Ocean thermal energy conversion

Abstract

Ocean thermal energy conversion, or OTEC, is a way to generate electricity using the temperature difference of seawater at different depths. The method involves pumping cold water from the ocean depths (as deep as 1 km) to the surface and extracting energy from the flow of heat between the cold water and warm surface water.

OTEC utilizes the temperature difference that exists between deep and shallow waters — within 20° of the equator in the tropics — to run a heat engine. Because the oceans are continually heated by the sun and cover nearly 70% of the Earth's surface, this temperature difference contains a vast amount of solar energy which could potentially be tapped for human use. If this extraction could be done profitably on a large scale, it could be a solution to some of the human population's energy problems. The total energy available is one or two orders of magnitude higher than other ocean energy options such as wave power, but the small size of the temperature difference makes energy extraction difficult and expensive. Hence, existing OTEC systems have an overall efficiency of only 1 to 3%.

The concept of a heat engine is very common in engineering, and nearly all energy utilized by humans uses it in some form. A heat engine involves a device placed between a high temperature reservoir (such as a container) and a low temperature reservoir. As heat flows from one to the other, the engine extracts some of the heat in the form of work. This same general principle is used in steam turbines and internal combustion engines, while refrigerators reverse the natural flow of heat by "spending" energy. Rather than using heat energy from the burning of fuel, OTEC power draws on temperature differences caused by the sun's warming of the ocean surface.

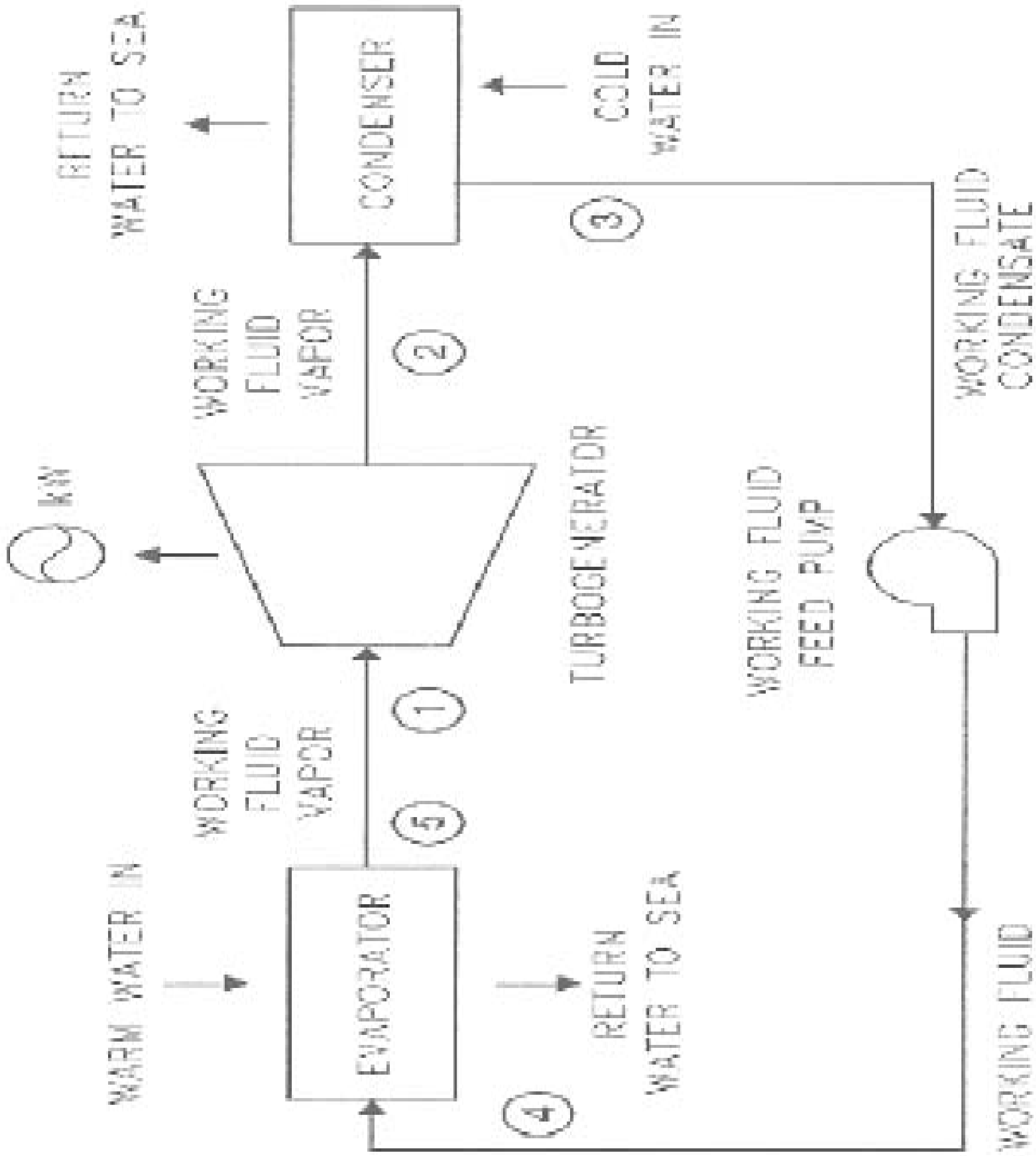
CONTENTS

Introduction

Ocean Thermal Energy conversion:-

Ocean Thermal Energy Conversion (OTEC) is a process which utilizes the heat energy stored in the tropical ocean. The world's oceans serve as a huge collector of heat energy. OTEC utilizes the difference in temperature between warm, surface seawater and cold, deep seawater to produce electricity. OTEC requires a temperature difference of about 36 deg F (20 deg C). This temperature difference exists between the surface and deep seawater year round throughout the tropical regions of the world. In one, simple form of OTEC a fluid with a low boiling point (e.g. ammonia) is used and turned into vapor by heating it up with warm seawater. The pressure of the expanding vapor turns a turbine and produces electricity. Cold sea water is then used to reliquify the fluid. Other forms of OTEC also exist as explained in the sites listed below. One important bi-product of many of these techniques is fresh water. This is also an indirect method of utilizing solar energy. A large amount of solar energy is collected and stored in tropical oceans. The surface of the water acts as the collector for solar heat, while the upper layer of the sea constitutes infinite heat storage reservoir. Thus the heat contained in the oceans, could be converted into electricity by utilizing the fact that the temperature difference between the warm surface waters of the tropical oceans and the colder waters in the depths is about 20 – 25o k. Utilization of this energy, with its associated temperature difference and its conversion into work, forms the basis of ocean thermal energy conversion (OTEC) systems. The surface water which is t higher temperature could be used to heat some low boiling organic fluid, the vapours of which would run a heat engine. The exit vapours would be condensed by pumping cold water from the deeper regions. The amount of energy available for ocean thermal power generation is enormous, and is replenished continuously. Several such plants are built in France after World War II (the largest of which has a capacity of 7.5 MW) wit6h a 22o K temperature difference between surface and depths, such as exists in warmer ocean areas than the north sea, the carnot efficiency is around 7%. This is obviously very low.

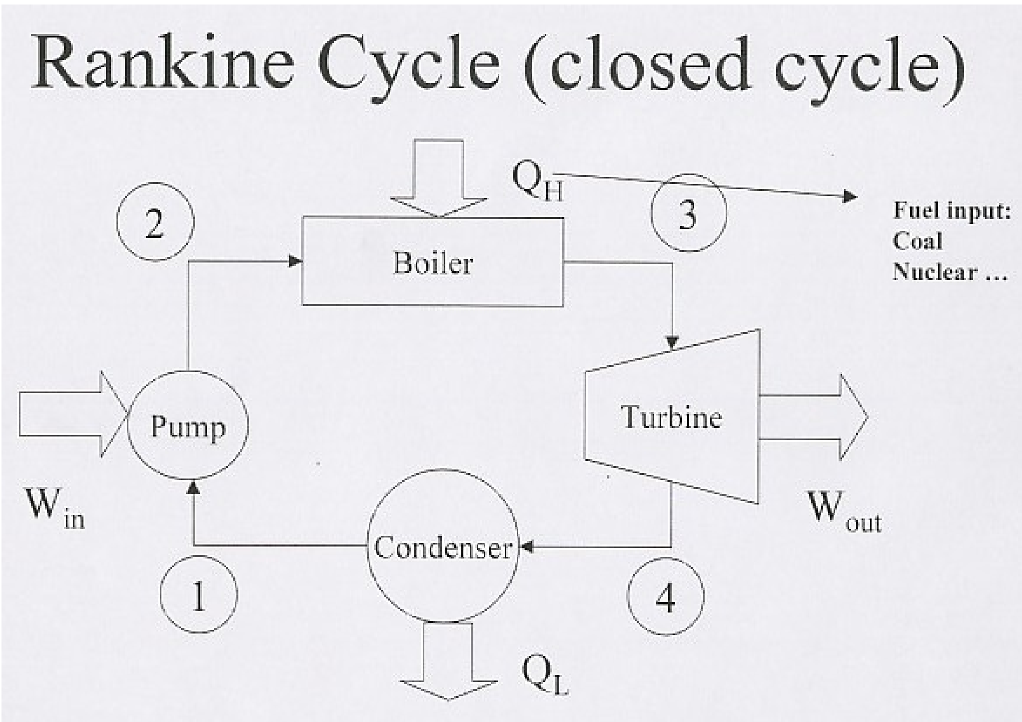
<u>Ocean Thermal Energy Conversion: OTEC</u>: -



<u>Rankine cycle OTEC plant</u>: -

The warm surface water is used for supplying the heat input in boiler, while the cold water brought up from the ocean depths is used for extracting the heat in the condenser.

