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THE VIABILITY AND BEST LOCATIONS FOR OCEAN THERMAL ENERGY CONVERSION SYSTEMS AROUND THE WORLD

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ABSTRACT

Marine renewable energies offer alternatives to fossil and nuclear energies. Ocean thermal energy conversion (OTEC) is one of these alternatives, which also provides a range of additional products - food, air conditioning, water, pharmaceuticals included - hence the term deep ocean water applications (DOWA). It is also, unusually, a base-load system. Applications are in both developed and developing nations, but with particular application to island locations. Economics have significantly improved, due to advances in both design and materials, and OTEC/DOWA has many environmental advantages. Small (up to 1 MW) experimental units have been designed and built, and performance has been measured. These results confirm the growing practicality of OTEC/DOWA, and the next requirement is design, construction and operation of a representative scale demonstrator, typically 5 - 10 MW, to evaluate the feasibility of full scale production systems.

KEYWORDS

Energy; renewable; ocean; economics; products; environment.

A PLACE FOR MARINE RENEWABLE ENERGY

Marine related renewable energy systems have been the subject of particularly close study in Japan, USA, France, Germany, The Netherlands and Sweden in addition to the UK. In part this interest arose as a result of the increased price of oil in the 1970s, and the availability of new materials, which together improved the comparative economics and technical feasibility of these energy systems. There will be a long lead time for any major market in these systems, since the market is a function of demand, technical viability, financial resources, political acceptability and increasingly the environmental friendliness - or otherwise - of the energy systems. Assessments of opportunities must take note of all these factors and the way they inter-relate; the opportunities have clearly been reduced by the fall in oil prices. However, there was an economic justification for certain marine renewable energies in specific and restricted markets at the lowest recent oil prices. With the presently rising oil prices (about US$19/bbl) the economically justified market for marine renewables is improving significantly.

Despite the world recession, energy usage continues to rise overall in the world, due to the increase in energy consumption by developing countries. This is expected to continue well into the next century with the share of world consumption for the developing countries rising from about 25% in 1978 to 33% in 2000, and 35-40% by 2020 (World Energy Balance, 1984). This is a %age of <u>total</u> world demand; it is frequently thought that large %age increases in energy consumption by developing countries are a reflection of the relatively low base of present energy consumption in those countries - and it is in part true; but the %age figures quoted above are absolute values in terms of total world demand. The increases are therefore large. This is important because much of the potential market for renewable marine energies lies in the developing world.

Estimates for the 'new' energies (not just marine related) also show a substantial growth over the same periods from virtually zero in 1978 to 3% in 2000 and 6% in 2020 - again expressed as %ages of total world demand.

Despite the apparent smallness of these %age figures, they too are large in absolute terms, since the overall world energy consumption figures were 6815 mtoe (million tons of oil equivalent) in 1978, and are estimated at 10,100 mtoe in 2000 and 13,760 mtoe in 2020 - the latter two figures being on the pessimistic assumption of increased world tension and worsening of 'North-South' relations. The corresponding figures for a stable world economic and political order, with 'average harmony' between North and South, would be 11,730 mtoe in 2000 and 17,960 mtoe in 2020.

In terms of GNP, the optimistic figures correspond to an average annual growth of 3.3%, and for the pessimistic figures 2.3%, over the period 1978-2020. These should be compared with the actual annual growth in GNP, world wide, from 1960 to 1978, of 5% and which has subsequently reduced, but not to the figures quoted above.

Taking full note of the pessimistic scenario, the increase in absolute world energy demand, and in world 'new energy' in developing countries, is still very large indeed. 3% of 10,100 mtoe is 303 mtoe and 6% of 13,760 mtoe is 826 mtoe. In electrical terms these correspond to 3.6×10^{12}kWh and 9.9×10^{12}kWh. If that 'oil equivalent' was burnt in a modern oil fired power station (with overall efficiency of about 30%) and assuming that the station generated maximum power 24 hours a day every day of the year, these figures correspond to capacities of 137,000 MW and 377,000 MW respectively of new generating capacity - if all the new demand for energy was to be used to generate electrical power. Of course this will not be the case, but nor will the plant be used 24 hours a day, 365 days of the year. The first of these factors will diminish the figures for power generated, but the latter will require higher installed capacity to cater for the peaks and troughs which give rise to the average figure. The figures are useful though in giving an order of magnitude to the 'new' or 'novel' energy requirements. On the basis of these figures, 'new' energies would be tapped at an *average* annual rate of 6200 MW up to 2000 and 12,000 MW between 2000 and 2020. With renewable (or 'new') energies costing of the order of £3000/kW in capital terms, this means a turnover for manufacturers of £18.6 x 10^9/year and £36 x 10^9/year for the earlier and later periods quoted above. These are world-wide figures, giving a general indication of the scale of market potentially available.

