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C.M. Wang [a] , A.A. Yee [b] , H. Krock [b] & Z.Y. Tay [a]
[a] Engineering Science Programme and Department of Civil and Environmental Engineering , National University of Singapore , Kent Ridge, Singapore , 119260
[b] Energy Harvesting Systems , LLC, 1217 Palolo Avenue, Honolulu, Hawaii, 96816, USA
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REVIEW PAPER

Research and developments on ocean thermal energy conversion

C.M. Wang[a], A.A. Yee[b], H. Krock[b] and Z.Y. Tay[a]*

[a]*Engineering Science Programme and Department of Civil and Environmental Engineering, National University of Singapore, Kent Ridge, Singapore 119260;* [b]*Energy Harvesting Systems, LLC, 1217 Palolo Avenue, Honolulu, Hawaii 96816, USA*

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Ocean thermal energy conversion (OTEC) is a very promising source of clean and renewable energy for our planet. This review article presents the research and developments on OTEC with regard to energy utilisation, platform design and mooring system, heat exchanger system and environmental impact. It also includes very recent developments in realising the construction of large scale OTEC facilities.

Keywords: OTEC; Kalina cycle; floating platforms; spars; clean energy; heat exchangers; environmental impact

1. Introduction

The oceans of our planet constitute about 71% of the earth's surface area, and contain enormous and virtually unlimited deposits of natural resource and energy potential. As the world's population grows, civilisation as we know it continues to demand increasingly greater amounts of material resources and energy to survive. At present, the most abundant energy sources are the fossil fuels but the consumption of this form of energy could result in catastrophic global warming effects. It is imperative that ways of developing unlimited sources of new energy that do not result in greenhouse gases and global warming are found and implemented. One such promising way is the ocean thermal energy conversion (OTEC) approach.

The concept of OTEC was originally introduced in 1881 by a French Scientist Arsene D'Arsonval in Paris. According to D'Arsonval, if you take a liquid with a low boiling point, such as liquid ammonia and use the warm tropical sea surface water (24°C) to boil the ammonia, the change from a liquid to gas would involve a significant volumetric increase of at least 600:1. This great increase in volume in a confined chamber will create a draft that turns a turbine to generate electric power. Then, the deep cold water is drawn from the ocean bottom at about 1000 m depth at 4°C to cool the vaporised ammonia and by using some of the power generated to compress the cooled ammonia gas, it will return the ammonia gas back to the original liquid form. The cycle is then repeated again with the warm sea surface water boiling and evaporating ammonia to generate more power, etc. This can go on 24 h a day, year after year, with virtually no workers or fuel required and very little maintenance if at all.

This OTEC cycle operates in a tropical area where water depths of about 1000 m and a 20°C or more differential temperature exists between sea surface and sea bottom water. In the tropical zone between Tropic of Cancer and Tropic of Capricorn girdling the earth along the equator, the sea water warmed by the sun's rays daily receives about 10,000 times the energy consumed by all mankind in that same 24-h period. The cold water originates from the Arctic and Antarctic and because of its cold temperature it is heavier than the warm water. So, the cold water sits close to the bottom of the sea. The deep cold water has been there for millions of years and all of this potential energy has remained virtually untapped.

OTEC is the only source of energy that is virtually limitless and sustainable, and so far is the only known source of energy large enough to replace fossil fuels. The operation of OTEC involves no green house gases emissions to our atmosphere. With the energy produced by OTEC, we can manufacture hydrogen and oxygen by separating the H_2 from the O in seawater by hydrolysis. The H_2 and O can then be liquefied, transported in cryogenic tankers to the various destinations for use in the space programmes, fuel cell cars, industrial manufacturing, power generation, etc. The virtues of the fuel cell vehicles are well known as these will result in a major reduction in emissions of CO_2, NO_x, CO, etc., into our atmosphere, thus helping to mitigate the impending global warming catastrophe.

With the OTEC process, fresh water can be produced from the seawater as a by-product of

*Corresponding author. Email: cvetzy@nus.edu.sg

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generating electric power. The electric power can also be used to power the reverse osmosis desalination process. If we were to substitute seawater for liquid ammonia in the OTEC process (open cycle method) we can vaporise the seawater by simply inducing a vacuum in a chamber so that the seawater can boil at a lower temperature when activated by the warm surface seawater. When water is vaporised in this manner, we will have a change in volume that create a draft to turn the turbine generating power and when we condense the water vapour with the deep ocean cool water, the condensed water vapour will become distilled fresh water.

