWh, a figure which will be of very good commercial interest.

Talib et al. (1978) have performed a comprehensive cost analysis for the production and transmission of OTEC power as $H_2(g)$, $H_2(l)$, $NH_3(l)$, methane, methanol and synthetic gasoline. The results of their cost estimates are summarized in Table 1, excluding those for the carbonaceous carriers which are more expensive to produce with OTEC power and offer no advantage over

Table 1: Delivered costs of OTEC produced hydrogen and ammonia

Chemical Energy Carrier	Distance (miles)	Production ($/$10^6$Btu)	Transmission ($/$10^6$Btu)	Terminal ($/$10^6$Btu)	Total ($/106Btu)
Hydrogen Gas	100	7.98	2.10	NA	10.08
(by pipeline)	1000	7.98	25.00	NA	32.98
Liquid Hydrogen	100	12.75	2.07	0.66	15.48
(by barge)	1000	12.75	7.09	2.37	22.21
Liquid Ammonia	100	11.74	0.82	0.11	12.67
(by barge)	1000	11.74	1.29	0.12	13.15

Based on an OTEC shaft-power cost of 20 mils/kWh, improved electrolysis technology for hydrogen production and 100 MW plant.
Data-source: Talib *et al* (1978).

their land-based syntheses from coal. By 1978 standards, the estimated costs of OTEC-produced hydrogenous fuels are admittedly very high compared with those projected for coal-derived synfuels. But, with continuing escalation of fossil-fuel prices at an exponential rate and the almost certain prospects of economies in OTEC plant costs due to improvements in technology, there is good reason to expect OTEC to succeed as a cost-competitive, abundant source of hydrogen fuels in the not too distant future. This prediction is supported by recent studies carried out at the Institute of Gas Technology, Chicago, (Talib *et al, loc. cit.*), which indicate that the costs for "new" natural gas supplies may escalate to US\$3.00-4.00/10^6 Btu by 1986, and that the prices of SNG and methanol from coal may also be in the same range: US\$2.50 to 4.00/10^6 Btu for SNG and US\$6.00 to 7.50/10^6 Btu for syn-methanol. Ammonia production from gas supplies in this price range may cost US\$280 to 310/ton. Other energy forms – electricity and oil – are also expected to be substantially higher in cost by 1985. Electricity costs may rise to an average of 3.75 to 4.0 cents/kWh by 1985, and fuel oil prices may go up to about US\$3.50/10^6 Btu, or even higher. As such, it would appear that at the time when OTEC plants become commercial (1995-2000), the cost of ocean thermal power (whether as electricity or as chemical energy carriers) will be at least competitive with traditional energy sources. In fact, OTEC-ammonia could be very competitive in price with ammonia domestically produced from natural gas or coal.

Roney (1980) favours the use of liquid ammonia as a bulk carrier for OTEC-produced hydrogen, since the infrastructure for marine transportation of liquid ammonia in special tankers already exists and as it offers greater flexibility of end-use as a chemical and as a hydrogen source for fuel cells. At a fuel cell efficiency of 55%, 3.54 kWh(e) can be produced per kilogram of NH_3. For an ammonia cost of US\$160 per tonne, the busbar cost of electricity production works out to 45 mils/kWh which makes it attractive for peak-load boosting in power-supply systems. Presently, peaking with oil/gas-fueled generators costs 100 mils/kWh and this is bound to escalate further as petroleum supplies become more restricted and expensive. It is of interest to note in this context that an experimental 4.5 MW(e) fuel-cell plant is being installed in New York city, with hydrogen produced by naptha-reforming. This should open the prospects of small and medium sized fuel-cell plants to be used as independent, decentralised power-units in remote rural areas, small islands and other dispersed locations – a proposition which becomes particularly attractive if the hydrogen fuel is produced locally with solar or wind energy.

