Ocean Thermal Energy Conversion: An Extensive, Environmentally Benign Source of Energy for the Future

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ABSTRACT

Ocean thermal energy conversion (OTEC) has been shown to work at research scales, and plans are underway to build pilot scale plants. Private sector developers will probably be unwilling to make the enormous initial investment required by the inherent large scale of commercial OTEC, until the price of fossil fuels increases dramatically and/or governments provide suitable financial incentives. If, however, the pilot scale plants now being planned for some expensive-energy niche markets are successful in demonstrating low cost long-term operation, OTEC will be much more financially attractive. It offers tremendous potential for reducing man's input of CO_2 into our atmosphere, and the development should not be further delayed.

INTRODUCTION[1]

French Scientist Jacques D'Arsonval first proposed in 1881 that useful energy could be extracted from the temperature difference between the surface and deep water in the tropical ocean. For this process, now called ocean thermal energy conversion (OTEC), he proposed using a working fluid such as ammonia in a closed cycle engine (Figure 1)[2]. In the 1920s and '30s, D'Arsonval's student, Georges Claude, developed the idea of an open cycle system that uses the seawater itself as the working fluid (Figure 2)[3]. Claude actually built a plant in Cuba that generated energy from this process. In 1935, Claude obtained a patent for a 50 MW open cycle plant that used eight turbines, each generating about 6 MW. Little further progress was made on OTEC until the 1970's, when a dramatic increase in oil prices led to renewed interest in alternative energy sources. Governments around the world formed executive units such as the Energy Research and Development Agency (later the U.S. Department of Energy) in the United States which initiated programs to investigate a wide range of alternative energy sources, including OTEC. In 1974 the State of Hawaii, largely dependent on increasingly expensive fossil fuels, formed both the Hawaii Natural Energy Institute at the University of Hawaii and the Natural Energy Laboratory of Hawaii, at Keahole Point on the Big Island of Hawaii (Figure 3). The latter operates under the State's Department of Planning and Economic Development, now the Department of Business, Economic Development and Tourism. The Natural Energy Laboratory of Hawaii Authority has grown to become the world's foremost site for research, development and commercialisation of OTEC and related technologies.

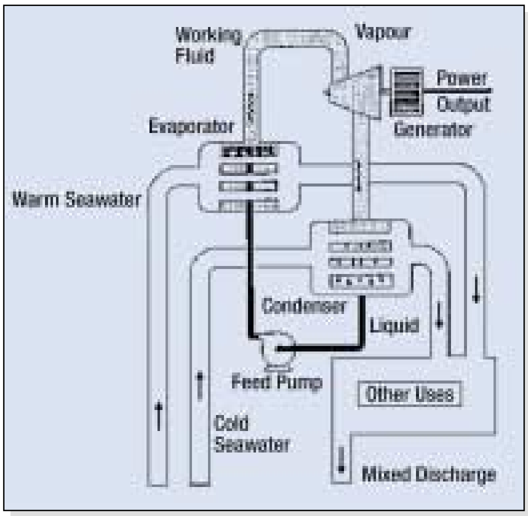

Figure 1
Closed-Cycle OTEC Schematic Diagram. Surface seawater flowing through the evaporator vaporises a working fluid, such as ammonia, which expands through the turbine, turning the generator to provide electrical output. The working fluid vapour is condensed by thermal contact with deep seawater flowing through the condenser. The condensed liquid is then pumped back to the evaporator, where the cycle (named the 'Rankine' cycle) repeats. Much development work has focused on the evaporator and condenser heat exchangers, which must have large surface area and must be resistant to seawater corrosion. Research indicates that aluminium heat exchangers can work well in these applications

Work at NELHA and elsewhere has produced engineering advances and some creative modifications to the basic cycles proposed by D'Arsonval and Claude. Specifically, a recent proposal for a Kalina Cycle plant[4] that uses an ammonia water mixture, provides a significant efficiency improvement over the traditional Rankine cycle proposed by D'Arsonval. The 'Mist Lift' cycle tested at NELHA by Stuart Ridgway[5] overcomes the scale-up problems of the large turbine required for low pressure operation in the Claude cycle. Liquid water droplets couple with water vapour and are thereby lifted to sufficient height so that their potential energy can operate a hydraulic turbine.