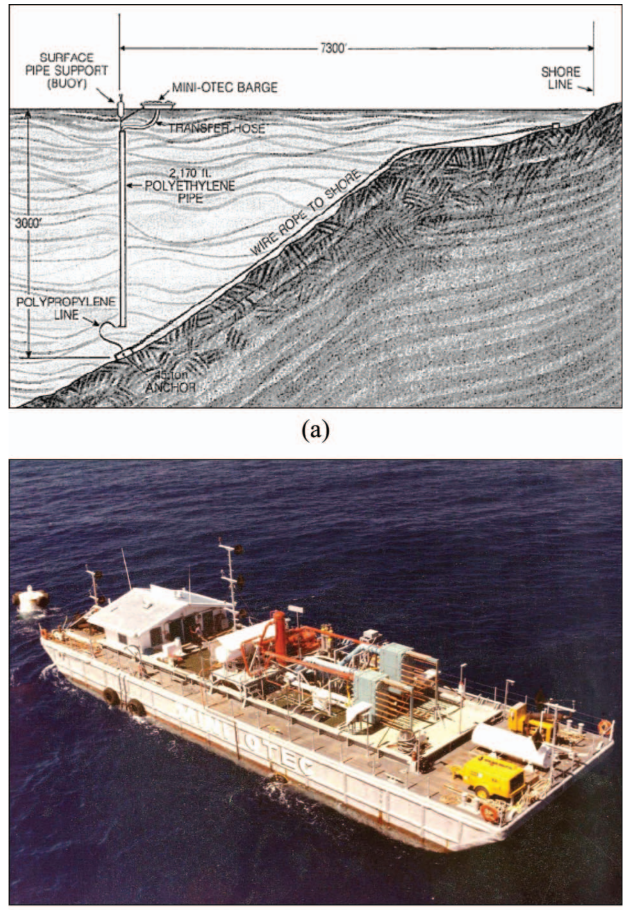
2. OTEC plants

Georges Claude, D'Arsonval's student, built the first OTEC plant in Cuba in 1930. The system generated 22 kW of electricity with a low-pressure turbine (Takahashi 2000). In 1935, Claude constructed another plant on board of a 10,000-ton cargo vessel moored off the coast of Brazil. Weather and waves destroyed the cold water supply pipes of both plants before they could become net power generators (Takahashi 2000).

Beginning in 1970, the Tokyo Electric Power Company successfully built and deployed a 100 kW closed-cycle OTEC plant on the island of Nauru (Bruch 1994). The plant, which became operational in 1981, produced about 120 kW of electricity where 90 kW was used to power the plant itself and the remaining electricity was used to power a school and several other places in Nauru. This set a world record for power output from an OTEC system where the power was sent to a real power grid.

In 1979, the State of Hawaii sponsored serious research in OTEC. Dr. Alfred Yee was given the job to structurally modify a steel barge loaned from the US Navy to serve as a floating platform to support the heat exchange and turbine system along with an 825 m long plastic pipe to reach the cold deep water off the western coast of the island of Hawaii at Keahole Point (see Figure 1). This facility known as MINI OTEC proved the D'Arsonval theory by generating 50 kW of electric power while using 40 kW of the 50 kW generated to operate the system, resulting in a net 10 kW output. This was a defining moment as no fossil fuel was involved in producing the electric power cycle. In the years following since 1979, a large amount of research and subsequent significant commercial activity has begun and now continues to grow at the Natural Energy Laboratory of Hawaii Authority (NELHA) established on land near the first MINI OTEC offshore location after 1979.

India piloted a 1-MWe floating OTEC plant near Tamil Nadu in 2000. Its government continues to sponsor various research projects in developing floating OTEC facilities.



(a)

(b)

Figure 1. (a) Cold deep water pipe connected to land based and floating OTEC power plant. (b) MINI OTEC power plant. Courtesy of Dr. Alfred Yee.

Presently Dr. Alfred Yee of Precast Design Consultants Pte Ltd (PDC) and Dr. Hans Krock of Energy Harvesting Systems, LLC (EHS) are designing very large concrete floating vessels to support OTEC facilities to generate electric power, manufacture liquid hydrogen and desalinate seawater. Using the honeycomb concrete framing system, some of these vessels are 356 m long $\times$ 70.7 m wide $\times$ 25 m deep and are designed to withstand severe hurricane, wind and wave conditions (see Figure 2).

3. Research on OTEC

3.1. *Energy utilisation*

Earlier researches on OTEC technology were carried out with the main focus on investigating its feasibility to produce sustainable energy and promoting its possibility to replace hydrocarbon as major energy sources in the future. As a renewable energy, OTEC uses the temperature difference between the surface waters of the tropical oceans (22°C–24°C) and the cold water stored at deep water (4°C–8°C) to convert solar energy to mechanical and electrical energy (Avery 2001, Lennard 2004). The greater the temperature difference, the greater the efficiency of the OTEC power plant. Hence, the sea site with large temperature differential (see Figure 3) is an essential requirement for an OTEC platform to operate. The US Department of Energy has placed major emphasis on OTEC because of its potential and the availability of thermal resources in the US coasts; viz., off the south-eastern coast of the USA, the Gulf of Mexico (GOM) and islands, such as Hawaii, Puerto Rico, Virgin Islands, Guam and Mariana (Avery *et al*. 1985). Lockheed Missiles and Space Co. had proposed a spar type OTEC power plant to be deployed in the GOM and off the Florida coast (Pont 1979). The OTEC power plant was designed to transmit energy to the shore by submarine cables through a shore-side electrical grid system. The DC transmission cable is preferable as it would reduce transmission losses for power plants located 30 km or more offshore as claimed by Marland (1978).

Extensive exploratory and development efforts have been performed on OTEC at the Argonne National Laboratory at the Keahole Point, Hawaii. The generated electricity from the OTEC power plant has been explored for various applications, such as hydrogen production from water through the electrolysis process (Ikegami *et al*. 2002). The hydrogen could then be liquefied and transported to land (Avery *et al*. 1985).

Figure 2. 125 MWe OTEC plant. Courtesy of Dr. Alfred Yee.