In India, Department of Non – conventional energy sources (DNES) has proposed to install a 1 MW OTEC plant in Lakshadweep Island at Kavaratti and Minicoy. Preliminary oceanographic studies the eastern side of Lakshadweep Island suggest the possibility of the establishment of shore based OTEC plant at the Island with a cold water pipe line running down the slope to a depth of 800-1000m. Both he Islands have large lagoons on the western side. The lagoons are very shallow with hardly any nutrient in the sea water. The proposed OTEC plant will bring up the water from 1000m depth which has high nutrient value. After providing the cooling effect in the condenser, a part of sea waster is proposed to be diverted to the lagoons for the development of aqua culture.



Rankine Cycle Description: -

1-2: Liquid water pumped to a higher pressure adiabatically: -

T1<T2, P1<P2

Work is added to run the pump Win= (-)

No heat is transferred Q = 0

2-3: Heat is added by boiling the water: -

T2<T3, P2=P3

No work is added W = 0

Heat is added QH= 0

3-4: High pressure steam drives the turbine adiabatically: -

T3>T4, P3>P4

Work is generated by the turbine Wout= (+)

No heat is transferred Q = 0

4-1: Steam is condensed to liquid water: -

T4=T1, P4=P1

No work is added W = 0

Heat is removed QL= (-)

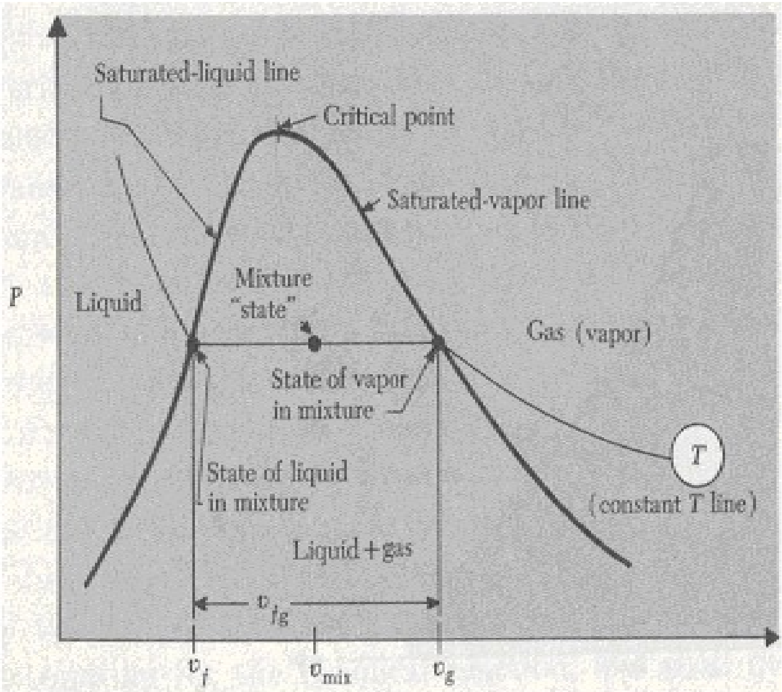
Rankine Cycle PV diagram: -

•Water is the working fluid in the Rankine Cycle

•The water exists in two phases: liquid and steam

•The heat (QH) added to the boiler comes from burning coal, burning liquid fuels, or from a nuclear reactor

•The steam exiting the turbine is converted to a liquid in the condenser because it is more efficient to pump a liquid



Background and History of OTEC Technology

In 1881, Jacques Arsene d'Arsonval, a French physicist, was the first to propose tapping the thermal energy of the ocean. Georges Claude, a student of d'Arsonval's, built an experimental open-cycle OTEC system at Matanzas Bay, Cuba, in 1930. The system produced 22 kilowatts (kW) of electricity by using a low-pressure turbine. In 1935, Claude constructed another open-cycle plant, this time aboard a 10,000-ton cargo vessel moored off the coast of Brazil. But both plants were destroyed by weather and waves, and Claude never achieved his goal of producing net power (the remainder after subtracting power needed to run the system) from an open-cycle OTEC system.

Then in 1956, French researchers designed a 3-megawatt (electric) (MWe) open-cycle plant for Abidjan on Africa's west coast. But the plant was never completed because of competition with inexpensive hydroelectric power. In 1974 the Natural Energy Laboratory of Hawaii (NELHA, formerly NELH), at Keahole Point on the Kona coast of the island of Hawaii, was established. It has become the world's foremost laboratory and test facility for OTEC technologies.

In 1979, the first 50-kilowatt (electric) (kWe) closed-cycle OTEC demonstration plant went up at NELHA. Known as "Mini-OTEC," the plant was mounted on a converted U.S. Navy barge moored approximately 2 kilometers off Keahole Point. The plant used a cold-water pipe to produce 52 kWe of gross power and 15 kWe net power.

In 1980, the U.S. Department of Energy (DOE) built OTEC-1, a test site for closed-cycle OTEC heat exchangers installed on board a converted U.S. Navy tanker. Test results identified methods for designing commercial-scale heat exchangers and demonstrated that OTEC systems can operate from slowly moving ships with little effect on the marine environment. A new design for suspended cold-water pipes was validated at that test site. Also in 1980, two laws were enacted to promote the commercial development of OTEC technology: the Ocean Thermal Energy Conversion Act, Public Law (PL) 96-320, later modified by PL 98-623, and the Ocean Thermal Energy Conversion Research, Development, and Demonstration Act, PL 96-310.

At Hawaii's Seacoast Test Facility, which was established as a joint project of the State of Hawaii and DOE, desalinated water was produced by using the open-cycle process. And a 1-meter-diameter col seawater/0.7-meter-diameter warm-seawater supply system was deployed at the Seacoast Test Facility to demonstrate how large polyethylene cold-water pipes can be used in an OTEC system.

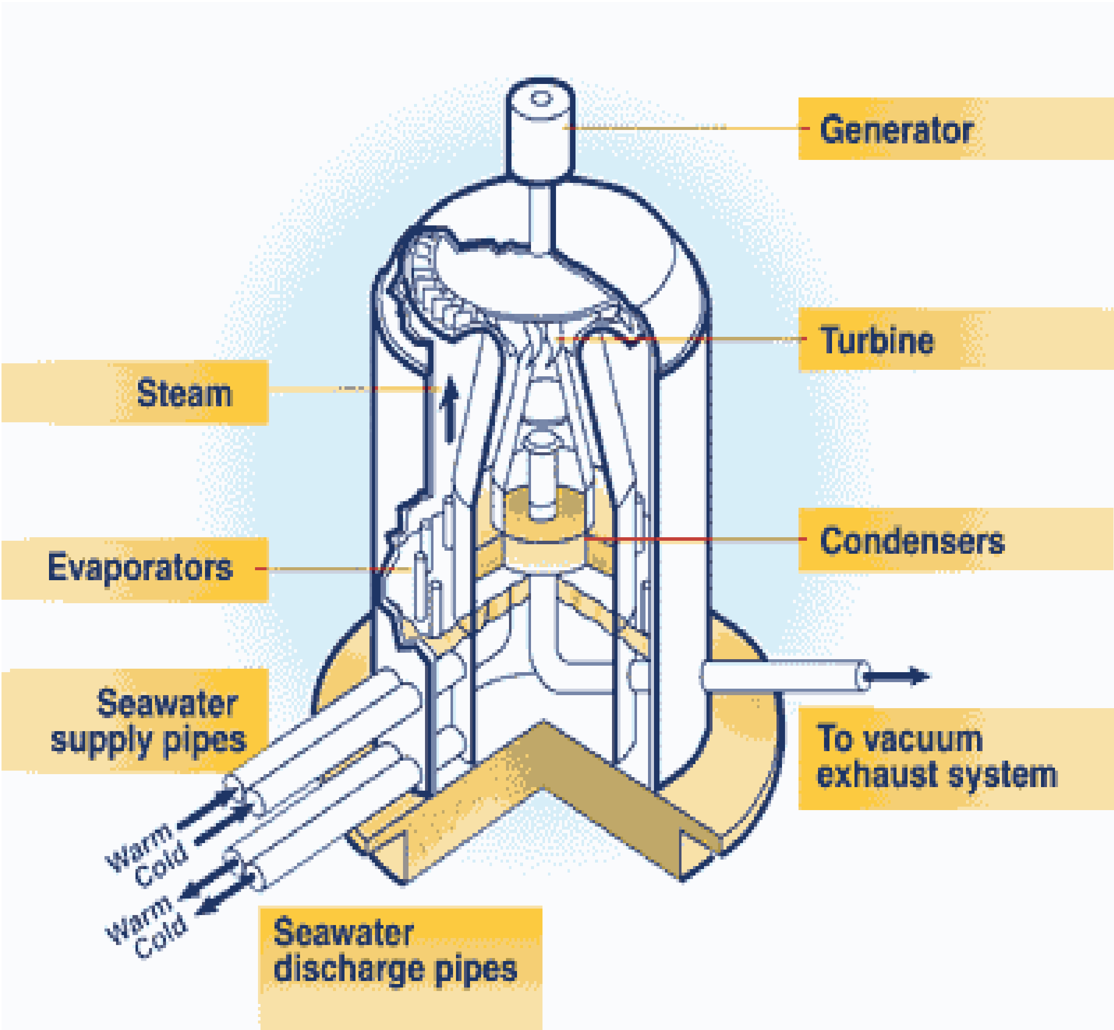
In 1981, Japan demonstrated a shore-based, 100-kWe closed-cycle plant in the Republic of Nauru in the Pacific Ocean. This plant employed cold-water pipe laid on the sea bed to a depth of 580 meters. Freon was the working fluid, and a titanium shell-and-tube heat exchanger was used. The plant surpassed engineering expectations by producing 31.5 kWe of net power during continuous operating tests.

