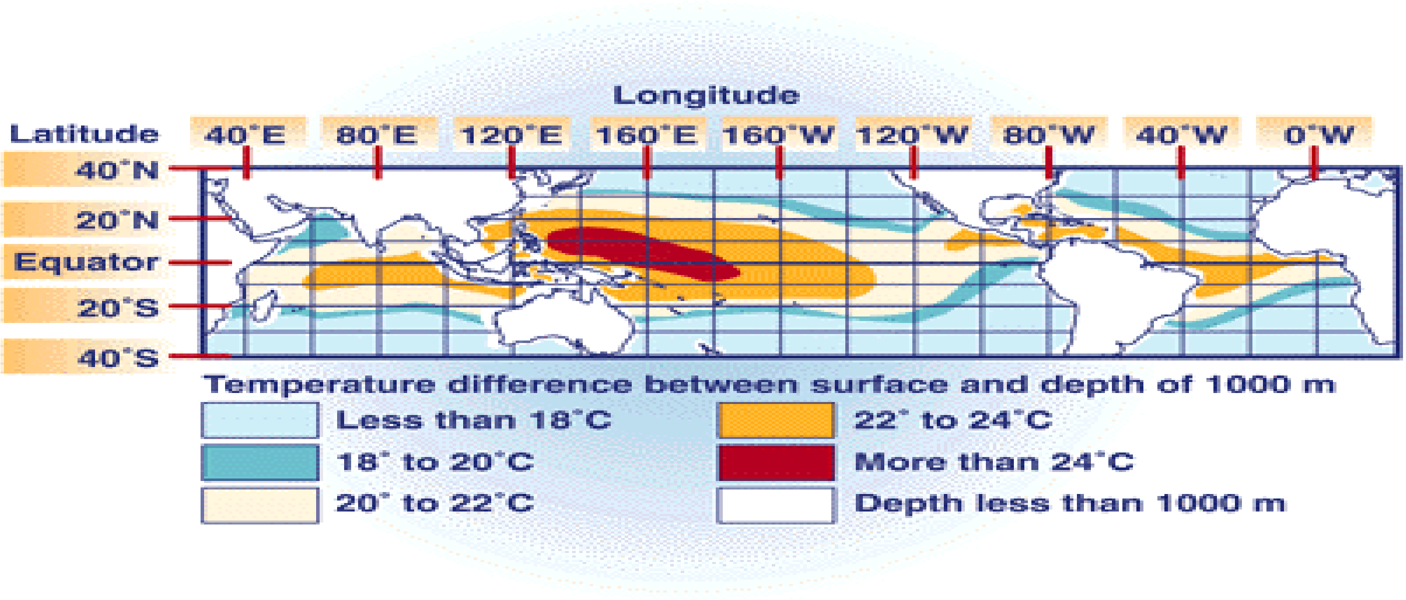
OCEAN THERMAL ENERGY COVERSION

1.0 INTRODUCTION

The oceans cover a little more than 70 percent of the Earth's surface. This makes them the world's largest solar energy collector and energy storage system. On an average day, 60 million square kilometers (23 million square miles) of tropical seas absorb an amount of solar radiation equal in heat content to about 250 billion barrels of oil.



A process called Ocean Thermal Energy Conversion (OTEC) uses the ocean's natural thermal gradient—the fact that the ocean's layers of water have different temperatures—to drive a power-producing cycle. OTEC works best when the temperature difference between the warmer, top layer of the ocean and the colder, deep ocean water is about 20ºC (36ºF). These conditions exist in tropical coastal areas, roughly between the Tropic of Capricorn and the Tropic of Cancer. The ideal energy conversion for 26 °C and 4 °C warm and cold seawaters is 8 percent. An actual OTEC plant will transfer heat irreversibly and produce entropy at various points in the cycle yielding an energy conversion of 3 to 4 percent. Considering practical sizes for the cold water pipe OTEC is presently limited to sizes of no more than about 100 MW. In the case of the open-cycle, due to the low-pressure steam, the turbine is presently limited to sizes of no more than 2.5 MW.