POTENTIAL BENEFITS OF OTEC

The extent of the resource

OTEC represents a tremendous potential energy resource for the future. Figure 4 shows contours of the annual average temperature difference between the sea surface and 1000 m depth for the world ocean. OTEC is feasible with temperature differences of 20ºC or

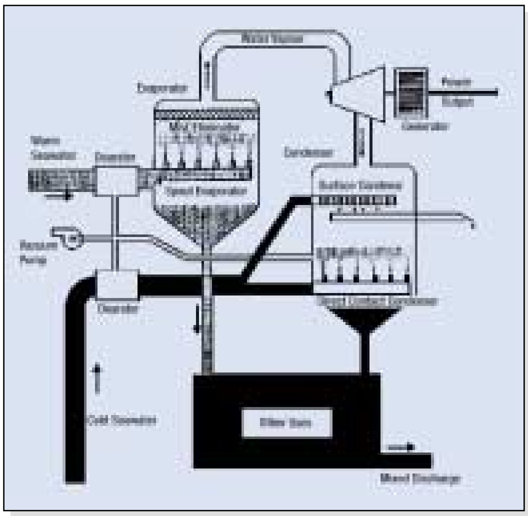

Figure 2
Open Cycle OTEC Schematic Diagram. Surface seawater vaporizes due to low pressure in the evaporator. The water vapour (low temperature steam) then expands through a turbine to the condenser where cold seawater condenses it back to liquid water. Since the salt is left behind in the evaporator, a surface condenser (such as that used in the closed-cycle process) will condense potable water. A direct contact condenser, in which the seawater directly contacts the vapour, will provide more electrical output but no potable water. The pressure drop across the turbine is very small (<3.5 kPa), so the turbine must be very large for relatively small electrical outputs. Turbines larger than ~6 MW cannot be built with present technology

greater, so all of the area between these contours in Figure 4, i.e. most of the area of the tropical ocean, is available for extraction of energy. Though the relatively small available temperature difference limits the achievable thermodynamic efficiency to less than 3%, various methods yield estimates that about 10 TW (10^13 watts) of continuous electrical output could be extracted from this resource without significantly changing the thermal structure of the ocean[1]. The sun continues to replace heat removed from the surface layer, and the tremendous mass of the cold deep ocean water (the average temperature of the ocean is 3.5ºC!) represents an essentially inexhaustible heat sink. OTEC could thus potentially supply most of the present energy consumption for all human activities, which was estimated at 386 EJ/yr in 1997 (1 EJ = 10^{18} J, 386 EJ/yr ≈1.22 x 10^{13} W = 12.2 TW)[6]. Other non-nuclear alternatives to fossil fuel energy sources, such as hydroelectric, wind, photovoltaic, geothermal, waves and tides each have, with presently available technology, at least two orders of magnitude less potential than OTEC[7].

Environmental considerations

OTEC can fulfil its tremendous potential with minimal impact on our environment. First, OTEC is not inherently exothermic, so large-scale utilisation will not contribute directly to global warming. Also, though the deep and surface seawater do contain dissolved carbon dioxide, straightforward engineering techniques can prevent its release into the atmosphere, so that OTEC produces much less greenhouse gas than fossil fuel generation systems. In addition, reasonable engineering and suitable spacing of plants throughout the tropical ocean can keep impacts on ocean temperatures and living resources well below objectionable levels.

By-products

The feature that most distinguishes OTEC from other renewable energy sources is the tremendous range of by-products that derive from downstream uses of the cold deep ocean water (Figure 5)[8,9]. The following paragraphs summarise some of those that have been investigated at the Natural Energy Laboratory of Hawaii Authority.