Later, tests by the U.S. DOE determined that aluminum alloy can be used in place of more expensive titanium to make large heat exchangers for OTEC systems. And at-sea tests by DOE demonstrated that biofouling and corrosion of heat exchangers can be controlled. Biofouling does not appear to be a problem in cold seawater systems. In warm seawater systems, it can be controlled with a small amount of intermittent chlorination (70 parts per billion per hour per day).

In 1984, scientists at a DOE national laboratory, the Solar Energy Research Institute (SERI, 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% were achieved. Direct-contact condensers using advanced packings were also shown to be an efficient way to dispose of steam. Using freshwater, SERI staff developed and tested direct-contact condensers for open-cycle OTEC plants.

British researchers, meanwhile, have designed and tested aluminum heat exchangers that could reduce heat exchanger costs to $1500 per installed kilowatt capacity. And the concept for a low-cost soft seawater pipe was developed and patented. Such a pipe could make size limitations unnecessary, as well as improve the economics of OTEC systems.

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. Today, scientists are developing new, cost-effective, state-of-the-art turbines for open-cycle OTEC systems.



How OTEC works

Some energy experts believe that if it could become cost-competitive with conventional power technologies, OTEC could produce gigawatts 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.

Depending on the location

- Land based plant
- Shelf based plant
- Floating plant
- Submerged plant (conceptual)

Depending on the cycle used

- Open cycle
- Closed cycle
- Hybrid cycle

This cold seawater is an integral part of each of the three types of OTEC systems: closed-cycle, open-cycle, and hybrid.

Closed-cycle: -

Closed-cycle systems use fluid with a low boiling point, such as ammonia, to rotate a turbine to generate electricity. 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.

In 1979, the Natural Energy Laboratory and several private-sector partners developed the mini OTEC experiment, which achieved the first successful at-sea production 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 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. Outside the United States, the government of India has taken an active interest in OTEC technology. India has built and plans to test a 1 MW closed-cycle, floating OTEC plant.

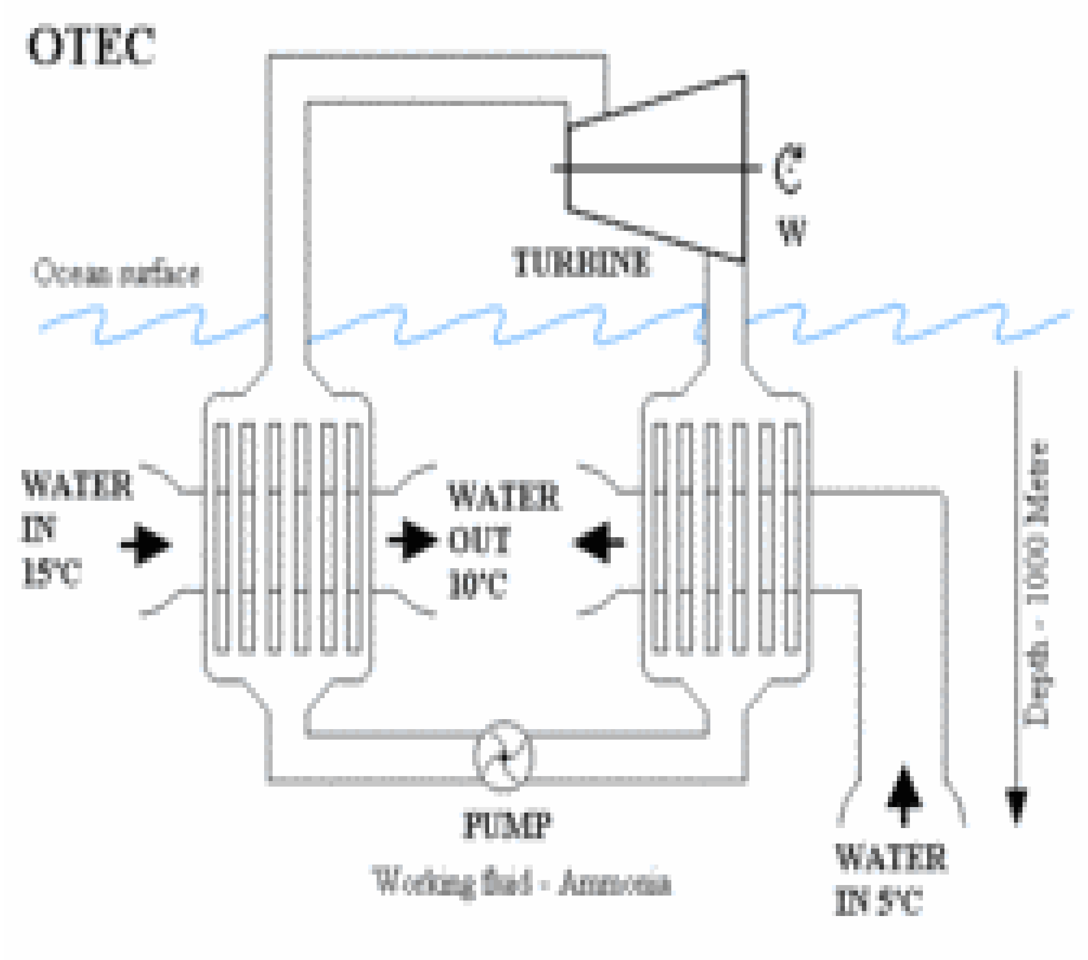


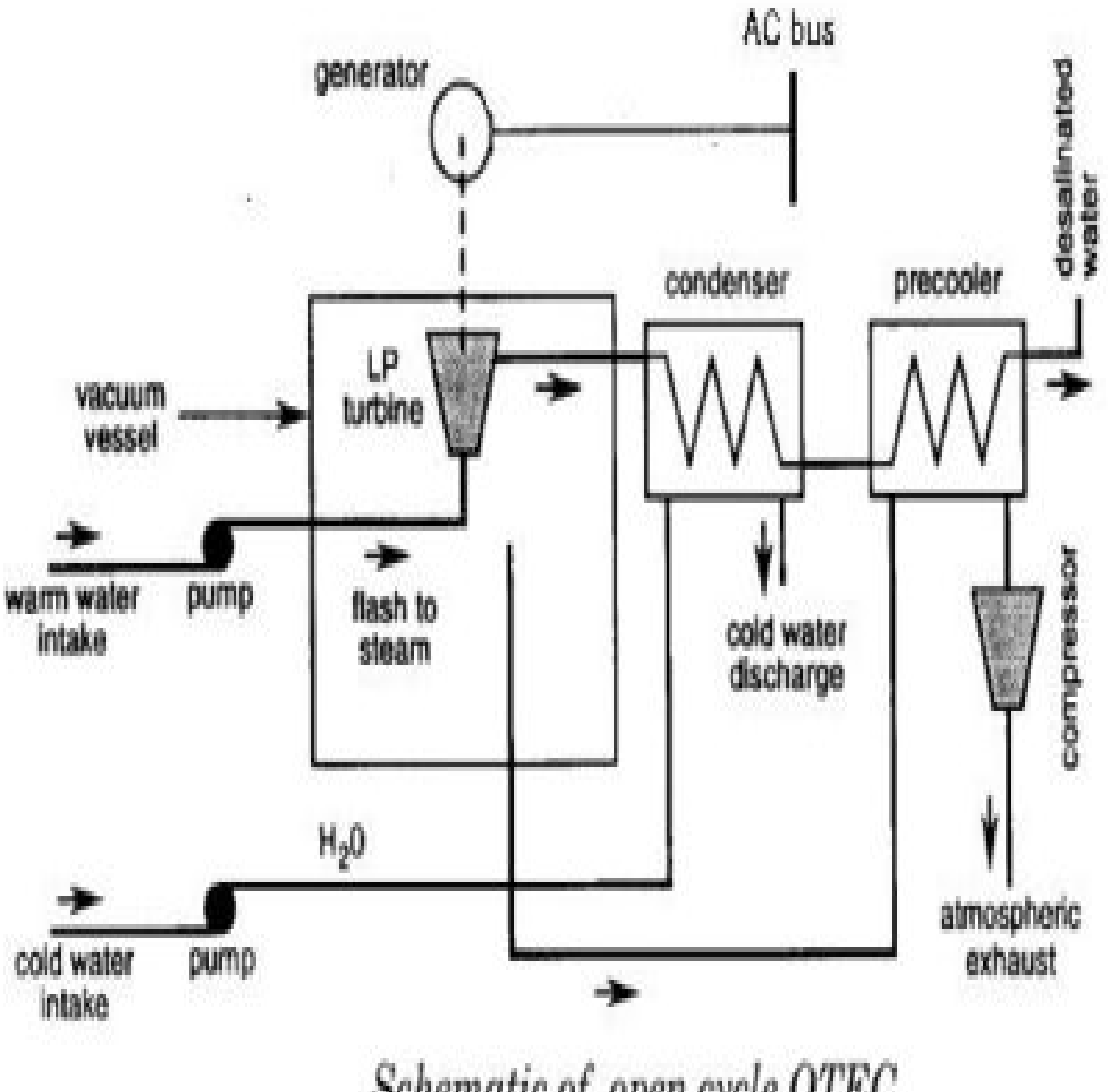
Diagram of a closed cycle OTEC plant

<u>Open-cycle</u>: -

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.