An alternative to the transmission of OTEC-produced power or fuel to land-based consumer areas, is its *in situ* utilization for energy-intensive manufacturing processes, such as the production of aluminium from bauxite. This alternative is considered to be particularly attractive for island locations such as Puerto Rico, Jamaica and Surinam in the Caribbean, which have rich deposits of bauxite but lack the energy resources to reduce it to metal. 14 MWh(e) are required per ton of aluminium produced. Other energy-intensive sea-based industries, notably those involved in the production of magnesium, sodium and marine chemicals, can also be conceived as possible outlets for OTEC power utilization.

CONCLUSION AND SUMMARY

Ocean thermal energy conversion (OTEC) is a viable and technologically accessible means of harvesting the solar energy collected and stored in the ocean surface and converting it continuously on a massive scale to electricity or other usable forms of energy. It has the potential to generate substantial amounts of power in the order of several tens of terawatts indefinitely.

The principle of OTEC is well-established and simple. It is essentially a low pressure, low temperature, closed Rankine cycle heat engine with ammonia vapour as the (usual) "working fluid," warm surface sea-water as the "boiler fuel" (heat source), and cold deep sea water as the "condenser coolant" (heat sink). The utilization of small temperature differentials for the generation of electrical power has been demonstrated experimentally on a small scale for a few tens of kilowatts. To scale this up to the order of tens of megawatts requires a major effort in design and fabrication, because of the hugeness of plant dimensions and because of problems native to marine locales. The Governments of the United States of America, Japan and the European Economic Community are, at present, engaged in intensive R & D efforts for OTEC technology development. Significant advancement in this area is expected during the next two decades and the first major OTEC plant may be expected to go on stream by the year 2000.

Hydrogen has been proposed as a very practical and economical carrier of energy from large OTEC plants sited too far from mainland areas for direct transmission through submarine power cables to be practicable. This article focuses on this issue and discusses the comparative merits and economics of transporting hydrogen as liquid hydrogen and as liquid ammonia.

Alternatively, OTEC-generated electrical energy can be utilized *in situ* in electrochemical and electrometallurgical processes such as the production of aluminium, magnesium and marine chemicals.

OTEC is a highly capital intensive proposition. The first few commercial-scale plants are bound to cost 3 to 4 times as much as conventional fossil or nuclear fueled power plants. This, coupled with the 'dark horse' notion about OTEC, would act as a strong deterrent against big-business involvement in OTEC development. Unless and until OTEC's economic viability and profitability are convincingly demonstrated over a period of time, it would be well-nigh impossible to find the required venture capital either from governmental or from private industrial sources.

Let us consider how big the capital involved would be. Curto (in Lavi, 1980) has deduced from an assumed 90 percent experience curve that the capital cost of OTEC plants, initially rated at US$3,625/kWe, will drop to about one-half this value when a total capacity of 1 GWe has been established with a gross investment of US$2.12 billion (+ R & D costs), and will ultimately level off at US$1,268/kWe when a gross installed capacity of 10 GWe has been reached with a cumulative total expenditure of US$14.95 billion on plant cost + US$1 billion (approx) on R & D expenses. Considering that the total outlay of US$16 billion is to be spread over a period of 10-15 years, the task of capital-resource mobilization does not seem all that formidable – especially for affluent countries, like the USA and Japan. However, other issues of an inter-governmental political nature (cf. G.H. Lavi in A. Lavi, 1980) may intervene and thwart the approach to the 10 GWe milestone, especially if the immense thermal resource of open sea sites in the tropics is sought to be exploited by any one nation or group of nations. International rights and issues will surface where none existed before. To avert such an undesirable development and also recognizing that the regions of the world to benefit most from OTEC lie in the tropics (and these are woefully lacking in conventional energy sources), it would be appropriate to internationalize OTEC development (at least until it attains economic stability) under the auspices of the United Nations. This will ensure that the fruits of the internationally funded R & D efforts are available to all nations alike. Moreover, the suggested venture-capital of US$16 billion is well within the capability of the UN organization to mobilize and to manage.

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