Air Conditioning – The most financially attractive of these by-products at the present time is ‘space cooling’ (air conditioning). The cold seawater can either chill freshwater in a heat exchanger or flow directly into a suitable chilled water loop, effectively replacing the chiller which consumes more than 90% of the energy of a traditional air-conditioning system. Simple systems of this type have operated for several years cooling buildings at NELHA, saving almost $4000/month in electricity costs for the facility. Economic and engineering analyses[10] indicate that the pay-back period may be as short as 3 or 4 years for commercial-sized projects. Developers in many tropical locations, such as Curacao, the Philippines, Guam and the Cape Verde Islands, are seriously considering installation of deep seawater air conditioning systems for new resorts. The positive experience at NELHA has led Cornell University in Ithaca, New York to install a ‘lake source cooling’ system that uses cool water from nearby Cayuga Lake to cool the

Figure 3
Aerial view of The Natural Energy Laboratory of Hawaii Authority, Keahole Point, Island of Hawaii. Mount Hualalai is in the background, and the Kona International Airport is immediately shoreward of the facilities. The green ponds are part of the facilities of Cyanotech Corporation, a NELHA tenant which grows microalgae for healthfood and pharmaceutical products

campus in the summer[12]. The University determined that the reduction in energy usage and consequent reduction in CO_2 emissions to the atmosphere more than justified the investment in the project. This system now serves as a model of potential savings for new developments in the tropics.

Industrial Cooling – The deep seawater represents a large 'heat sink' for many potential industrial applications. Specific examples tested at NELHA include condenser cooling for distillation processes, moisture and CO_2 removal during drying of algal products and cost-effective assistance to refrigeration and freezing systems.

Chilled Soil Agriculture – Cold seawater flowing through underground pipes chills the surrounding soil, providing a large temperature difference between roots and leaves – a 'perpetual springtime' for plants. Many temperate plants thus thrive in an arid sub-tropical climate where they would not normally grow. The cold also induces significant condensation from the humid atmosphere, providing a large fraction of the irrigation needed for the crops. The Common Heritage Corporation[13], started by NELHA founder Dr. John Craven, maintains a demonstration garden with more than 100 different fruits and vegetables, many of which would not normally survive in Hawaii. Strawberries grown in the chilled soil have five times the sugar content of those grown in neighbouring control beds. Varying the temperature by modifying the cold seawater flow through the underground pipes has induced pear trees to flower and produce fruit four times in a year. In June 2000, the Japanese Prefecture of Okinawa initiated a deep seawater system on Kume Island that will provide 600m-deep seawater to chill the soil to allow the year-round cultivation of spinach, a staple crop that will not grow locally in the hot summer. Projections indicate that the high summer spinach prices will quickly pay back the cost of the pipelines.

Aquaculture – The most visible and publicly recognised by-products of OTEC are the wide range of marine organisms that are being grown in suitable mixtures of deep cold and warm surface seawater being pumped ashore for OTEC research and development. The deep seawater is important to aquaculture for three basic characteristics:

1. Its **cold** temperature not only allows culture of many valuable organisms – such as salmon and Maine lobster – that would not normally grow in the tropics, it also provides cost-effective temperature control of large seawater volumes over a wide temperature range.
2. The deep water is significantly enriched in **nutrients** compared to normal oligotrophic tropical surface water, providing enhanced growth of marine algae.
3. The water is **clean** – it contains few of the pathogens that typically cause problems with culture of marine organisms.

Many private companies are now commercial tenants at NELHA, growing a variety of valuable crops in suitable mixtures of surface and deep seawater[14]. Organisms now being cultured include: microalgae such as *Spirulina* (a popular healthfood supplement) and *Hematococcus* (being used as a source of astaxanthin, a pigment and pharmaceutical), macroalgae (seaweeds being cultured largely for local consumption in Hawaii), oysters (being grown both for food and pearls), clams, abalone, shrimp and food fish such as hirame (Japanese flounder used in sushi) and moi (pacific threadfin), a Hawaiian fish delicacy.

OBSTACLES TO OTEC DEVELOPMENT

Though the OTEC resource is very large, it exists mostly where people don't (Figure 5). There are only at most a few hundred land-based sites where deep water

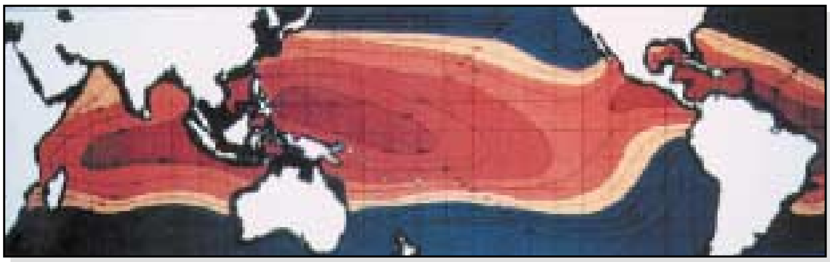

Figure 4
Distribution of the OTEC Resource. This map portrays contours of the annual average temperature difference between the surface and 1000 m depth throughout the world ocean. Since OTEC will work where the temperature difference is at least 20°C, the orange to red colours on the map shows that the resorce is generally available between the tropics