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% were achieved for the seawater to steam conversion process (note: the overall efficiency of an OTEC system using a vertical-spout evaporator would still only be a few per cent). 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.



Schematic of open cycle OTEC

Hybrid cycle: -

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 produce electricity.

OTEC Plant Design and Location

Commercial ocean thermal energy conversion (OTEC) plants must be located in an environment that is stable enough for efficient system operation. The temperature of the warm surface seawater must differ about 20°C (36°F) from that of the cold deep water that is no more than about 1000 meters (3280 feet) below the surface. The natural ocean thermal gradient necessary for OTEC operation is generally found between latitudes 20 deg N and 20 deg S. Within this tropical zone are portions of two industrial nations—the United States and Australia—as well as 29 territories and 66 developing nations. Of all these possible sites, tropical islands with growing power requirements and a dependence on expensive imported oil are the most likely areas for OTEC development.

Commercial OTEC facilities can be built on

* Land or near the shore
* Platforms attached to the shelf
* Moorings or free-floating facilities in deep ocean water.

Land-Based and Near-Shore Facilities

Land-based and near-shore facilities offer three main advantages over those located in deep water. Plants constructed on or near land do not require sophisticated mooring, lengthy power cables, or the more extensive maintenance associated with open-ocean environments. They can be installed in sheltered areas so that they are relatively safe from storms and heavy seas. Electricity, desalinated water, and cold, nutrient-rich seawater could be transmitted from near-shore facilities via trestle bridges or causeways. In addition, land-based or near-shore sites allow OTEC plants to operate with related industries such as mariculture or those that require desalinated water.

Favored locations include those with narrow shelves (volcanic islands), steep (15-20 deg) offshore slopes, and relatively smooth sea floors. These sites minimize the length of the cold-water intake pipe. A land-based plant could be built well inland from the shore, offering more protection from storms, or on the beach, where the pipes would be shorter. In either case, easy access for construction and operation helps lower the cost of OTEC-generated electricity.

Land-based or near-shore sites can also support mariculture. Mariculture tanks or lagoons built on shore allow workers to monitor and control miniature marine environments. Mariculture products can be delivered to market with relative ease via railroads or highways.

One disadvantage of land-based facilities arises from the turbulent wave action in the surf zone. Unless the OTEC plant's water supply and discharge pipes are buried in protective trenches, they will be subject to extreme stress during storms and prolonged periods of heavy seas. Also, the mixed discharge of cold and warm seawater may need to be carried several hundred meters offshore to reach the proper depth before it is released. This arrangement requires additional expense in construction and maintenance.

OTEC systems can avoid some of the problems and expenses of operating in a surf zone if they are built just offshore in waters ranging from 10 to 30 meters deep (Ocean Thermal Corporation 1984). This type of plant would use shorter (and therefore less costly) intake and discharge pipes, which would avoid the dangers of turbulent surf. The plant itself, however, would require protection from the marine environment, such as breakwaters and erosion-resistant foundations, and the plant output would need to be transmitted to shore.

Shelf-Mounted Facilities

To avoid the turbulent surf zone as well as to have closer access to the cold-water resource, OTEC plants can be mounted to the continental shelf at depths up to 100 meters. A shelf-mounted plant could be built in a shipyard, towed to the site, and fixed to the sea bottom. This type of construction is already used for offshore oil rigs. The additional problems of operating an OTEC plant in deeper water, however, may make shelf-mounted facilities less desirable and more expensive than their land-based counterparts. Problems with shelf-mounted plants include the stress of open-ocean conditions and more difficult product delivery. Having to consider strong ocean currents and large waves necessitates additional engineering and construction expense. Platforms require extensive pilings to maintain a stable base for OTEC operation. Power delivery could also become costly because of the long underwater cables required to reach land. For these reasons, shelf-mounted plants are less attractive for near-term OTEC development.

Floating Facilities

Floating OTEC facilities could be designed to operate off-shore. Although potentially preferred for systems with a large power capacity, floating facilities present several difficulties. This type of plant is more difficult to stabilize, and the difficulty of mooring it in very deep water may create problems with power delivery. Cables attached to floating platforms are more susceptible to damage, especially during storms. Cables at depths greater than 1000 meters are difficult to maintain and repair. Riser cables, which span the distance between the sea bed and the plant, need to be constructed to resist entanglement.

As with shelf-mounted plants, floating plants need a stable base for continuous OTEC operation. Major storms and heavy seas can break the vertically suspended cold-water pipe and interrupt the intake of warm water as well. To help prevent these problems, pipes can be made of relatively flexible polyethylene attached to the bottom of the platform and gimballed with joints or collars. Pipes may need to be uncoupled from the plant to prevent damage during storms. As an alternative to having a warm-water pipe, surface water can be drawn directly into the platform; however, it is necessary to locate the intake carefully to prevent the intake flow from being interrupted during heavy seas when the platform would heave up and down violently.

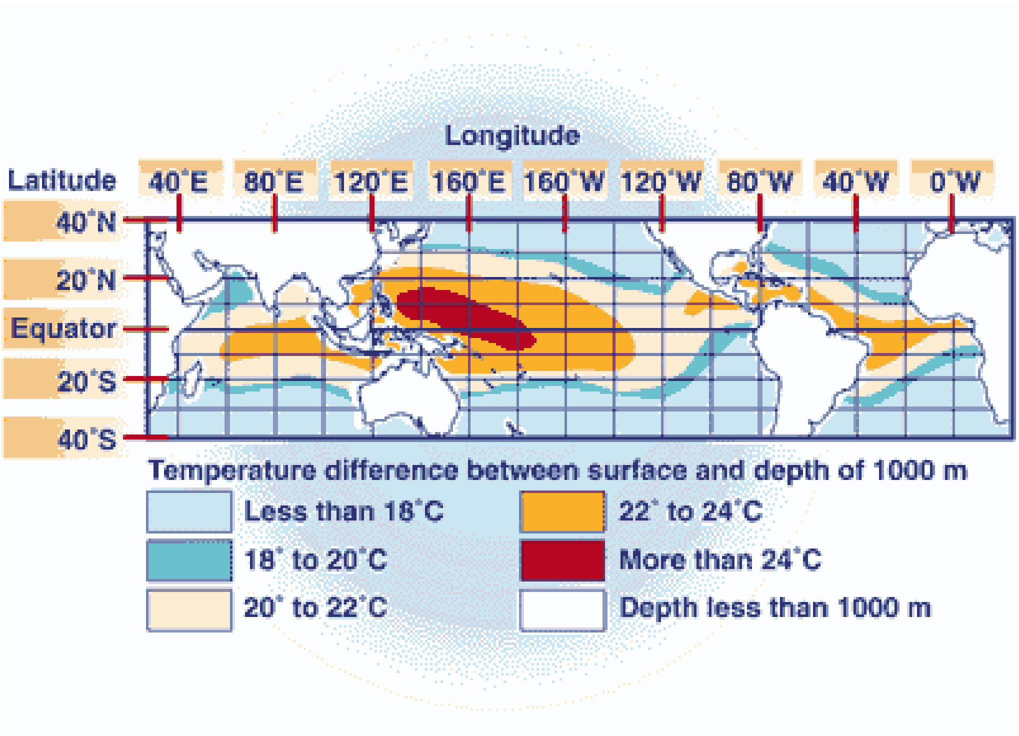
If a floating plant is to be connected to power delivery cables, it needs to remain relatively stationary. Mooring is an acceptable method, but current mooring technology is limited to depths of about 2000 meters (6560 feet). Even at shallower depths, the cost of mooring may prohibit commercial OTEC ventures. An alternative to deep-water OTEC may be drifting or self-propelled plantships. These ships use their net power on board to manufacture energy-intensive products such as hydrogen, methanol, or ammonia (Francis, Avery, and Dugger 1980).Electricity generated by plants fixed in one place can be delivered directly to a utility grid. A submersed cable would be required to transmit electricity from an anchored floating platform to land.