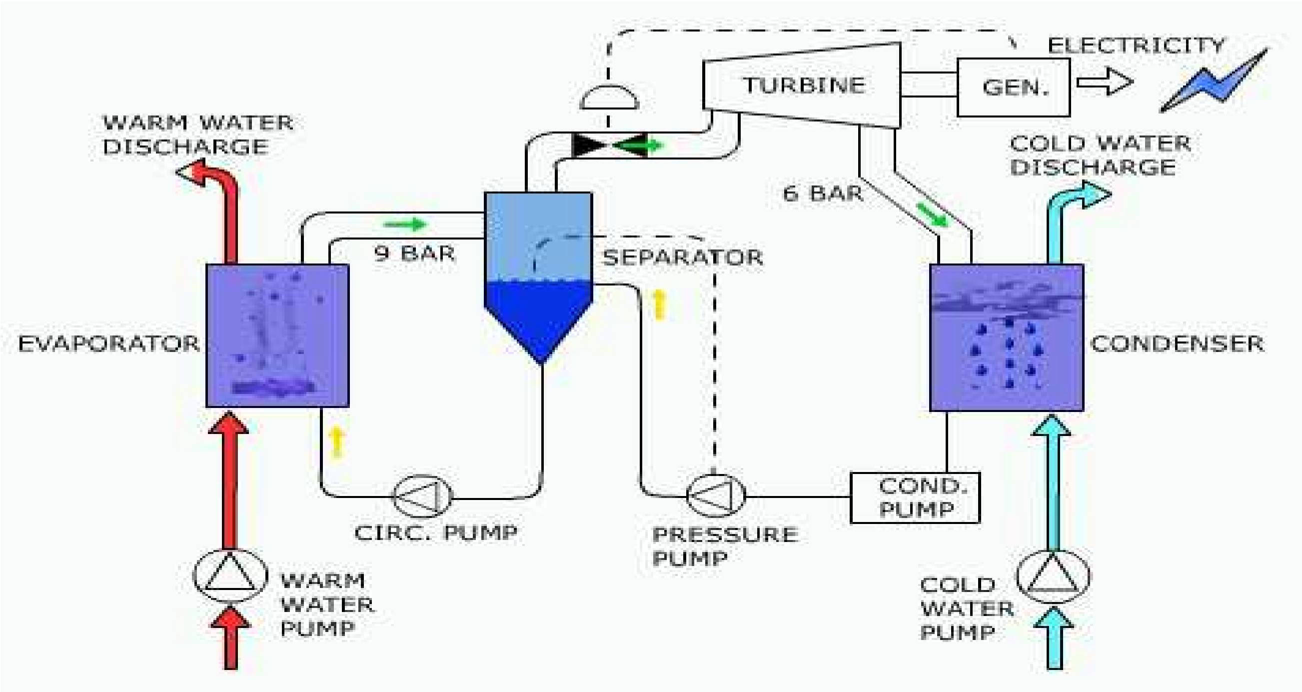
OTEC systems have many applications or uses. OTEC can be used to generate electricity, desalinate water, support deep-water mariculture, and provide refrigeration and air-conditioning as well as aid in crop growth and mineral extraction. These complementary products make OTEC systems attractive to industry and island communities even if the price of oil remains low. OTEC can also be used to produce methanol, ammonia, hydrogen, aluminum, chlorine, and other chemicals. Floating OTEC processing plants that produce these products would not require a power cable, and station-keeping costs would be reduced.

Some energy experts believe that if it could become cost-competitive with conventional power technologies, OTEC could produce billions of watts of electrical power. Bringing costs into line is still a huge challenge, however. All OTEC plants require an expensive, large diameter intake pipe, which is submerged a mile or more into the ocean's depths, to bring very cold water to the surface. This cold seawater is an integral part of each of the three types of OTEC systems: closed-cycle, open-cycle, and hybrid.

2.0 TECHNOLOGY DESCRIPTION

2.1 Closed-Cycle

Closed-cycle systems use fluid with a low-boiling point, such as ammonia, to rotate a turbine to generate electricity. Here's how it works. Warm surface seawater is pumped through a heat exchanger where the low-boiling-point fluid is vaporized. The expanding vapor turns the turbo-generator. Then, cold, deep seawater—pumped through a second heat exchanger—condenses the vapor back into a liquid, which is then recycled through the system.



2.2 Open-Cycle

Open-cycle OTEC uses the tropical oceans' warm surface water to make electricity. When warm seawater is placed in a low-pressure container, it boils. The expanding steam drives a low-pressure turbine attached to an electrical generator. The steam, which has left its salt behind in the low-pressure container, is almost pure fresh water. It is condensed back into a liquid by exposure to cold temperatures from deep-ocean water.

2.3 Hybrid

Hybrid systems combine the features of both the closed-cycle and open-cycle systems. In a hybrid system, warm seawater enters a vacuum chamber where it is flash-evaporated into steam, similar to the open-cycle evaporation process. The steam vaporizes a low-boiling-point fluid (in a closed-cycle loop) that drives a turbine to produces electricity.