The electrolytically-produced hydrogen and oxygen could also be used as feedstocks for methanol production (Pelc and Fujita 2002). Production of OTEC methanol involves the transportation of coal to the OTEC power plant where the coal is oxidised by using oxygen and steam to produce carbon monoxide. The process is followed by the reaction of the carbon monoxide with added electrolytic hydrogen to yield methanol (Avery *et al*. 1985). The OTEC methanol offers an important alternative to future dependence on the dwindling petroleum resources since it could be produced from an abundant source of coal as well as natural gas (Avery *et al*. 1985).

The generated hydrogen could also be used to produce ammonia (for fertiliser and chemicals) by combining with nitrogen from the air. A baseline design for a 100 MWe OTEC plant ship had been developed by Dugger and Francis (1977) with the view of conserving the supplies of natural gas or other fossil fuels for producing ammonia on shore. The proposed 100 MWe OTEC plant ship features a novel concept of low-cost OTEC heat exchangers integrated in a rectangular and relatively low draft concrete hull that can be built and launched from existing US shipyards. Dugger and Francis (1977) claimed that the ammonia obtained via electrolytically-produced hydrogen appeared to be attractive economically and environmentally as compared to their counterparts produced from coal. It could also be attractive to nations that do not have an abundant and assured supply of natural gas or oil. As the OTEC generation belt coincides with most of the North Equatorial manganese nodule zone, the generated ammonia could also be utilised for hydrometallurgical process to extract metal from the ocean-mined nodules (Dugger and Francis 1977, The United Nations Ocean Economics and Technology Office 1979, Rey and Lauro 1981).

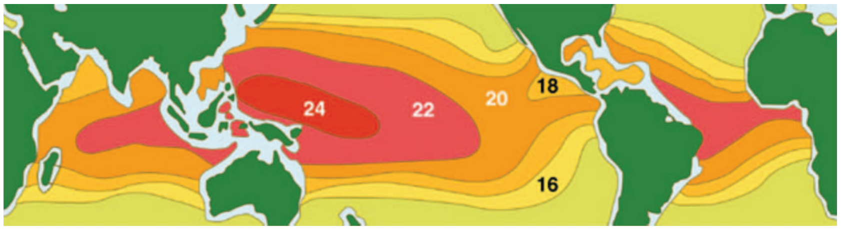


Figure 3. Temperature differences between surface and depth of 1000 m (source: http://www.xenesys.com/english/otec/product.html) (reprinted with permission from Elsevier).

Another attractive use of the OTEC power is in bauxite mining and refining for aluminium production at tropical sites, such as in Jamaica and Indonesia (Fuller 1978, Crews, 1997). Water supplies are a problem in these countries because of silt from deforestation and poor maintenance of treatment plants. The electricity generated from the OTEC plant could be used to power the reverse osmosis desalination process (Kumar *et al*. 2007) in order to produce fresh water for the mining industry as well as for consuming purpose. Rey and Lauro (1981) have proposed the combination of an OTEC plant with a desalination plant located on a barge which is moored offshore. Their studies showed that the OTEC desalination plant is more economical as compared to the land-based desalination plant in producing both water and electricity. Suitable sites for the shore-based OTEC are also found in the tropical islands which have limited resources of fossil fuels such as Maldives, the Seychelles and Guam (Crews 1997). The distilled water produced as a by-product of generating electric power in the OTEC plant can be used to support their tourism and industry. Researchers from the University of Hawaii have also investigated the potential of using OTEC for agricultural purposes by burying an array of cold water pipes (CWPs) in the ground to simulate cool weather growing conditions that are not found in tropical environments. Such a system could help in cultivating strawberries and other spring crops and flowers throughout the year in the tropical countries (Takahashi and Trenka 1992).

The cold water obtained from the OTEC plant could also be used to create cold storage space (Takahashi and Trenka 1992). The cold storage space is used as an economical substitute for refrigeration in the aquaculture industry. Economic studies on the new development of air-conditioning by using cold seawater have indicated that such technology is economically attractive for metropolitan and resort applications (Takahashi and Trenka 1992).

Besides the USA, island countries such as Japan and Taiwan have shown keen interests on OTEC in order to reduce their heavy dependency on foreign sources of non-renewable energy. The research and development programme of OTEC has been carried out in Japan since 1970 (Kamogawa 1980). An OTEC barge was designed in 1976 by the Japanese with the capability of producing 100 MWe of energy and the produced electricity is used to extract uranium to fuel nuclear power plants located on land. It was estimated that 110 tonnes of uranium could be exploited each year by this 100 MWe OTEC plant. In addition to that, 22.5 tonnes of enriched uranium could be exploited, which is sufficient to operate a 700 MWe of boiling water reactor (BWR) nuclear power plant for a year. The OTEC power plant and subsystems proposed by the Committee on Investigation of New Power Generation Methods (Kamogawa 1972) in Japan could also utilise the nutrient-rich cold water discharged from the plant for the production of marine culture. For this purpose, two OTEC power plants were sited in the offshore of Osumi Islands and Toyama Bay which are rich in pelagic fish eggs and fish larvae (Kamogawa 1980). These OTEC power plants were found to be well suited in these two sites due to its ability to generate power and marine products simultaneously. The extraction of cold water with a temperature of about 4°C from the deep sea also make possible the reproduction of the seafloor environment which is feasible for cultivation of organisms such as lobsters, oysters, sea urchins, abalone, and macro- and micro- algae (Tanner 1995, Masutani and Takahashi 1999). Wei *et al*. (1980) and Chen *et al*. (2010) have also investigated the engineering feasibility of pumping cold, deep nutrient-rich seawater for mariculture and nuclear power plant cooling in Taiwan.