Less-Developed Countries with Adequate Ocean-Thermal Resources 25 Kilometers or Less from Shore		
Country/Area	**Temperature Difference (°C) of Water Between 0 and 1,000 m**	**Distance from Resource to Shore (km)**
Africa		
Benin	22-24	25
Gabon	20-22	15
Ghana	22-24	25
Kenya	20-21	25
Mozambique	18-21	25
São Tomé and Príncipe	22	1-10
Somalia	18-20	25
Tanzania	20-22	25
Latin America and the Caribbean		
Bahamas, The	20-22	15
Barbados	22	1-10
Cuba	22-24	1
Dominica	22	1-10
Dominican Republic	21-24	1
Grenada	27	1-10
Haiti	21-24	1
Jamaica	22	1-10
Saint Lucia	22	1-10
Saint Vincent and the Grenadines	22	1-10

Trinidad and Tobago	22-24	10
U.S. Virgin Islands	21-24	1
Indian and Pacific Oceans		
Comoros	20-25	1-10
Cook Islands	21-22	1-10
Fiji	22-23	1-10
Guam	24	1
Kiribati	23-24	1-10
Maldives	22	1-10
Mauritius	20-21	1-10
New Caledonia	20-21	1-10
Pacific Islands Trust Territory	22-24	1
Philippines	22-24	1
Samoa	22-23	1-10
Seychelles	21-22	1
Solomon Islands	23-24	1-10
Vanuatu	22-23	1-10

Markets for OTEC

An economic analysis indicates that, over the next 5 to 10 years, ocean thermal energy conversion (OTEC) plants may be competitive in four markets. The first market is the small island nations in the South Pacific and the island of Molokai in Hawaii. In these islands, the relatively high cost of diesel-generated electricity and desalinated water may make a small [1 megawatt (electric) (MWe)], land-based, open-cycle OTEC plant coupled with a second-stage desalinated water production system cost effective. A second market can be found in American territories such as Guam and American Samoa, where land-based, open-cycle OTEC plants rated at 10 MWe with a second-stage water production system would be cost effective. A third market is Hawaii, where a larger, land-based, closed-cycle OTEC plant could produce electricity with a second-stage desalinated water production system. OTEC should quickly become cost effective in this market, when the cost of diesel fuel doubles, for plants rated at 50 MWe or larger. The fourth market is for floating, closed-cycle plants rated at 40 MWe or larger that house a factory or transmit electricity to shore via a submarine power cable. These plants could be built in Puerto Rico, the Gulf of Mexico, and the Pacific, Atlantic, and Indian Oceans. Military and security uses of large floating plantships with major life-support systems (power, desalinated water, cooling, and aquatic food) should be included in this last category.



OTEC's greatest potential is to supply a significant fraction of the fuel the world needs by using large, grazing plantships to produce hydrogen, ammonia, and methanol. Of the three worldwide markets studied for small OTEC installations—U.S. Gulf Coast and Caribbean regions, Africa and Asia, and the Pacific Islands—the Pacific Islands are expected to be the initial market for open-cycle OTEC plants. This prediction is based on the cost of oil-fired power, the demand for desalinated water, and the social benefits of this clean energy technology. U.S. OTEC technology is focused on U.S. Coastal areas, including the Gulf of Mexico, Florida, and islands such as Hawaii, Puerto Rico, and the Virgin Islands

OCEAN THERMAL ENERGY CONVERSION: -

Ocean Thermal Energy Conversion (OTEC) is a means of converting into useful energy the temperature difference between surface water of the oceans in tropical and sub-tropical areas, and water at a depth of approximately 1 000 metres which comes from the polar regions. For OTEC a temperature difference of 20^{o}C is adequate, which embraces very large ocean areas, and favours islands and many developing countries. The continuing increase in demand from this sector of the world (as indicated by World Energy Council figures) provides a major potential Depending on the location of their cold and warm water supplies, OTEC plants can be land-based, floating, or – as a longer term development – grazing. Floating plants have the advantage that the cold water pipe is shorter, reaching directly down to the cold resource, but the power generated has to be brought ashore, and moorings are likely to be in water depths of, typically, 2 000 metres. The development of High Voltage DC transmission offers substantial advantage to floating OTEC, and the increasing depths for offshore oil and gas production over the last decade mean that mooring is no longer the problem which it once was – but still a significant cost item for floating OTEC. Land-based plants have the advantage of no power transmission cable to shore, and no mooring costs. However, the cold water pipe has to cross the surf zone and then follow the seabed until the depth reaches approximately 1 000 metres – resulting in a much longer pipe which has therefore greater friction losses, and greater warming of the cold water before it reaches the heat exchanger, both resulting in lower efficiency.

The working cycle may be closed or open, the choice depending on circumstances. All these variants clearly develop their power in the tropical and sub-tropical zones, but a longer-term development – a grazing plant – allows OTEC energy use in highly developed economies which lie in the world’s temperate zones. In this case the OTEC plant is free to drift in ocean areas with a high temperature difference, the power being used to split sea water into liquid hydrogen and liquid oxygen. The hydrogen, and in some cases where it is economic the oxygen too, is offloaded to shuttle tankers which take the product to energy-hungry countries. So, in time, all the world can benefit from OTEC, not just tropical and sub-tropical areas.

A further benefit of OTEC is that, unlike most renewable energies, it is base-load – the thermal resource of the ocean ensures the power source is available day or night, and with only modest variation from summer to winter. It is environmentally benign, and some floating OTEC plants would actually result in net CO_2 absorption. A unique feature of OTEC is the additional products which can readily be provided – food (aquaculture and agriculture); potable water; air conditioning; etc. (see Figure 16.2). In large part these arise from the pathogen-free, nutrient-rich, deep cold water. OTEC is therefore the basis for a whole family of Deep Ocean Water Applications (DOWA), which can also benefit the cost of generated electricity. Potable water production alone can reduce electrical generating costs by up to one third, and is itself in very considerable demand in most areas where OTEC can operate.

The relevance of environmental impact was given a considerable boost by the Rio and Kyoto summits, and follow-up actions have included a much greater emphasis on this aspect by a number of energy companies. Calculations for generating costs now take increasing account of "downstream factors" – for example the costs associated with CO_2 emissions. With such criteria included, OTEC/DOWA is becoming an increasingly attractive option. Even without this aspect, the technological improvements – such as the much smaller heat exchangers now required – have contributed to significantly reduced capital expenditure. On top of these two factors the world-wide trend to whole-life costing benefits all renewables when compared with those energy systems which rely on conventional fuels (and their associated costs), even when the higher initial maintenance costs of early OTEC/DOWA plants are taken into account. When compared with traditional fuels the economic position of OTEC/DOWA is now rapidly approaching equality, and work in Hawaii at the Pacific International Center for High Technology Research has contributed to realistic comparisons, as well as component development. Nations which previously might not have contemplated OTEC/DOWA activities have been given legal title over waters throughout the 200 nautical mile Exclusive Economic Zone (EEZ) associated with the UN Convention on the Law of the Sea (UNCLOS). Prior to that no investor – private or public – would seriously contemplate funding a new form of capital plant in such seas and oceans, but since UNCLOS a number of nations have worked steadily to prepare overall ocean policies and recent years have seen a number of these introduced – for example in Australia.

Despite the existence of EEZs, the low costs of many "traditional" energy resources in the recent past had not encouraged venture capital investment in OTEC/DOWA, but the currently higher costs of oil, plus the growing recognition of environmental effects noted above (and the associated costs) of some traditional fuels, are rapidly changing the economics of these in relation to OTEC/DOWA and other renewables. Technology transfer is a major factor in many maritime activities and OTEC/DOWA is no exception, in this case borrowing from the oil and gas industry – again as already noted.

It is *all* these factors which now place OTEC/DOWA within realistic reach of full economic commercialisation early in the 21st century. But, whilst a number of the components for an OTEC/DOWA plant are therefore either available, or nearly so, the inherent simplicity of a number of key elements of OTEC/DOWA still require refinement into an effective system, and this will need further R&D investment. Before OTEC/DOWA can be realised, this R&D must be completed to show clearly to potential investors, via a demonstration-scale plant, that the integrated system operates effectively, efficiently, economically, and safely.