3.0 TECHNOLOGY STATUS

Even though it sounds technologically sophisticated, OTEC technology is not new. It has progressed in fits and starts since the late 1800s. In 1881, Jacques Arsene d'Arsonval, a French physicist, proposed tapping the thermal energy of the ocean. But it was d'Arsonval's student, Georges Claude who actually built the first OTEC plant. Claude built his plant in Cuba in 1930. The system produced 22 kW of electricity with a low-pressure turbine. In 1935, Claude constructed another plant, this time aboard a 10,000-ton cargo vessel moored off the coast of Brazil. Weather and waves destroyed both plants before they became net power generators. (Net power is the amount of power generated after subtracting power needed to run the system.)

In 1956, French scientists designed another 3-MW OTEC plant for Abidjan, Ivory Coast, West Africa. The plant was never completed, however, because it was too expensive. The United States became involved in OTEC research in 1974, when the Natural Energy Laboratory of Hawaii Authority was established at Keahole Pointe on the Kona coast of Hawaii. The Laboratory has become one of the world's leading test facilities for OTEC technology. The Japanese government also continues to fund research and development in OTEC technology.

In 1979, the Natural Energy Laboratory and several private-sector partners developed the mini OTEC experiment, which achieved the first successful at-sea production of net electrical power from closed-cycle OTEC. The mini OTEC vessel was moored 1.5 miles (2.4 km) off the Hawaiian coast and produced enough net electricity to illuminate the ship's light bulbs, and run its computers and televisions.

Then, the Natural Energy Laboratory of Hawaii (NELHA) in 1999 tested a 250-kW pilot OTEC closed-cycle plant, the largest such plant ever put into operation. Since then, there have been no tests of OTEC technology in the United States, largely because the economics of energy production today have delayed the financing of a permanent, continuously operating plant.

In 1984, the Solar Energy Research Institute (now the National Renewable Energy Laboratory) developed a vertical-spout evaporator to convert warm seawater into low-pressure steam for open-cycle plants. Energy conversion efficiencies as high as 97 percent were achieved. In May 1993, an open-cycle OTEC plant at Keahole Point, Hawaii, produced 50,000 watts of electricity during a net power-producing experiment. This broke the record of 40,000 watts set by a Japanese system in 1982.

Other Uses of OTEC

OTEC has important benefits other than power production. For example, air conditioning can be a byproduct. Spent cold seawater from an OTEC plant can chill fresh water in a heat exchanger or flow directly into a cooling system. Simple systems of this type have air conditioned buildings at the Natural Energy Laboratory for several years.

OTEC technology also supports chilled-soil agriculture. When cold seawater flows through underground pipes, it chills the surrounding soil. The temperature difference between plant roots in the cool soil and plant leaves in the warm air allows many plants that evolved in temperate climates to be grown in the subtropics. The Natural Energy Laboratory maintains a demonstration garden near its OTEC plant with more than 100 different fruits and vegetables, many of which would not normally survive in Hawaii.

Aquaculture is perhaps the most well-known byproduct of OTEC. Cold-water delicacies, such as salmon and lobster, thrive in the nutrient-rich, deep, seawater from the OTEC process. Microalgae such as Spirulina, a health food supplement, also can be cultivated in the deep-ocean water.

As mentioned earlier, another advantage of open or hybrid-cycle OTEC plants is the production of fresh water from seawater. Theoretically, an OTEC plant that generates 2-MW of net electricity could produce about 4,300 cubic meters (14,118.3 cubic feet) of desalinated water each day.

OTEC may one day provide a means to mine ocean water for 57 trace elements. Most economic analyses have suggested that mining the ocean for dissolved substances would be unprofitable because so much energy is required to pump the large volume of water needed and because of the expense involved in separating the minerals from seawater. But with OTEC plants already pumping the water, the only remaining economic challenge is to reduce the cost of the extraction process.