3.2. *Platform design and mooring system*

The design of the OTEC platform depends on the weight and volume of the components on the structure as well as the operating sea conditions. The OTEC platform is usually built in large scale in order to stabilise the structure against wave motion, improve its sea keeping performance and reduce the stresses induced in the CWP. Various designs of the OTEC platform and mooring systems have been considered by researchers over the past few decades. The simplest form being the rectangular barge type such as the first MINI OTEC plant (see Figure 1) and the Sea Solar Power Inc.' s OTEC power plant (United Engineers and Constructors Inc 1975). Besides the barge type OTEC power plant, the other four most complete OTEC design concepts offered in the 1980s were the spar OTEC plant by Lockheed Missiles and Space Co. (Trimble 1975), the spar-buoy OTEC plant by Carnegie-Mellon University (Lavi 1975), the submerged catamaran OTEC plant by the University of Massachusetts (Goss *et al*. 1975) and the cylindrical surface vessel OTEC plant by TRW Inc. (TRW Systems Group 1975). Often, the design concepts of the OTEC platform depend on the conditions of the site. For instance, the researchers of the University of Massachusetts were considering their OTEC platform to be deployed at the GOM with strong currents and hence they considered the use of submerged catamaran design for their OTEC plant in order to minimise the strong currents flow. On the other hand, the engineers of TRW Inc. assumed a harsh open ocean condition, and thus they utilised the cylindrical surface vessel design which is good in withstanding the severe sea state. The Lockheed Missiles and Space Co. spar type OTEC power plant (Trimble 1975) has improved survivability and station keeping system in order to withstand severe hurricane winds and waves in the GOM (see Figure 4). The platform is a large steel-reinforced concrete structure measuring 180 m in height and 76 m in diameter with large built-in variable ballast tanks to maintain its stability during severe sea condition.

The *Grazing OTEC Plant Ship* equipped with a propulsion system has been proposed and designed by the Applied Physics Laboratory of Johns Hopkins University as shown in Figure 5 (Dugger and Francis 1977, Sasscer and Ortabasi 1979). This OTEC plant is able to 'roam' the Pacific Ocean and the Atlantic Ocean in order to seek for a high temperature differential. As the operating conditions are located at the hurricane belt and subjected to iceberg impact, the OTEC platform has to be designed against these environmental loads. The OTEC tugboat concept was later proposed for the same purpose but without the need to install a propulsion system. In order to provide good sea keeping characteristics, the hull is proposed to have a dimension of approximately 60 m in the direction of the motion (Sasscer and Ortabasi 1979).

Japan had also considered the surface ship design and the submerged cylindrical design (Kamogawa 1980; see Figure 6) in order to meet the rough sea conditions around Japan. Dynamic forces acting on these platforms were calculated based on a sea state with a maximum wind velocity of 60 m/s, a maximum wave height of 18.5 m and a surface current of 2 knots.

Figure 4. Lockheed spar-type OTEC platform (Trimble 1975) (reprinted with permission from Elsevier).

The 100 MWe dOmeTEC power plant (Kleute *et al.* 2009) was proposed by the students from the Delft University of Technology for the island of Curacao. The power plant is of a dome shape and it was concluded that the floating dome is the cheapest way to protect the OTEC system from harsh environment conditions. The dOmeTEC design also incorporates an

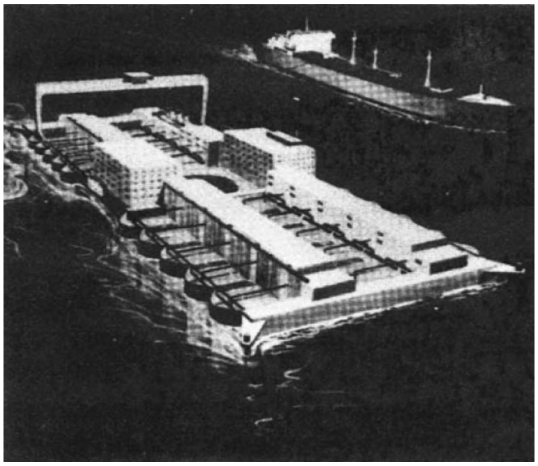


Figure 5. Applied physics laboratory grazing OTEC plant ship (Dugger and Francis 1977) (reprinted with permission from Elsevier).