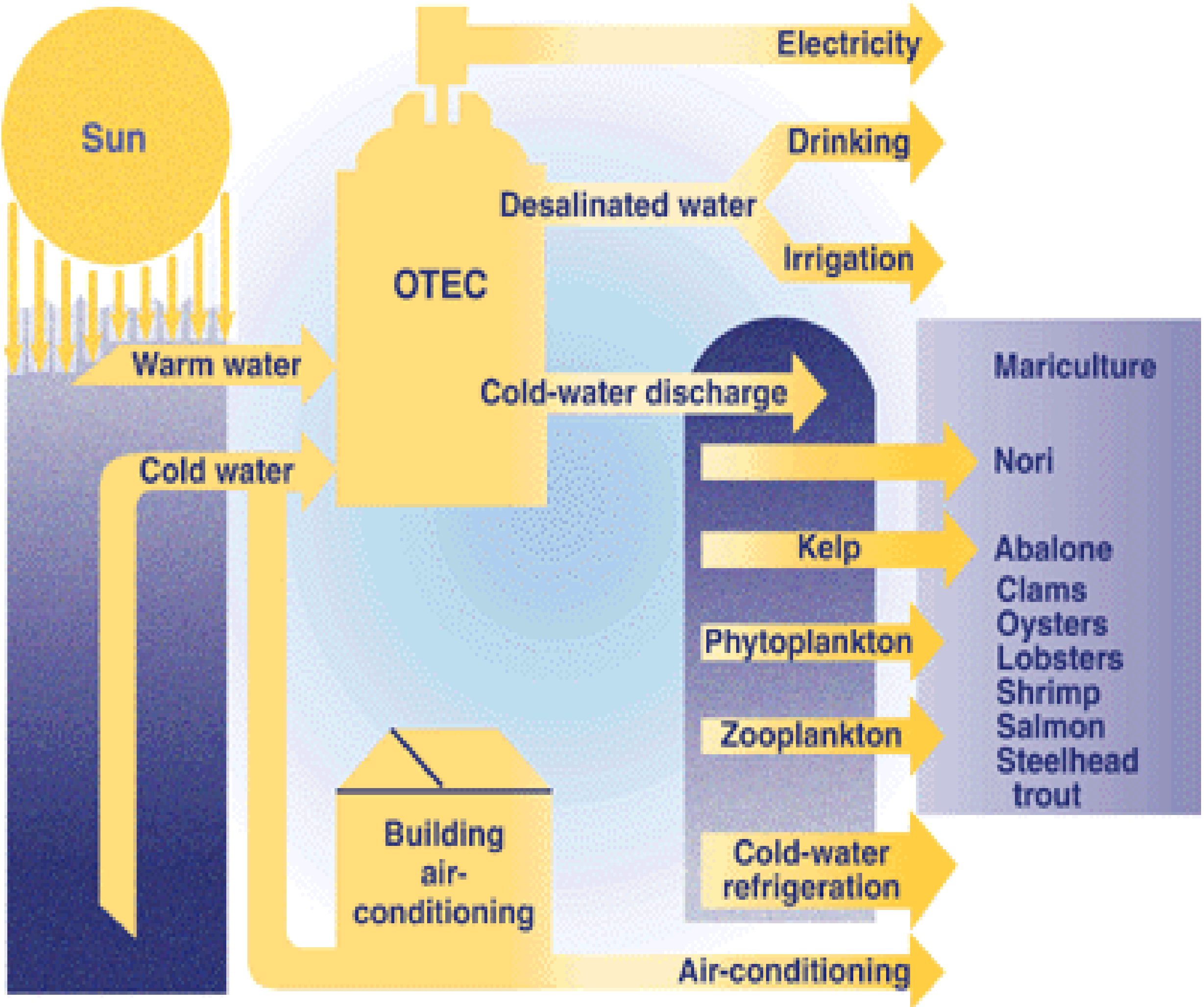


Figure: - OTEC Applications

(Source: US National Renewable Energy Laboratory)

Figure 16.3: 210kW OC-OTEC Experimental Plant (1993-1998) in Hawaii (Source: Luis A. Vega, Ph.D. Project Director)

Until such a representative-scale demonstrator plant is built and successfully operated, conventional capital funds are unlikely to be available. Whilst, therefore, the establishment of renewable energy subsidiaries of energy companies is important, there is no doubt that the principal hurdle remaining for OTEC/DOWA is not economic or technical, but the convincing of funding agencies – such as the World

Bank or the European Development Bank – that these techno-economic values are sufficiently soundly based for the funding of a demonstrator.

Specific national activities are referred to in the Country Notes which follow, but mention should be made here of Taiwan, China, which initiated and still hosts The International OTEC/DOWA Association (IOA), and which among other activities produces a regular Newsletter (Ref. 1) dealing with the subject of OTEC/DOWA. Over a lengthy period Taiwan, China has been extensively evaluating its DOWA/OTEC resource and a number of candidate sites for land-based OTEC and aquaculture were evaluated on the east coast. In 1995 a Master Plan was prepared for an extensive and ambitious floating OTEC programme, again for the east coast, an early stage of which would be a demonstrator, and extensive international review of these concepts was obtained.

In Europe, both the European Commission and the industrially based Maritime Industries Forum examined OTEC opportunities with relevance to DOWA in general rather than just OTEC, and in 1997 the UK published its Foresight document for the marine sector (Ref. 2), looking five to twenty years ahead, and both OTEC and DOWA were included in the energy sector of the paper (Ref. 3). It is significant that the emphasis in the recommendations from all three European groupings has, again, been on the funding and construction of a demonstrator. It is recommended to be in the 5-10 MW range, and remains the highest single priority. A further indication of the interest in DOWA, rather than OTEC alone, is provided by Japan where the industrial OTEC Association was succeeded by the Japan Association of Deep Ocean Water Applications. More recently there has been joint Indian/Japanese work. The island opportunities have already been mentioned, and in addition to Japan and Taiwan, the European work has stressed these as the best prospects, and it is noteworthy that both Japanese and British evaluations have identified Fijian prime sites, one each on the two largest islands of that group.

The worldwide market for renewables has been estimated (Ref. 4) for the timescales from 1990 to 2020 and 2050, with three scenarios, and all show significant growth. Within those total renewable figures, opportunities exist for the construction of a significant amount of OTEC capacity, even though OTEC may account for only a small percentage of total global electricity generating capacity for some years.

Estimates have been made by French, Japanese, British and American workers in the field, suggesting worldwide installed power of up to 1 000 OTEC plants by the year 2010, of which 50 % would be no larger than 10 MW, and less than 10 % would be of 100 MW size. On longer timescales the demand for OTEC in the Pacific/Asia region has been estimated at 20 GW in 2020 and 100 GW in 2050 (Ref. 5). But, again, realisation of all these numbers depends on the operation of the demonstrator at an early date.

In short, the key breakthrough now required for OTEC/DOWA is no longer technological or economic, but the establishment of confidence levels in funding agencies to enable building of a representative-scale demonstration plant. Given that demonstrator, the early production plants will be installed predominantly in island locations where conventional fuel is expensive, or not available in sufficient quantity, and where environmental impact is a high priority. Both simple OTEC and OTEC/DOWA combined plants will feature, depending on the particular requirements of each nation state. It can now realistically be claimed that the economic commercialisation of OTEC/DOWA is close – the demonstrator plant is likely to be built in the early years of the new century, and the higher profile of the IOA since 1995 is an indication of the "coming of age" of OTEC/DOWA resource recovery and exploitation

Other related technologies: -

Air conditioning: -

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.

Chilled-soil agriculture: -

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: -

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.

Desalination: -

Desalination, the production of fresh water from seawater, is another advantage of open or hybrid-cycle OTEC plants. Theoretically, an OTEC plant that generates 2 MW of net electricity could produce about 4,300 cubic meters (151,853 cubic feet) of desalinated water each day. This is equivalent to 4.3 million liters or 1.13 million (U.S.) gallons.

Mineral extraction: -

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.

Political Concerns: -

Because OTEC facilities are more-or-less stationary surface platforms, their exact location and legal status may be affected by the United Nations Convention on the Law of the Sea treaty (UNCLOS). This treaty grants coastal nations 3-, 12-, and 200-mile zones of varying legal authority from land, creating potential conflicts and regulatory barriers to OTEC plant construction and ownership. OTEC plants and similar structures would be considered artificial islands under the treaty, giving them no legal authority of their own. OTEC plants could be perceived as either a threat or potential partner to fisheries management or to future seabed mining operations controlled by the International Seabed Authority. The United States has not ratified the treaty as of 2006 despite strong internal support.

Cost and Economics: -

For OTEC to be viable as a power source, it must either gain political favor (ie. favorable tax treatment and subsidies) or become competitive with other types of power, which may themselves be subsidized. Because OTEC systems have not yet been widely deployed, estimates of their costs are uncertain. One study [1] estimates power generation costs as low as $.07 USD per kilowatt-hour, compared with $.07 for subsidized wind systems [2] and $.0192 for nuclear power. [3].

Besides regulation and subsidies, other factors that should be taken into account include OTEC's status as a renewable resource (with no waste products or limited fuel supply), the limited geographical area in which it is available [4], the political effects of reliance on oil, the development of alternate forms of ocean power such as wave energy and methane hydrates, and the possibility of combining it with aquaculture or filtration for trace minerals to obtain multiple uses from a single pump system.

Technical Analysis of OTEC systems: -

OTEC systems can be classified as two types based on the thermodynamic cycle (1) Closed cycle and (2) Open cycle.

Variation of ocean temperature with depth: -

The total insolation received by the oceans = (5.457×10^{18} MJ/yr) × 0.7 = 1.9×10^{18} MJ/yr. (taking an average clearness index of 0.5)

Only some 15% of this energy is absorbed. But this 15% is still huge enough.

We can use Lambert's law to quantify the solar energy absorption by water,

$$-\frac{dI(y)}{dy} = \mu I$$

Where, y is the depth of water, I is intensity and μ is the absorption coefficient. Solving the above differential equation,

$$I(y) = I_0 \exp(-\mu y)$$

The absorption coefficicent μ may range from 0.05 m^{-1} for very clear fresh water to 0.5 m^{-1} for very salty water.