Summary of OTEC Demonstration Plants in the World

S. No.	Agency	Year, Location	Power Rating(kW)		Cycle	Type of plant
			Gross	Net		
1.	Claude (France)	1930,Cuba	22	-	Open	Shore based
2.	Mini OTEC (US)	1979,Hawaii	53	18	Closed (Rankine)	Floating
3.	OTEC-1 (US)	1980,Hawaii	1MWe	-	Closed (Rankine)	Floating
4.	Toshiba & TEPC (Japan)	1982,Nauru,	120	31.5	Closed (Rankine)	Shore based
5.	NELHA (US)	1992,Hawaii	210	100	Open	Shore based
6.	Saga University (Japan)	1984,Saga	75	-	Closed (Rankine)	Lab model
7.	Saga University (Japan)	1995,Saga	9	-	Closed (Uehara)	Lab model
8.	NELHA (US)	1992-98, Hawaii	50	-	Closed (Rankine)	Floating
9.	*NIOT, India*	*2000, Tuticorin*	*1000*	-	*Closed (Rankine)*	*Floating*

Feedback about the above plants is enclosed at Annexure

4.0 COSTS

The OTEC power can be cost effective only if the unit cost of power produced is comparable with the fossil¡Vfuelled plants. OTEC system can also have other benefits like enhanced mari culture, desalination or even air conditioning, which might reduce the cost of electricity generated. As OTEC is capital intensive, Government agencies may provide substantial initiative in developing the technology. Dr. Luis A. Vega has done extensive work on OTEC economics for open cycle plants and closed cycle plants.

The co-production of fresh water along with power is to be considered for the estimation of unit cost for OTEC plants in islands. It is apparent from the study of Dr. Vega that OTEC is economical and production cost is comparative for higher range of plants. It could notice that OTEC plants of 100 MW range are competitive with other conventional energy sources such as coal or hydel power plants. There are steep cost improvements for these energy sources. The learning rate (the pattern of diminishing costs with increasing experience) is nearly 20% for photovoltaics and windmills. The same result can be expected for OTEC in future with increase in experience and development of technology.

Comparison of Unit Cost of OTEC with Conventional Energy Sources in Pacific Region (1990)

Technology	Plant capacity (MWe)	Plant Life (Years)	Capacity factor	Annual output (GWh)	Cost of energy (US$/kWh)
Wave	1.5	40	68%	9	0.062-0.072
Hydro	1.2	40	48%	5	0.113
Diesel	0.9	20	64%	5	0.126
OTEC	1.256	30	80%	8.8	0.149

Estimation of Unit Cost of Electricity from OTEC Power in India (1999)

Power Output Gross (MW)	Power Output Net (MW)	Heat Exchanger cost Million US$	Cost of cold water pipe Million US$	Cost of barge Million US$	Mooring cost Million US$	Turbine +Instn. cost Million US$	Total Cost Million US$	Cost of electricity US$/kWh
1.0	0.167	1.70	0.69	0.69	2.09	1.16	6.42	0.189
25.0	15.39	44.40	1.74	2.33	3.49	17.44	69.42	0.082
50.0	30.88	878.00	2.67	4.65	4.65	34.48	134.67	0.079
100.0	64.23	1526.00	4.65	9.30	5.81	69.76	242.10	0.068

5.0 CURRENT ISSUES & FUTURE PROSPECTS

It is postulated that most of the future commercial OTEC plants are closed-cycle, floating plants of 10-50 MW range. But plants of 200-400 MW range are also feasible and economically more attractive. The commercial plants should be proceeded by demonstration plants of smaller range for power cycle optimization and also for operational information. The design, development and operation of a power system in a hostile sea environment is a great challenge.

The capital cost of the plant is depending much on the heat exchanger cost and hence any improvement in the performance in this single component is an added advantage. Attempts are to be done to find out a proven technology for heat exchangers in seawater conditions with higher heat transfer co-efficient for considerable period of time. The design, fabrication and deployment of seawater system in the environment of the sea is a matter of considerable attention. New materials for the cold water pipe is to be developed to withstand the marine conditions and also for easy fabrication and deployment. The design of the barge also requires care so as to position the seawater pumps for the required Net Positive Suction Head (NPSH). The equipment and the piping system are to be assembled on the barge such a way that the static head and the minor losses are the least. Bio fouling on the warm water circuit and the release of the dissolved gasses in the cold water circuit is a problem to be attended for a considerably long period. As the floating plants are away from seashore under- water power transmission to the land is an area needed further study.

