The Blue Revolution – *ocean of energy in 'Ocean' (A review)*

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Abstract

India is blessed with a well-established maritime tradition has long coastline. In our tropical oceans, within about 25 degrees north and south latitudes, a temperature difference of about 20¼ °C exists between the waters at the surface of the ocean and at a depth of 1,000 m or so. The process of harnessing the energy due to this temperature difference is called Ocean Thermal Energy Conversion (OTEC). OTEC is an untapped, non-polluting, renewable energy source, which is appropriate for an energy starved nation like India. This method is capital intensive but the unit cost comes down drastically with higher rating plant and improvement in technology. This paper describes an outlook and a trend of the new OTEC technologies spreading rapidly now in the world.

1. Introduction

Ocean thermal energy conversion (OTEC) is a renewable energy technology that is applicable to most parts of the world's deep oceans between 20° North and 20° South latitude including the Caribbean and Gulf of Mexico, the Pacific, Atlantic and Indian Oceans, and the Arabian Sea, where the temperature difference between the warm surface ocean water and the cold deep ocean water is equal or greater than 20°C. In essence, OTEC basically recovers part of the solar energy absorbed by the ocean. Its main application is in tropical zones where deep ocean water is available at short distance from the shore (less than 6 miles or 10 km). In addition, the potential site must have a marine environment that allows the operation of a stable system.

2. History

The concept of OTEC was initially proposed by Jules Verne in the novel "20,000 Leagues under the Sea", which was published in France in 1869. French physicist Jacques Arsene D'Arsonval formally proposed the idea in 1881. His disciple, French engineer and businessman Dr. Georges Claude, adopted the idea and in 1930 built an OTEC open cycle plant at Matanzas Bay (Cuba), where a 22-kW generator system was used to light an array of lamps. The plant operated for a few days before being destroyed by a major storm (Brown et al. 2002; Claude 1930). During the 1950's and 1960's a number of research and development projects were conducted including design proposals by *Energie de Mers* or "Energy from the Sea" (Club des Argonautes) and by the Sea Water Conversion Laboratory at the University of California at Berkley.

In the following two decades the U.S. federal government launched various R&D programs that included performance tests, preliminary designs and demonstration plants. Major efforts include the preliminary design for a 40-MWe closed cycle floating plant by the Applied Physics Laboratory at the Johns Hopkins University, heat exchangers performance tests by the Argonne National Laboratory, and the demonstration plants in Hawaii (Mini-OTEC and OTEC-1). Other major R&D efforts during this period include the Toshiba/Tokyo Electric Power 100-kW closed cycle land-based plant at the Republic of Nauru, and the studies completed at the Natural Energy Laboratory of Hawaii (NELHA). This last one led to the construction and operation of a 210-kW open-cycle pilot plant for the co-production of electric power and potable water (Daniel 1999).

Today, the technology to build an OTEC plant is well known and the required components and equipment are available commercially, since these are used for other applications. The reason why a commercial plant has not been constructed yet has been essentially economical (Cohen 1982; Avery and Wu 1994). The focus of the federal government during the 1970's and 1980's was on nuclear energy, which had an impact on the available funds that could have been used to develop precommercial and commercial OTEC plants. Later on, during the 1990's price of oil went down to as low as $10 a barrel. This situation, plus the fact that there was no significant awareness in regards to global warming, made OTEC and other renewable energy sources less attractive.

3. What is OTEC? and Why?

Ocean Thermal Energy Conversion (OTEC) is a process that can produce electricity by using the temperature difference between deep cold ocean water and warm tropical surface waters. OTEC plants pump large quantities of deep cold seawater and surface seawater to run a power cycle and produce electricity. OTEC is firm power (24/7), is a clean energy source, is environmentally sustainable and is capable of providing massive levels of energy.

A basic closed-cycle OTEC plant is shown in the Figure 2 below. Warm seawater passes through an evaporator and vaporizes the working fluid, ammonia. The ammonia vapor passes through a turbine which turns a generator making electricity. The lower pressure vapor leaves the turbine and condenses in the condenser connected to a flow of deep cold seawater. The liquid ammonia leaves the condenser and is pumped to the evaporator to repeat the cycle.

The recent world events have created a new interest in OTEC. First, the price of oil has increased vertiginously, reaching high. The rise in the cost of oil will generate an increase in demand and cost of other fossil fuels such as coal and natural gas. More importantly, there is a general concern about the potential contribution to global warming of greenhouse gas emissions from combustion of fuels (from renewable or non-renewable sources).

For tropical countries the combination of high year-round sea surface temperature, relatively short distance from shore and excellent thermal profile of the oceans as shown in Figure 1, represent the ideal conditions for OTEC.