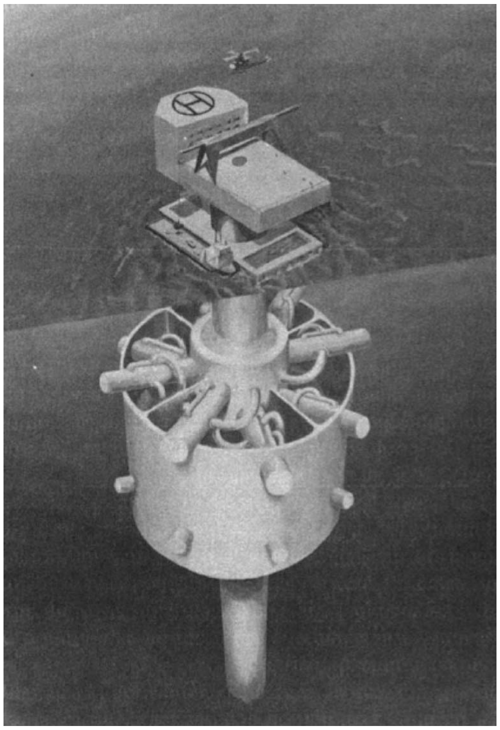


Figure 6. Artist impression of Japan's cylindrical OTEC plant (Kamogawa 1980) (reprinted with permission from Elsevier).

innovative 'airlift' pump system, where it allows air to be injected to the fluid in order to aerate the fluid and reduce its density. As a result, liquid could flow upwards due to the increase in pressure difference over the inlet of the pipe. The 'airlift' pump system is more robust and is able to increase its efficiency by 20–30% as compared to the conventional pumps.

A jacket-spar (J-spar) type of OTEC power plant was proposed by Srinivasan (2009) from Deepwater Structure Inc. as shown in Figure 7a. The J-spar consists of a simple jacket frame structure that is made of tubular steel members with welded connections. The deck is supported by eight legs at the top and the turbines and generators are placed over the deck structure. The J-spar configuration is able to suppress the alternate formation of Karman's vortex streets produced by the underwater currents. Srinivasan (2009) also proposed the tension-based tension leg platform (TBTLP) in which an artificial seabed is utilised at an intermediate depth from the real seabed to support the TLP vessel tether system (2009); thereby reducing the effective water depth of the upper TLP. The artificial seabed is created by using a flat plated structure with its own tethers as shown in Figure 7b. Such a novel design configuration is able to enhance the capacity of the tethers and reduce the sway and surge motion of the TLP. Instead of using the TLP, a semi-submersible vessel could also be used to support the OTEC system as shown in Figure 7c. The tethers are replaced by the moorings to provide mobility to the semi-submersible. By using dynamic positioning system (DPS) on the semi-submersible with disconnectable risers, the floating structure could also be relocated depending on the weather condition.

A 100MW ocean power plant concept for the production and use of renewable energy (see Figure 8) was proposed by Pflanz in The World Wind Energy Conference and Exhibition in 2002 (Pflanz 2002). The proposed power plant features an integrated system of various renewable energy plants (e.g. ocean thermal energy, wind and ocean waves) which are placed on the floating support structure to produce power.

Richard and Vadus (1981) presented various mooring systems for OTEC platforms (see Figure 9). These mooring systems are required to limit the motions of the platform and to minimise the bending of the CWP as well as the electrical umbilical cable used for power transmission. The selection of these different mooring systems depends on the water depth and the operational conditions of the OTEC plant. The single point mooring (Figure 9a) enables the OTEC plant to weathervane into the environmental conditions whereas the vertical tension mooring (Figure 9b) is able to minimise the heaving motion of the OTEC plant deployed in deepwater (An *et al.* 2000). On the other hand, the multi-leg catenary mooring (Figure 9c) provides greater stability to the power plant (Herbich 1999).

3.3. Heat exchanger system

The major cost of the OTEC power plant lies in the heat exchanger. The most common-heat cycle suitable for OTEC is the Rankine cycle using a low-pressure turbine. Two main types of the Rankine cycle heat