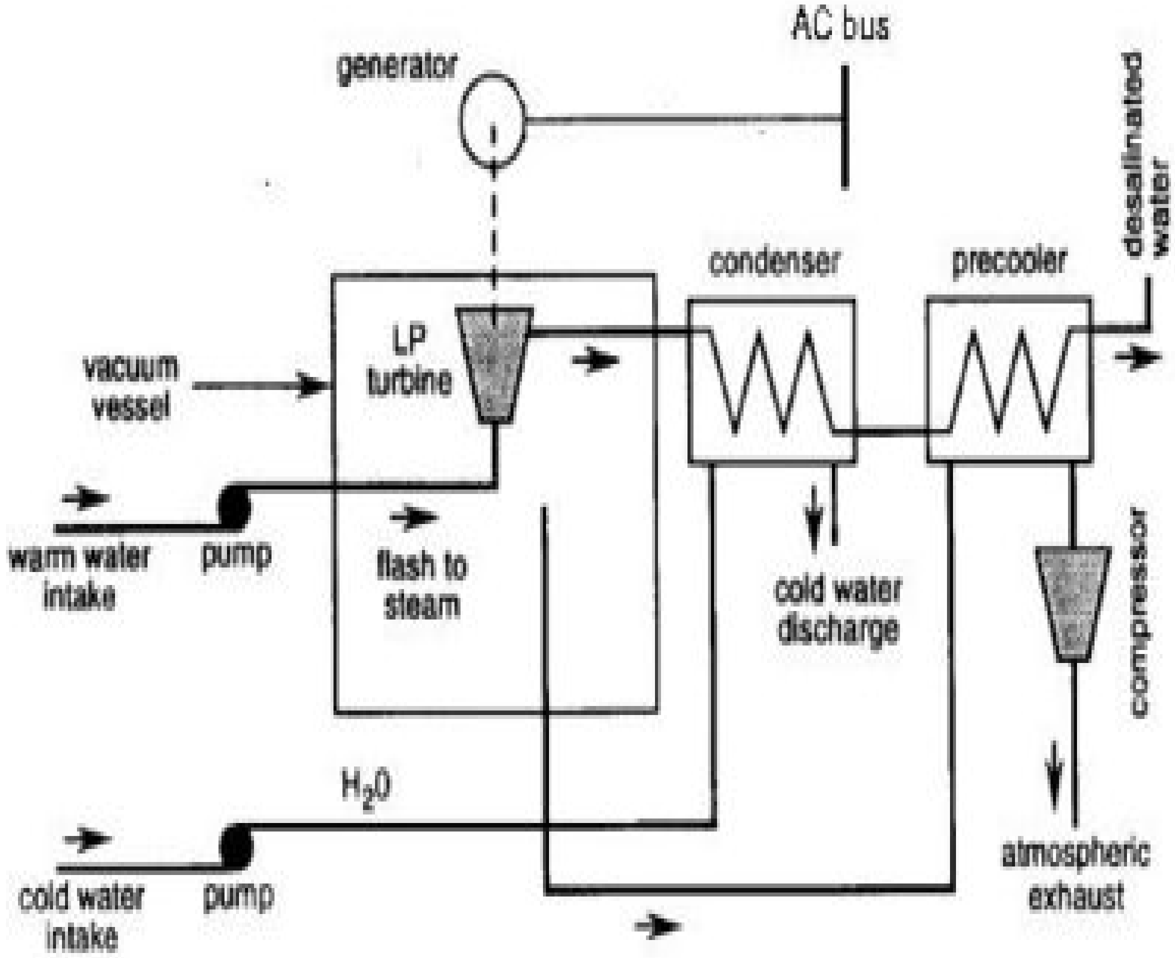
The open/Claude cycle

In this scheme, warm surface water at around 27 °C is admitted into an evaporator in which the pressure is maintained at a value slightly below the saturation pressure.

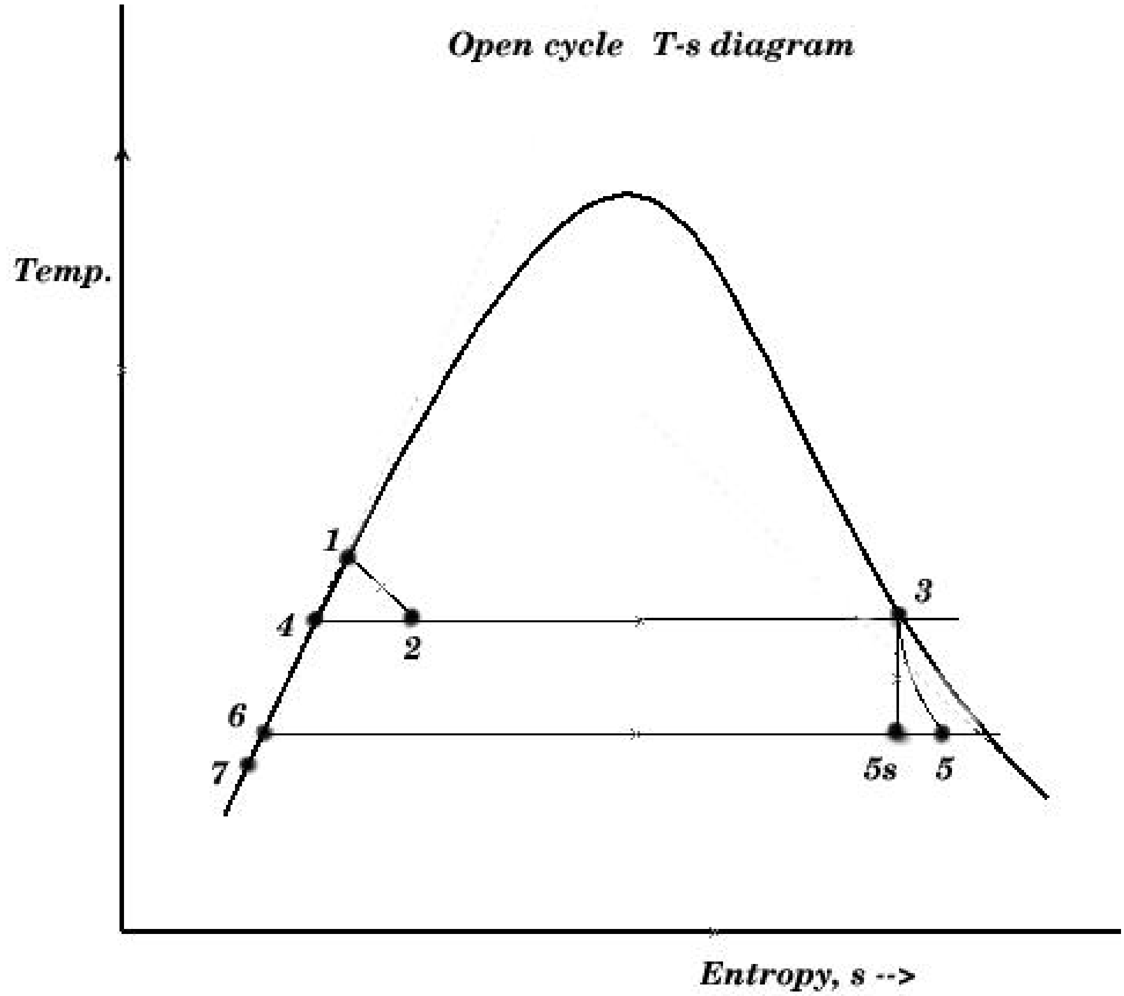
Water entering the evaporator is therefore superheated.

$$H_1 = H_f$$

Where H_f is enthalpy of liquid water at the inlet temperature, T_1



Schematic of open cycle OTEC



This temporarily superheated water undergoes volume boiling as opposed to pool boiling in conventional boilers where the heating surface is in contact. Thus the water partially flashes to steam with a two phase equilibrium prevailing. Suppose that the pressure inside the evaporator is maintained at the saturation pressure of water at T_2. This process being iso-enthalpic,

$$H_2 = H_1 = H_f + x_2 H_{fg}$$

Here, x_2 is the fraction of water by mass that has vaporized. The warm water mass flow rate per unit turbine mass flow rate is $1/x_2$.

The low pressure in the evaporator is maintained by a vacuum pump that also removes the dissolved non condensable gases from the evaporator. The evaporator now contains a mixture of water and steam of very low quality. The steam is separated from the water as saturated vapour. The remaining water is saturated and is discharged back to the ocean in the open cycle. The steam we have extracted in the process is a very low pressure, very high specific volume working fluid. It expands in a special low pressure turbine.

$$H_3 = H_g$$

Here, H_g corresponds to T_2. For an ideal adiabatic reversible turbine,

$$s_{5,s} = s_3 = s_f + x_{5,s} s_{fg}$$

The above equation corresponds to the temperature at the exhaust of the turbine, T_5. $x_{5,s}$ is the mass fraction of vapour at point 5.

The enthalpy at T_5 is,

$$H_{5,s} = H_f + x_{5,s} H_{fg}$$

This enthalpy is lower. The adiabatic reversible turbine work = H_3-$H_{5,s}$.