It is a very substantial market

OCEAN THERMAL ENERGY

Ocean thermal energy conversion (OTEC) has held out its promise now for over one hundred years - but so far without the realization of production systems. Improved materials, and experience gained from offshore oil and gas activities in deeper waters, are now removing many of the previous uncertainties. A recent change in outlook by OTEC protagonists has been to consider all the benefits which may be derived from the cold deep nutrient rich water of an OTEC plant, and its relatively benign environmental influence. As a result the term Deep Ocean Water Applications (DOWA)) has frequently been used.

For OTEC there are many variants available - floating, land based or shelf mounted; open or closed cycle; electricity generation alone or electricity/desalination/ aquaculture.

Programmes related to OTEC or Deep Ocean Water Applications (DOWA) have been undertaken during the last 25 years in Japan, Taiwan, France, USA, UK, Netherlands, and Sweden and Italy. Taking note of the fundamental thermal resource, shown in Fig.1, and other factors influencing the competitive position of OTEC when compared with traditional energy sources, it is possible to locate preferred sites for early OTEC plants. The basic feature is the temperature difference available in the water column, the standard being the difference between the surface and a depth of 1000m. The other factors included in the assessment were: the present electrical generating system at the location concerned, and specifically the delivered cost; for a number of the locations there are environmental factors which are perceived to be of growing importance - and usually a disadvantage for existing fuels - as environmental impact assumes a higher profile. In extreme cases already, clean-up associated with some fossil fuels is measured as an addition to the conventionally calculated generating cost. Two other factors considered were the distance of the thermal resource from the shore, and the relevance of currents and storms to the safe and continuous operation of OTEC plants. Because OTEC is a base load system, available 24 hours a day throughout the year, the incidence of currents and storms at all times is a key feature of site evaluation.

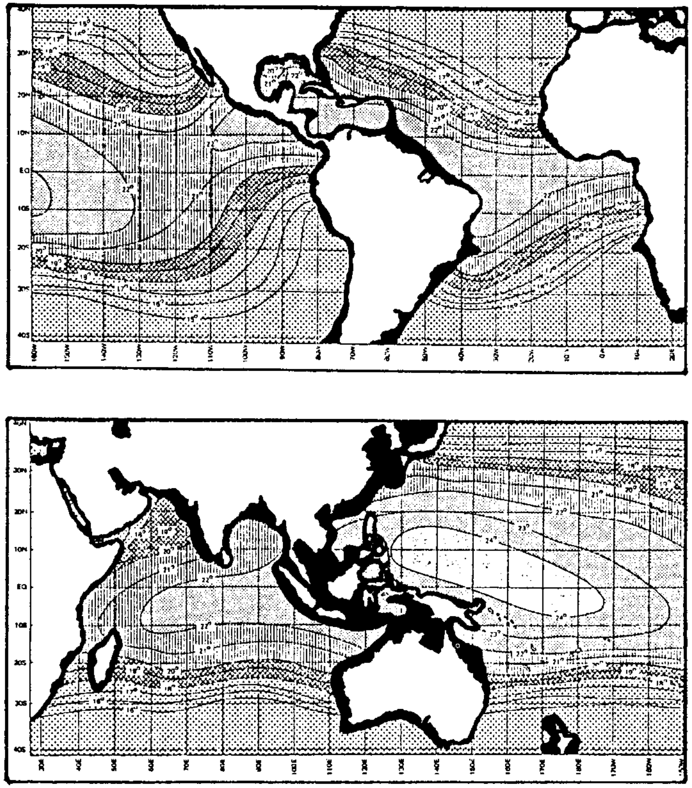

Fig. 1. The ocean thermal resource; worldwide distribution. Annual average of temperature differences in °C between the ocean surface and a depth of 1000 metres.

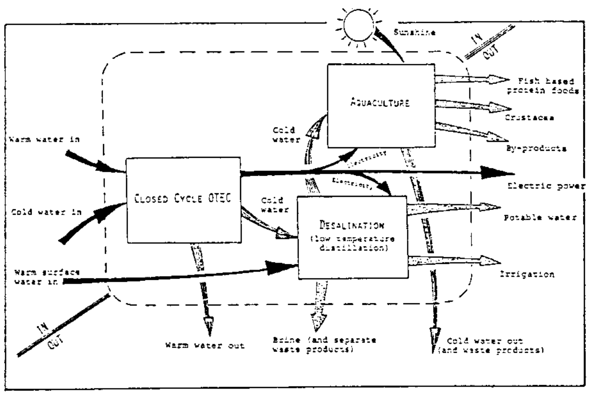

Fig.2. A range of products available from an OTEC/DOWA plant.