OTEC has tremendous potential to supply the world's energy. This potential is estimated to be about 10^{13} watts of baseload power generation. However, OTEC systems must overcome the significant hurdle of high initial capital costs for construction and the perception of significant risk compared to conventional fossil fuel plants. These obstacles can be overcome only by progressing beyond the present experimental testing and evaluation of small-scale demonstration plants to the construction of pilot-sized and, eventually, commerical-sized plants to demonstrate economic feasibility. As a UN Development Program study determined, the confidence to build commercial-sized OTEC plants will not develop until investors have the demonstration of a 5-megawatt pilot plant operating for 5 years. This demonstration will require a significant investment with little potential near-term return. It appears that OTEC technology might become more financially competitive if it could capitalize on the many value-added byproducts that can be produced from the deep seawater. Though many of these aquaculture and energy-related byproducts appear promising, insufficient data and economic models have thus far been developed to convince potential investors that the overall system will be profitable.

The key problem is now no longer technological or commercial, but the establishment of reliability and confidence. There is an absolute necessity to build demonstration plants representing the nature of future commercial plants.

Summary of OTEC Demonstration Plants in the World

S. No.	Agency	Year, Location	Power Rating(kW)		Cycle	Type of plant	Feedback
			Gross	Net			
1.	Claude (France)	1930, Cuba	22	-	Open	Shore based	The plant failed to achieve net power production because of a poor site selection (e.g., thermal resource) and a mismatch of the power and seawater systems. However, the plant did operate for several weeks. It did not survive for very long before being demolished by a storm.
2.	Mini OTEC (US)	1979, Hawaii	53	18	Closed (Rankine)	Floating	In 1979, the first successful at-sea, closed-cycle OTEC operation in the world was conducted aboard the Mini-OTEC, a converted Navy barge operating in waters off Keahole Point. This plant operated for three months, from August-October 1979, and generated approximately 50 kilowatts of gross power with net power ranging from 10-17 kilowatts. Its turbine generator produced a gross output of up to 55 kW. About 40 kW were required to pump up 2,700 gallons/min of 42°F water from 2200-ft depth through a 24-in diameter polyethylene pipe and an additional 2,700 gallons/min of 79°F surface water, leaving a maximum net power output of 15 kW. This was a joint effort by the State of Hawaii and a private industrial partner.
3.	OTEC-1 (US)	1980, Hawaii	1MWe	-	Closed (Rankine)	Floating	In 1980, OTEC-1, a converted Navy tanker moored in waters off Kawaihae on the Kona Coast, tested heat exchangers and other components of a closed-cycle OTEC plant and investigated the environmental effects of an ocean-stationed OTEC plant. It was not designed to generate electricity. This was a USDOE-funded project.
4.	Toshiba & TEPC (Japan)	1982, Nauru,	120	31.5	Closed (Rankine)	Shore based	In 1981, the Tokyo Power Company built a 100 kW shore-based, closed-cycle pilot plant on the island of Nauru. The plant achieved a net output of 31.5 kWe during continuous operating tests. This plant very effectively proved the principle of OTEC in practical terms over an extended period, before being decommissioned. This plant was operated for a few months to demonstrate the concept. They were

							too small to be scaled to commercial size systems.
5.	NELHA (US)	1992, Hawaii	210	100	Open	Shore based	The experimental plant was successfully operated for six years (1993-98). The highest production rates achieved were 255 kWe (gross) with a corresponding net power of 103 kW and 0.4 l s^{-1} of desalinated water. These are world records for OTEC. Following the experiments, the plant was demolished in January 1999.
6.	Saga University (Japan)	1984, Saga	75	-	Closed (Rankine)	Lab model	
7.	Saga University (Japan)	1995, Saga	9	-	Closed (Uehara)	Lab model	
8.	NELHA (US)	1992-98, Hawaii	50	-	Closed (Rankine)	Floating	A further PICHTR experiment at NELHA employed a closed-cycle plant to test specially developed aluminium heat exchangers. It used the (refurbished) turbine from "Mini-OTEC" to produce 50 kW gross power. During initial operation in May 1996, corrosion leaks developed in the heat exchanger modules; the plant had to be shut down and the units re-manufactured. From October 1998, when the new units were received until end-1999 – the end of the project - data were collected on the heat exchange and flow efficiencies of the heat exchangers and thus on the economic viability of competing types of heat exchangers.
9.	*NIOT, India*	*2000, Tuticorin*	*1000*	-	*Closed (Rankine)*	*Floating*	NIOT signed a memorandum of understanding with Saga University in Japan for the joint development of the plant. It has been reported that following detailed specifications, global tenders were placed at end-1998 for the design, manufacture, supply and commissioning of various sub-systems. The objective is to demonstrate the OTEC plant for one year, after which it could be moved to the Andaman & Nicobar Islands for power generation. NIOT has recently build the Sagar Shakti reseach vessel which will carry a 1 MW OTEC research plant