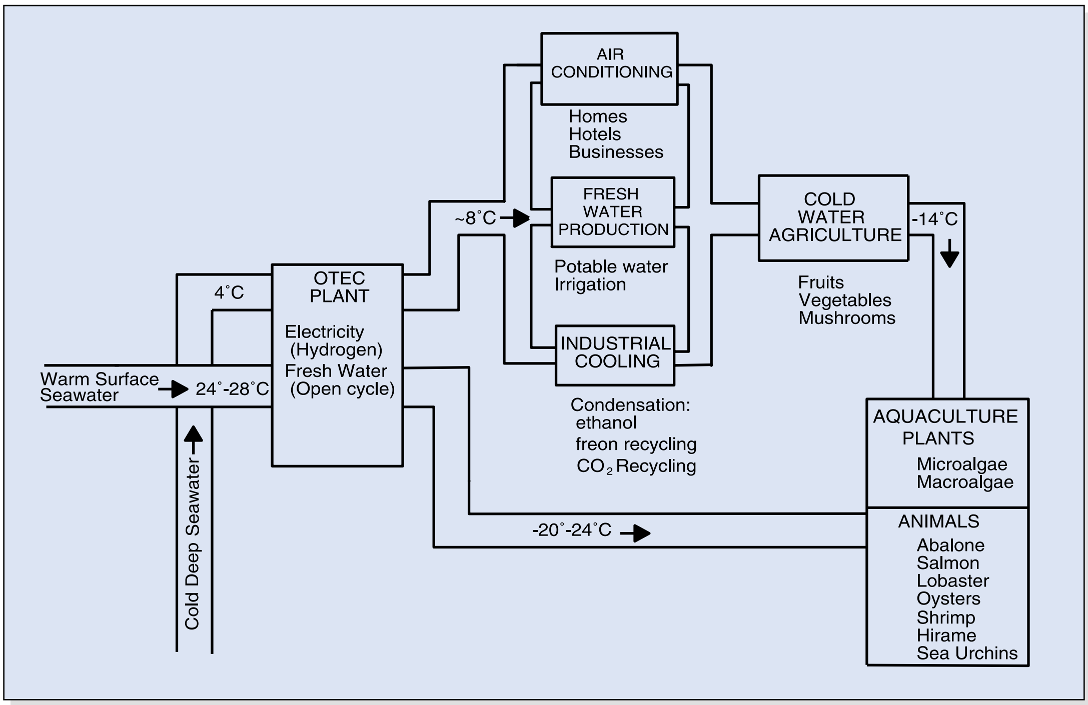

Figure 5
Schematic Diagram of a Multi-Product OTEC System. The seawater discharge from an OTEC plant can supply large volumes of flowing seawater at any temperature between the 4˚C of the deep seawater and the minimum 24˚C of the surface seawater, merely by twisting a valve. The value of this resource in the tropics is limited only by the imagination of the user

is close enough to shore in the tropics to make land-based OTEC plants feasible[2]. Any significant development of the resource will, therefore, require siting of plants in mid-ocean. Not only is the cost of working things at sea higher than on land, but there are also problems with transmitting energy generated offshore to land-based populations. Deep sea cables would be very expensive and are not efficient for long range power transmission, and alternative transmission schemes, such as microwave transmission via reflecting satellite, aren't feasible with current technology. The solutions currently considered most viable involve using electricity generated by OTEC on offshore platforms to produce alternative fuels such as methanol[15] and, eventually, hydrogen. OTEC could thus become a major component of the hydrogen-based economy that many envision for man's energy future[16].