Nominal Net Power (MWe)	Type	Scenario Requirements	Scenario Availability
1	Land-Based OC-OTEC with 2nd-Stage additional water production	• \$45/barrel of diesel • \$1.6/M^{3}water	South Pacific Island Nations by Year 1995
10	Land-based (as above)	• \$25/barrel of fuel oil • \$0.85/m^{3}water - or - • \$30/barrel with • \$0.8/m^{3}water	American Island Territories and other Pacific islands by Year 2000
40	Land-based hybrid (ammonia power cycle with flash evaporator downstream)	• \$44/barrel of fuel oil • \$0.4/m^{3}water - or - • \$22/barrel • \$0.8/m^{3}water	Hawaii, if fuel or water cost doubles by Year 2000
40	• Closed-cycle land-based • Closed-cycle plantship	• \$36/barrel • \$23/barrel	By Year 2005

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

Fig. 3. OTEC market penetration scenarios.

The prioritization derived from this evaluation produced a list which is exclusively island locations. These are (in alphabetical order) Bahamas, Cayman Islands, Fiji, Guam, Hawaii, Jamaica, Pacific Islands (Trust Territories) Papua New Guinea, St. Lucia Seychelles, Taiwan and Trinidad & Tobago. A priority ordering within this list is not possible because of the extensive options available for products from an OTEC plant as indicated in Fig.2. By way of example (Vega and Trenka, 1989) the trade-off between electrical power generation and potable water production is shown in Fig.3.

THE ECONOMICS OF OTEC-DOWA

Whilst, therefore, the practical realisation of OTEC (or DOWA) must depend on economic and environmental attractiveness, the number of variables involved effectively means that calculations must be both site specific and product-combination specific. An indication of the spread of generating costs for all known OTEC schemes is given in Fig.4. Within that, the generating costs for a 10MW closed-cycle floating OTEC plant, of the type shown in Fig.5, has been calculated at approximately 14 USc/kWh for a demonstrator, where the temperature difference is 20C degrees.

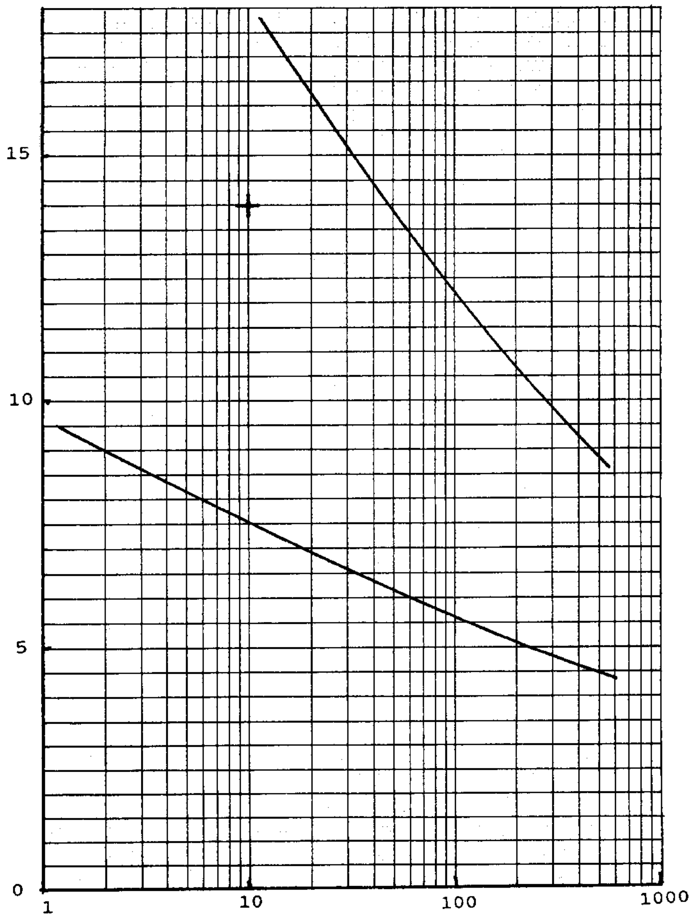

Fig.4. Spread of electrical generating costs (USc/kWh) for all known OTEC schemes, against size (MW).