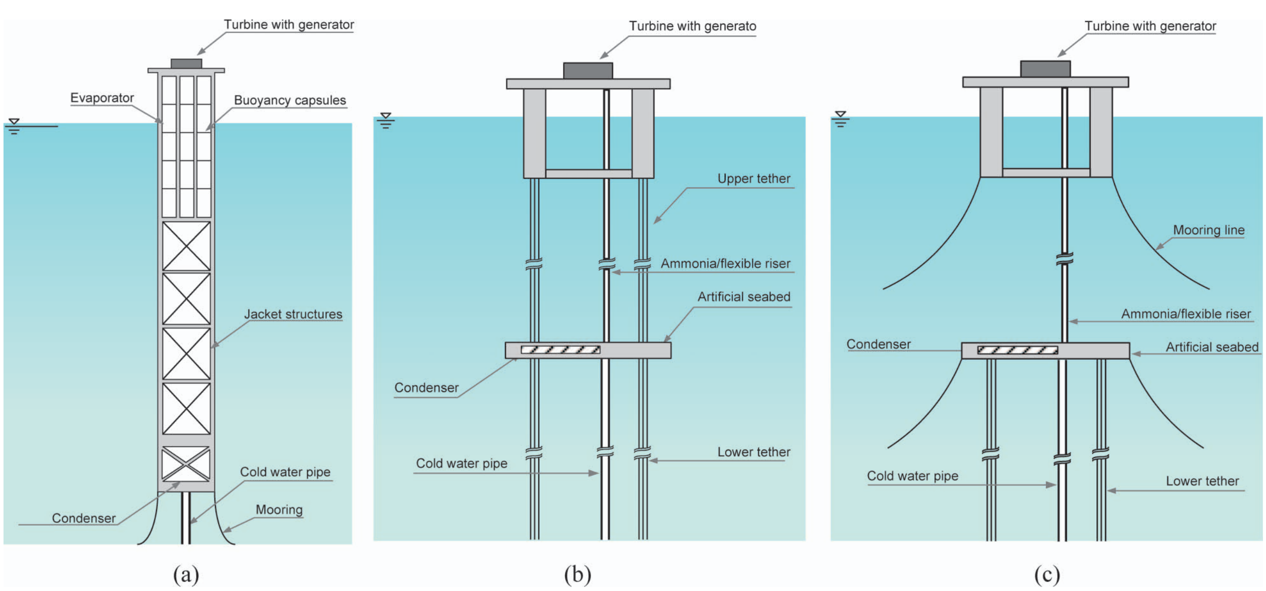


Figure 7. New OTEC power plant proposed by Srinivasan (2009). (a) jacket-spar OTEC power plant; (b) tension-base condenser with TLP OTEC power plant; (c) tension-base condenser with semi-submersible OTEC power plant. Courtesy of Dr. Tay Zhi Yung.

exchanger are used in the OTEC, i.e. the closed Rankine cycle process and the open Rankine cycle process. Most of the research studies on OTEC heat exchangers focused on the closed cycle heat exchanger due to its energy efficiency. The closed-cycle system uses working fluid with low boiling point to rotate a turbine. The working fluid is vaporised by heat exchanged with the warm surface water and the vapour used to drive the power turbine/turbo-generator. The vapour is then condensed by heat exchanged with cold sea water after driving the power turbine/turbo-generator. Such a design is also used in the OTEC plants designed by the University of Massachusetts (Goss *et al*. 1975), Carnegie-Mellon University (Lavi 1975) and the industrial teams headed by the TRW Inc. (TRW Systems Group 1975) and Lockheed Missiles and Space Co. (Trimble 1975).

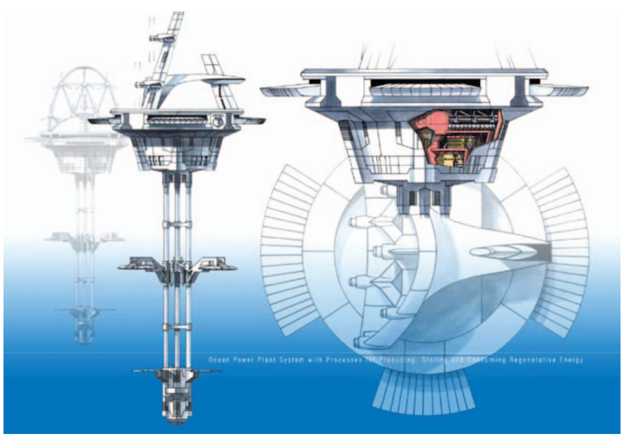


Figure 8. 100 MW ocean power plant concept proposed by Pflanz (2002) (source: http://www.ocean-power-plant.com).

The earlier design of the OTEC closed-cycle heat exchanger was of the shell and tube type. The Alfa-laval plate heat-exchanger was successfully applied in the 50 kW MINI OTEC pilot plant (Griekspoor 1981). A new titanium plate-type heat exchanger was then developed by Uehara of Saga University in the 1976 (Uehara *et al*. 1978). The titanium is used to replace the more common copper–nickel alloys due to its good resistance to pitting, stress and inter-granular corrosion (Richards and Vadus 1981). This plate-type heat exchanger utilised the flon-114 as the working fluid because it is easier to meet the Japanese industrial safety regulations as compared to ammonia. The main advantages of the plate-type heat exchangers are due to its compactness, efficient integration in platform design and cost reduction potential through mass-production techniques. Arima *et al*. (2002) also carried out an experiment on an ammonia/water mixture OTEC plant to investigate the effect of heated surface roughness towards the heat transfer coefficient. It was found that the heat transfer coefficients of the OTEC heat exchanger system increase significantly when a metal-sprayed heated surface is used.

Other types of working fluids were also considered in the closed-cycle system. The Japanese had investigated 12 different working fluids including *Flon* compounds (halocarbon or Freons), hydrocarbons and ammonia (Kamogawa 1980). They found that the R-22 (i.e. Freon-22), propane and ammonia were suitable for turbines rated at 25 MWe and 1800 rpm. By taking into account, the size reduction of the heat exchangers and

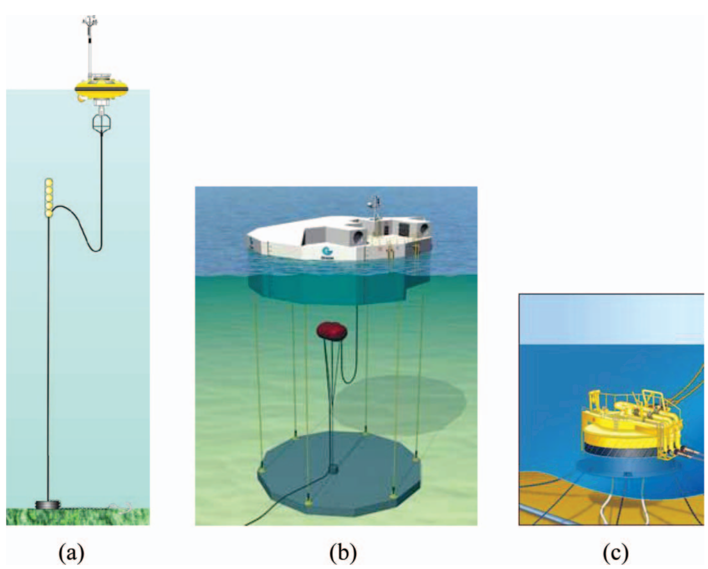
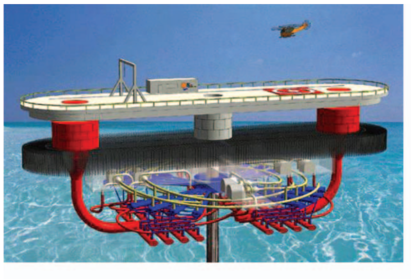