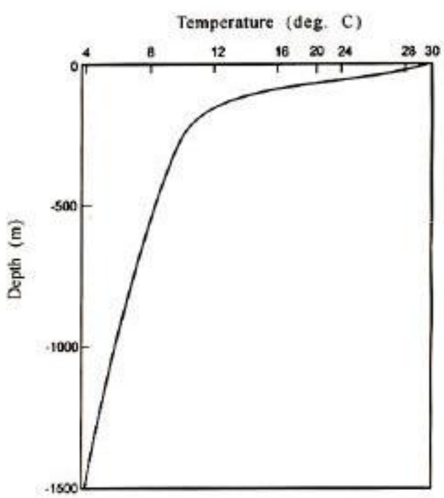

Figure 1. Ideal temperature profile for OTEC

While there are other renewable energy resources such as solar photovoltaic (PV) and wind power in existence, these cannot compete with the potential of OTEC. The wind power, for example, is limited in the amount of energy because of site requirement; PV is very costly, and available only during sunny daytime. Neither wind power nor PV can provide reliable base load power compared to OTEC. Additionally, they have no direct linkage with water and food production. Clearly, OTEC is in a class by itself as the best renewable energy resource.

4. Types of OTEC plants

Three basic OTEC system designs have been demonstrated to generate electricity: closed cycle, open cycle and hybrid cycle.

4.1. Closed-Cycle OTEC System

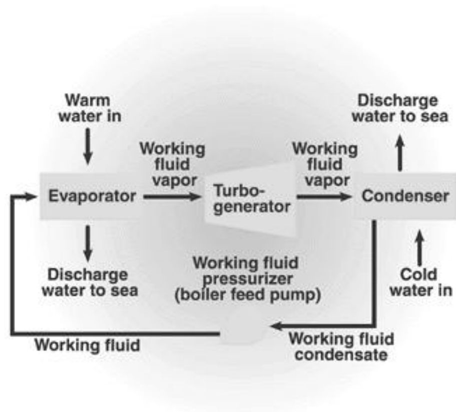

Figure 2. Closed-cycle OTEC system

In the closed-cycle OTEC system, warm seawater vaporizes a working fluid, such as ammonia, flowing through a heat exchanger (evaporator). The vapor expands at moderate pressures and turns a turbine coupled to a generator that produces electricity. The vapor is then condensed in another heat exchanger (condenser) using cold seawater pumped from the ocean's depths through a cold-water pipe. The condensed working fluid is pumped back to the evaporator to repeat the cycle. The working fluid remains in a closed system and circulates continuously.

4.2. Open-Cycle OTEC System

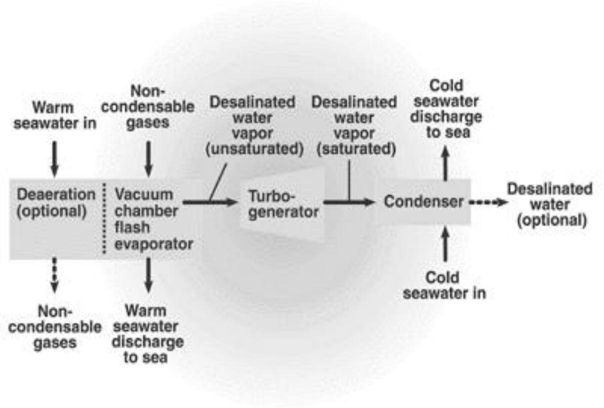

Figure 3. Open-Cycle OTEC System

In an open-cycle OTEC system, warm seawater is the working fluid. The warm seawater is "flash"-evaporated in a vacuum chamber to produce steam at an absolute pressure of about 2.4 kilopascals (kPa). The steam expands through a low-pressure turbine that is coupled to a generator to produce electricity. The steam exiting the turbine is condensed by cold seawater pumped from the ocean's depths through a cold-water pipe. If a surface condenser is used in the system, the condensed steam remains separated from the cold seawater and provides a supply of desalinated water.

4.3. Hybrid OTEC System

A hybrid cycle combines the features of both the closed-cycle and open-cycle systems. In a hybrid OTEC system, warm seawater enters a vacuum chamber where it is flash-evaporated into steam, which is similar to the open-cycle evaporation process. The steam vaporizes the working fluid of a closed-cycle loop on the other side of an ammonia vaporizer. The vaporized fluid then drives a turbine that produces electricity. The steam condenses within the heat exchanger and provides desalinated water.

The electricity produced by the system can be delivered to a utility grid or used to manufacture methanol, hydrogen, refined metals, ammonia, and similar products. Now let's take a closer look at some of the main components of an OTEC system—specifically, the heat exchangers, evaporators, turbines, and condensers.

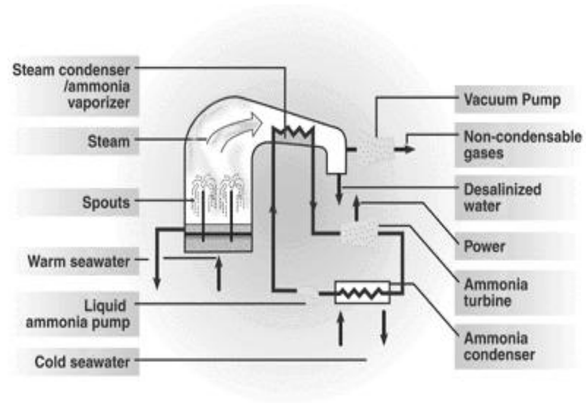

Figure 4. Hybrid OTEC System

5. World's only Open cycle OTEC System

Pacific International Center for High Technology Research (PICHTR) has been a leader in the continuing effort to extract energy from the ocean and other renewable systems. PICHTR has developed sustainable systems through its Engineering Systems group including the design, construction, and operation of the world's only Open Cycle Ocean Thermal Energy Conversion (OC-OTEC) system located at the Natural Energy Laboratory of Hawaii Authority (NELHA) at Keyhole Point on the Big Island of Hawaii.