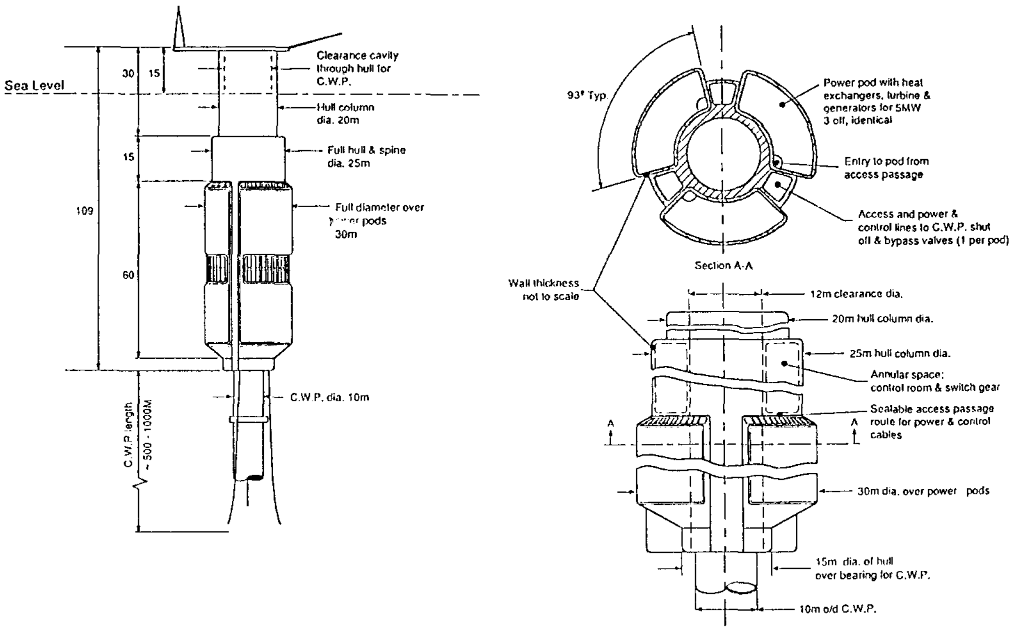

Fig 5. General arrangement, and cross-sectional details, for OTECS Ltd 10MW floating plant.

Components	% of total
Site specific data	1.7
Heat exchangers	20.2
CWP	6.1
Moorings	4.9
Electrical transmission (seabed and riser)	8.3
Pumps, turbines, generators and control	12.9
Hull, including warm-water circuit	18.0
Installation and maintenance	4.1
Start-up and test	8.0
Miscellaneous	1.9
Unknowns	13.9

Fig. 6. %age component costs for 10MW closed-cycle floating OTEC plant.

Components	% of target costs
Capital Costs:	
Heat exchangers	80-120
CWP	75-140
Warm water circuit	90-110
Moorings	85-135
Seabed power cable and junctions	90-120
Pumps, turbines, generators	85-115
Hull	90-120
Operational Costs:	
Operational labour	90-110
Maintenance labour	90-120
Replacement equipment	90-130

Fig. 7. Contingency cost estimates for items of floating 10MW OTEC plant.

Type of Plant	Electricity Cost (USc/kWh) with water production credit at:	
	40 USc/m^3	80 USc/m^3
1 MW OC OTEC Land Based	28	25
1 MW OC OTEC Land Based 2nd stage	32	25
10 MW OC OTEC Land Based	14	11
10 MW OC OTEC Land Based 2nd stage	16	8
50 MW OC OTEC Land Based	10	10
50 MW OC OTEC Land-Hybrid	12	9
50 MW CC OTEC Floater	8	8
50 MW CC OTEC Floater-Hybrid	9	6

OC = Open Cycle CC = Closed Cycle

Fig. 8. Cost of OTEC electricity with desalinated water credit (after Vega).

Economic analyses (Cavrot, 1992; Vega, 1994) provide further useful guidance. The former, in arriving at costings, indicates both the breakdown of component costs for a closed-cycle floating plant, Fig.6, and the contingency factor associated with both capital and operational elements, Fig.7. The latter shows generating costs, summarized in Fig.8, for a range of plant types, with two different credits for water production.

CONCLUSION

The lengthy gestation period for OTEC - and now the DOWA variant of OTEC - is resulting in costings which are approaching economic attractiveness with oil at present prices, particularly so where potable water or refrigeration/air conditioning are also products. As noted, the most attractive potential sites are all islands.

However, and with limited exceptions, these are theoretical calculations. The practical results have all been derived at small scale ($\ngtr$ 1 MW) and over limited periods. The fact that a number of further improvements in economy now look entirely feasible, and in particular for the expensive heat exchanger component of an OTEC plant (Creber & Johnson, 1994), means that the investment risk of the OTEC/DOWA system is now substantially reduced.

The key objective for the OTEC community is not to further enhance techno-economic values, important though those continue to be, but to locate the funding package for a representative scale demonstrator, in the size range 5-10 MW.

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