Figure 9. OTEC platform mooring systems (a) single buoy mooring (source: www.barentssea.no); (b) vertical tension mooring (source: www.powergenworldwide.com); (c) multi leg catenary mooring (source: www.tccs.odessa.ua).

the piping cost, the ammonia was found to be the best working fluid in the OTEC closed-cycle heat exchanger (Kamogawa 1980). Recently, experimental studies and dynamic model simulations were carried out to investigate the efficiency of the OTEC heat engine when the ammonia/water mixture is used as the working fluid (Bai *et al*. 2002, Ikegami *et al*. 2005, Ikegami *et al*. 2008). It was found that the cycle thermal efficiency using ammonia/water mixture increases with the warm water volumetric flow rate. Kim *et al*. (2009) have demonstrated that the system efficiency of the OTEC nuclear power plant could be increased by 2% if the condenser effluent from the nuclear power plant is used instead in evaporating the working fluid. The use of an ammonia/water mixture as a working fluid for low delta T heat engines is called the Kalina cycle and has been in commercial use for about 20 years. There are presently more than 10 commercial Kalina cycle plants in operation using waste heat from conventional power plants and steel mills as well as from low delta T geothermal resources. Dr. Hans Krock of Energy Harvesting Systems, LLC (EHS) has adapted the Kalina cycle for OTEC in collaboration with recurrent engineering, the patent holders of the Kalina cycle (Energy Harvesting Systems, LLC, 2010).

On the other hand, the open cycle used the vacuum flash vapourisation of warm water to drive a low-pressure steam turbine. Such a system was initially used in the OTEC plant by Claude in 1930. This system avoided the necessity of transmitting enormous quantities of heat through the inevitably dirty walls of the immense boilers which will result in the lost of efficiency. This remains a major problem faced by the modern versions of the OTEC (Marland 1978). To increase the efficiency of the open cycle heat exchange, an improved version of the open cycle heat exchanger which used a *steam lift water pump* and a foam lift concept was later developed by Beck (1975) and Zener and Fetkovich (1975), respectively. The steam lift water pump and foam lift were used to raise the warm water into a vacuum, where the vapour and liquid were separated at some elevation, with the vapour passing to a condenser and the liquid falling down to drive a hydraulic turbine (Marland 1978). In order to reduce the impact of released non-condensable gases during the vacuum flash-evaporation process, a pre-dearation chamber could be installed below the flashing chamber so that gas molecules could be removed before entering the steam turbine (Energy Harvesting Systems, LLC, 2010). Such design will result in a net gain of efficiency as well as the environmental benefits of oxygenated discharge water. Besides that, it could prevent the discharge of carbon dioxide and other greenhouse effect gases to the atmosphere (Kong *et al*. 2010).

The closed-cycle system has advantages over the open-cycle because of the use of ammonia as the working fluid which has less uncertainty in its detail design phase. The open cycle is however less expensive than the closed cycle (Coleman 1980) and the evaporator can be designed to produce distilled water since water is used as the working fluid. This has prompted engineers to combine the features of both closed and open cycle system in the OTEC plant. This proposed hybrid cycle system allows the intake of warm seawater into a vacuum chamber where it is flash-evaporated into steam, similar to the open-cycle evaporation process. The steam vaporises the working fluid of a close-cycle loop which is then used to drive a turbine to produce electricity (Takahashi and Trenka 1992). Straatman and van Sark (2008) have also proposed a hybrid OTEC system with an offshore solar pond design. The conceptual design of the sea solar power plant proposed by Sea Solar Power International is shown in Figure 10a. The temperature of the warm sea water was boosted by using a typical low-cost solar power thermal collector. Such system could lead to an improved efficiency to 12%, which is a 9% increase as compared to the conventional OTEC heat system (Lin and Chen 2008). The modelling and simulation of the solar-boosted ocean thermal energy conversion (SOTEC) proposed by Yamada *et al*. (2009) were carried out at the Kumejima Island in



(a)

(b)

Figure 10. Future OTEC power plants. (a) sea solar power conceptual design (source: www.seasolarpower.com); (b) solar hydrogen Island (source: www.phoenixprojectfoundation.us).

the southern part of Japan. By using a single-glazed flat-plate solar collector of 5000 m^2, they found that the proposed SOTEC plant can potentially enhance the annual mean net thermal by 1.5 times as compared to the conventional OTEC plant. Instead of using solar energy, Wang *et al.* (2010) proposed the use of wind power conversion device that is able to increase and adjust the speed of the gas turbine power generation, hence ensuring the continuity and stability in the OTEC electricity supply. The Phoenix Project Foundation (Phoenix Project Foundation 2010) has proposed the Solar Hydrogen Island where several OTEC power plants could also be integrated with both wind and photovoltaic solar cells as shown in Figure 10b. An underwater glider that glides up and down in the ocean by changing the vehicle buoyancy to harvest the thermal energy from the ocean thermocline is also proposed (Kong *et al.* 2010).