The OTEC cold water pipe (CWP) must transport large volumes of deep seawater to the plant from about 1000 m depth. For shore-based plants, the CWP must be at least 3 km long, even with the steepest bottom slopes known. Small pipeline diameters are inherently inefficient, due to friction losses and temperature increase. Because of this and the fact that the CWP represents almost 75% of the cost of current plant designs, optimisation studies conclude that plants smaller than about 50 MW cannot compete economically with other present energy alternatives. A 50 MW plant will require about 150 m/s of deep seawater, necessitating a pipeline with an inside diameter of at least 8 m. Current technology requires costly reinforced concrete pipe (RCP) or even more expensive fibreglass reinforced plastic (FRP) materials for pipelines of this diameter. Proposals for developing 'soft' pipelines, which deploy the pumps at the bottom end and use the water to 'inflate' the pipe, offer hope of significantly reducing the cost of these large pipelines.

OTEC is thus inherently a large-scale technology, requiring a large capital investment up front. The size of the investment dictates that, even though the process requires no fuel and will have relatively low operating costs, the investment will only be recouped over a number of years. The economic viability of OTEC is thus determined by factors such as the financing cost, the plant life-cycle and the future cost of competing energy sources. If an OTEC plant could be guaranteed to operate for 30 years without major overhaul, conservative projections of energy cost and interest rates predict a 30% return on investment, and investors would be eager to invest. However, it is not possible to predict the life cycle of a 50 MW plant from the limited intermittent operation of the largest plant built thus far, the 250 kW open cycle experiment at NELHA. World Bank advisors have determined that a pilot plant of about 5 MW operating for 5 years would be needed to justify investment in the full-scale technology. Such a plant would still be very expensive, however, and it would almost certainly lose money.

Some current projects plan to overcome this obstacle by building pilot-scale plants in situations where the high cost can be offset or justified by unusual circumstances. One such site is the US Navy base on the British Island of Diego Garcia in the Indian Ocean. The Navy is considering a proposal to replace the existing 15 MW gas turbine power plant there with an 8 MW OTEC plant backed up by a 2 MW gas turbine. This is possible because about 5 MW of the existing electrical load is for air conditioning and the existing 2 MW generator is primarily for backup anyway. An attractive side benefit is the ability to replace the island's dwindling freshwater supplies with drinking water that is either condensed from the atmosphere or produced from seawater in a flash distillation plant. Both of these processes use the deep seawater as a source of cold to promote the required condensation.

NELHA has also received a proposal to construct a closed-cycle plant using new 140 cm diameter surface and deep seawater pipelines that the State is installing primarily for aquaculture. The company plans to employ the new Kalina Cycle, producing about 1.3 MW gross electrical output to power the primary and secondary pumps that will supply seawater to the plant and to other users in the Hawaii Ocean Science and Technology (HOST), NELHA's commercial expansion area.

CURRENT STATUS

In addition to the pilot scale plants planned for Diego Garcia and Keahole Point, the State of Madras, India is preparing to build and test a 1 MW floating plant offshore[17]. Sea Solar Power, Inc. of York, PA, USA has proposed a 10 MW pilot plant on Guam and 100 MW floating plants for several areas around the world, but has been unsuccessful in obtaining financing[18]. The Puerto Rico Electric Power Authority has investigated OTEC for many years and has recently considered a plant on the offshore island of Vieques that is now used as a target island by the US Navy. The Japanese continue research and development on OTEC and sponsored a major 1999 symposium on OTEC and other deep ocean water applications (DOWA)[19]. The Taiwanese government has a long-standing interest in OTEC, and Taipei is home to the International OTEC/DOWA Association (IOA) which publishes a quarterly newsletter that serves as the primary link between OTEC/DOWA researchers worldwide[20].

PROSPECTS

As noted earlier, many island locations throughout the world are seriously considering installation of deep seawater supply systems for air conditioning. Most plan to develop additional by-product industries around the pipelines thus installed. Though such systems will not be of sufficient scale for economical OTEC power generation, they may lead to engineering developments in pipelines and pumps that will improve the feasibility of larger-scale OTEC systems.

In summary, OTEC has been shown to work at research scales, and plans are underway to build pilot scale plants. Private sector developers will probably be unwilling to make the enormous initial investment required by the inherent large scale of commercial OTEC until the price of fossil fuels increases dramatically and/or governments provide suitable financial incentives. If, however, the pilot scale plants now being planned for some expensive-energy niche markets are successful in demonstrating low-cost long-term operation, OTEC will be much more financially attractive. As it offers tremendous potential for reducing the input of CO_2 into our atmosphere, the development of OTEC should not be further delayed.

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