Actual turbine work $W_T = (H_3\text{-}H_{5,s}) \times$ *polytropic efficiency*

$$H_5 = H_3 - \text{ actual work}$$

The condenser temperature and pressure are lower. Since the turbine exhaust will be discharged back into the ocean anyway, a direct contact condenser is used. Thus the exhaust is mixed with cold water from the deep cold water pipe which results in a near saturated water. That water is now discharged back to the ocean.

H_6=H_f, at T_5. T_7 is the temperature of the exhaust mixed with cold sea water, as the vapour content now is negligible,

$$H_7 \approx H_f \ \ at\ T_7$$

There are the temperature differences between stages. One between warm surface water and working steam, one between exhaust steam and cooling water and one between cooling water reaching the condenser and deep water. These represent external irreversibilities that reduce the overall temperature difference.

The cold water flow rate per unit turbine mass flow rate,

$$m_c = \frac{\dot{H_5} - \ H_6}{H_6 - \ H_7}$$

Turbine mass flow rate, $\dot{M_T} = \dfrac{\text{turbine work required}}{W_T}$

Warm water mass flow rate, $\dot{M_w} = M_T \dot{m_w}$

Cold water mass flow rate $\dot{M_c} = \dot{M_T} m_C$

The closed/Anderson cycle

Developed starting in the 1960s by J. Hilbert Anderson of Sea Solar Power, Inc. In this cycle, Q_H is the heat transferred in the evaporator from the warm sea water to the working fluid. The working fluid exits from the evaporator as a gas near its dew point.

The high-pressure, high-temperature gas then is expanded in the turbine to yield turbine work, W_T. The working fluid is slightly superheated at the turbine exit and the turbine typically has an efficiency of 90% based on reversible, adiabatic expansion.

From the turbine exit, the working fluid enters the condenser where it rejects heat, -Q_C, to the cold sea water. The condensate is then compressed to the highest pressure in the cycle, requiring condensate pump work, W_C. Thus, the Anderson closed cycle is a Rankine-type cycle similar to the conventional power plant steam cycle except that in the Anderson cycle the working fluid is never superheated more than a few degrees Fahrenheit. It is realized that owing to viscous effects there must be working fluid pressure drops in both the evaporator and the condenser. These pressure drops, which are dependent on the types of heat exchangers used, must be considered in final design calculations but are ignored here to simplify the analysis. Thus, the parasitic condensate pump work, W_C, computed here will be lower than if the heat exchanger pressure drops were included. The major additional parasitic energy requirements in the OTEC plant are the cold water pump work, W_{CT}, and the warm water pump work, W_{HT}. Denoting all other parasitic energy requirements by W_A, the net work from the OTEC plant, W_{NP} is

$$W_{NP} = W_T + w_C + W_{CT} + W_{HT} + W_A$$

The thermodynamic cycle undergone by the working fluid can be analyzed without detailed consideration of the parasitic energy requirements. From the first law of thermodynamics, the energy balance for the working fluid as the system is

$$W_N = Q_H + Q_C$$

where $W_N = W_T + W_C$ is the net work for the thermodynamic cycle. For the special idealized case in which there is no working fluid pressure drop in the heat exchangers,

$$Q_H = \int_H T_H ds$$

and

$$Q_C = \int_C T_C ds$$

so that the net thermodynamic cycle work becomes

$$W_N = \int_H T_H ds + \int_C T_C ds$$

Subcooled liquid enters the evaporator. Due to the heat exchange with warm sea water, evaporation takes place and usually superheated vapor leaves the evaporator. This vapor drives the turbine and 2-phase mixture enters the condenser. Usually, the subcooled liquid leaves the condenser and finally, this liquid is pumped to the evaporator completing a cycle.

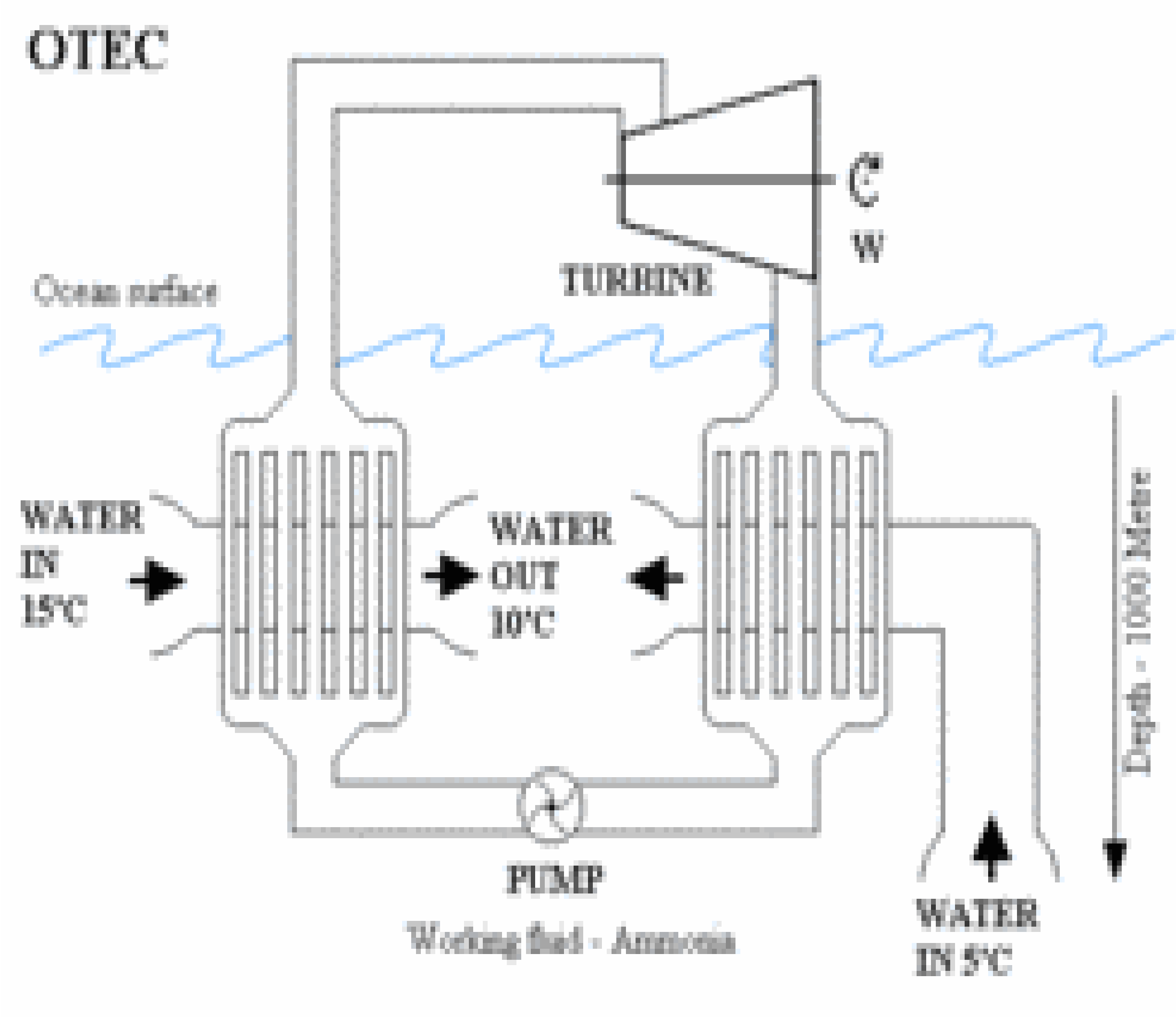


Figure: - Anderson cycle

<u>Working fluids</u>: -

Various fluids have been proposed over the past decades to be used in closed OTEC cycle. A popular choice is ammonia, which has superior transport properties, easy availability, and low cost. Ammonia, however, is toxic and flammable. Fluorinated carbons such as CFCs and HCFCs would have been a better choice had it not been for their contribution to ozone layer depletion. Hydrocarbons too are good candidates. But they are highly flammable. The power plant size is dependent upon the vapor pressure of the working fluid. For fluids with high vapor pressure, the size of the turbine and heat exchangers decreases while the wall thickness of the pipe and heat exchangers should increase to endure high pressure especially on the evaporator side.

Energy from temperature difference between cold air and warm water: -

In winter in coastal Arctic locations, the seawater temperature can be 40 degrees Celsius warmer than the local air temperature. Technologies based on closed-cycle OTEC systems could exploit this temperature difference. The lack of the need for long pipes to extract deep seawater might make a system based on this concept less expensive than OTEC.

Some proposed projects: -

OTEC projects on the drawing board include a small plant for the U.S. Navy base on the British island of Diego Garcia in the Indian Ocean. There, a proposed 8 MW OTEC plant, backed up by a 2 MW gas turbine, would replace an existing 15 MW gas turbine power plant. A private U.S. company also has proposed building at 10 MW OTEC plant on Guam.

References: -

1) Solar Engineering :- H.P. Gupta
2) Solar Thermal Engineering :- Duffie& Dackuran
3) Rewenable Energy Sources G.D. Rai
4) Solar Thermal Engineering system :- G.N. Tiwari.