6. Sagar Shakthi: India's first 'power plant' on sea

Sagar Shakthi - the Ocean Ther-mal Energy Conversion (OTEC) Barge – of capacity 1 MW of electricity power plant, is the first of its kind in the world to generate electricity utilising the temperature gradients between surface and deep-sea water. The barge is 68.5 m long, 16 m broad and 4 m deep, and houses the Rankine Cycle based power plant. The barge has been jointly conceived and developed by the National Institute of Ocean Technology, Chennai, and Dempo Shipbuilding and Engineering Pvt. Ltd, Goa.

7. Applications of OTEC

Ocean thermal energy conversion (OTEC) systems have many applications or uses in congruence to electricity generation. OTEC can be used to generate electricity, desalinate water, support deep-water Mari culture, 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.

The electricity produced by the system can be delivered to a utility grid or used to manufacture methanol, hydrogen, refined metals, ammonia, and similar products. The cold [5°C (41ºF)] seawater made available by an OTEC system creates an opportunity to provide large amounts of cooling to operations that are related to or close to the plant. Likewise, the low-cost refrigeration provided by the cold seawater can be used to upgrade or maintain the quality of indigenous fish, which tend to deteriorate quickly in warm tropical regions. The developments in other technologies (especially materials sciences) were improving the viability of mineral extraction processes that employ ocean energy.

8. Benefits of OTEC system

OTEC system presents economic as well as no economic benefits. OTEC's economic benefits include:

- Helps produce fuels such as hydrogen, ammonia, and methanol
- Produces base load electrical energy
- Produces desalinated water for industrial, agricultural, and residential uses
- Is a resource for on-shore and near-shore Mari culture operations
- Provides air-conditioning for buildings
- Provides moderate-temperature refrigeration
- Has significant potential to provide clean, cost-effective electricity for the future.
- Fresh Water-- up to 5 liters for every 1000 liters of cold seawater.
- Food--Aquaculture products can be cultivated in discharge water.

OTEC's no economic benefits, which help us achieve global environmental goals, include these:

- Promotes competitiveness and international trade
- Enhances energy independence and energy security
- Promotes international sociopolitical stability
- Has potential to mitigate greenhouse gas emissions resulting from burning fossil fuels.

In small island nations, the benefits of OTEC include self-sufficiency, minimal environmental impacts, and improved sanitation and nutrition, which result from the greater availability of desalinated water and Mari culture products.

9. Disadvantages of OTEC system

- OTEC-produced electricity at present would cost more than electricity generated from fossil fuels at their current costs.
- OTEC plants must be located where a difference of about 20º C occurs year round. Ocean depths must be available fairly close to shore-based facilities for economic operation. Floating plant ships could provide more flexibility.
- No energy company will put money in this project because it only had been tested in a very small scale.
- Construction of OTEC plants and lying of pipes in coastal waters may cause localized damage to reefs and near-shore marine ecosystems.

10. Market for OTEC system

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.

11. Challenges for OTEC system

Despite French Scientist Jacques D'Arsoval laying out the OTEC system almost 120 years ago, there has been very slow progress in developing the engineering systems that would make it possible to realize the enormous potential of this renewable energy technology. The first issue of economic viability arises from the high level of initial investment. For example a floating plant of OTEC needs the following complex systems:

- Power module components including heat exchangers and turbine.
- A floating platform with station keeping / mooring to position it in deep waters.
- A long cold water pipe to transfer large quantities of cold water from the depth to the surface.
- Offshore logistics.

All the above systems are facing severe technological challenges, which have not yet been tackled completely.

Based on engineering progress, in particularly the development of the Uehara cycle with a thermal efficiency of about 5 %, compared to earlier efficiency of about 3 %, has made the technology ready for commercialization. Ongoing research and development in institutions such as the Institute of Ocean Energy, Saga University (IOES) promises continued improvement over time.

The electricity from one to ten MW OTEC facilities will cost more than $0.25/kWh. There have been island communities long in this price range, with some approaching an unsubsidized $1/kWh. With freshwater, aquaculture, air-conditioning and other co-products, a major resort or military base could justify the installation an OTEC powerplant. A one MW OTEC plant can produce up to 3,500 cubic meters per day of potable water. The value added operational and marketing benefits of natural energy and selfsustainability are exploitable advantages. While the U.S. Department of Defense has carried out several studies to consider this alternative, there are hopes that an international governmental funding organization will have the will to break from tradition to symbolically demonstrate the value of this sustainable option.

While the OTEC system is potentially the most environmentally friendly development technology, there in no experience of the environmental impact assessment of the system.

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