One of the challenges in the design of OTEC heat exchanger relates to the CWP system. The CWP consists of a large diameter pipe or a group of pipes extended downwards below the OTEC hull to the seabed. The forces and motions due to the interaction between the OTEC hull and the CWP affect the design significantly (Chou *et al.* 1978). The pipe should also be designed to be flexible in order to minimise the stresses induced by the waves, currents and platform motion (Griekspoor 1981). The CWP has to be designed to minimise the effects of vortex shedding forces produced by the underwater currents (Anderson 1984). Griffin (1981) proposed the shrouds, strakes, fin and fairing attachments to the CWP in order to reduce vortex shedding. Recent development of oil and natural gas resources in very deep water has resulted in significantly more reliable deep water equipment, such as pumps, pipes and power cables. Dr. Hans Krock of EHS and Raymond Rojas of Intecsea have adapted these advances from the deep sea oil industry to OTEC and developed reliable designs of large scale flexible and retrievable CWPs with high volume, low head submersible pumps (Energy Harvesting Systems, LLC, 2010).

Recently, Srinivasan and Sridhar (2010) proposed an OTEC engine that uses new technologies like the sub-sea condenser, sub-sea pump, submerged evaporator and independent floating-pipe buoy platform to transport working fluid from the turbine outlet to the sub-sea condenser. The engineering analyses study showed that the new OTEC power plant is feasible to construct and the cost analysis study showed that the new OTEC power plant is viable for applications.

3.4. *Environmental impact*

The deployment of the OTEC power plant in the ocean can cause a significant impact on the environment. As one of the most benign power production technologies, the OTEC does not produce radioactive waste and does not involve any release of noxious pollutants to the environment (Vega 1999). The building materials for the OTEC plant such as steel, concrete and aluminium are also benign to the environment (Fuller 1978). However, on closer examination of the OTEC design, the handling of hazardous substances, such as ammonia, halocarbon and hydrocarbon (propane and isobutene) as the working fluid, would cause environmental problems should leakage occur (Fuller 1978). As these substances are easily soluble in water, it is harmful to the marine life and could damage the marine ecosystem. The release of the power plant's effluent (such as chlorine and other chemicals that are used to clean water passages in the power plant) and the discharge of biocide which is required for macrofouling control would cause impingement of nearshore organisms and commercially important species (Fava and Thomas 1978, Lavi and Lavi 1979, Quinby-Hunt *et al.* 1987).

The operation of the OTEC heat exchanger requires the up-welling of cold sea water from the deep ocean. The cold sea water is nutrient-rich and bacteria-free but is highly saturated with dissolved CO_2. Some experts have questioned the possibility of substantial CO_2 release into the atmosphere due to the pressure drop and temperature rise in the condenser (Lavi and Lavi 1979). The pressure drop and temperature rise of the sea surface are the results of the unbalance equilibrium conditions when the cold water enters the condenser located close to the sea surface. The decrease in sea surface temperature could also affect the performance of other OTEC power plants clustered nearby. However, Lavi and Lavi (1979) have pointed out that the release of CO_2 may not be an issue as the condenser discharge can be designed to be below the sea surface. Furthermore, by considering a spay-buoy platform, the discharge pipe could be protected by the hull, hence would not result in the increase of drag forces or causing instability to the platform. On the other hand, the nutrient-rich cold water brought to the sea surface could enhance productivity and cause blooms in the phyto-plankton, which is an advantage to the fisheries industry (Fuller 1978).

In recent years, concerns about the detrimental effects of anthropogenic emissions of CO_2 on the global heat balance have prompted a worldwide effort to measure any significant changes in the atmosphere and the ocean. This effort has resulted in defining several interrelated phenomena in the tropical ocean that are having detrimental effects. This sequence of effects starts with an increase in atmospheric CO_2 from the pre-industrial level of about 280 ppm to about

390 ppm in 2010. This has resulted in a temperature increase in the tropical ocean surface layer of about 0.7°C. This means that there is now a bigger difference in the density of the ocean surface layer and the underlying ocean deep layer – which has not changed in temperature. This bigger density difference means that there is less mixing of the nutrient-rich deep water into the surface layer photic zone. The effect of this has been a 40% reduction in the primary productivity (photosynthesis) of the tropical ocean. At the same time, there has been an increase in the amount of CO_2 being absorbed by the ocean surface layer because of the greater driving force due to the higher CO_2 concentration in the atmosphere and the higher rate of gas exchange into seawater in comparison to fresh water (Krock and Zapka 1986). This combination of a reduction on photosynthesis and an increase in CO_2 has significantly lowered the pH of the tropical ocean surface layer. This is primary cause of the observed damage to the coral reefs of the world.

The most effective way to counter these detrimental consequences of anthropogenic CO_2 emissions is to deploy large numbers of floating OTEC/hydrogen platforms. First, these systems will directly extract heat energy from the ocean surface layer and thereby, reduce the temperature of this layer as well as reduce the difference in density with the deep layer. Second, by substituting this renewable and non-emitting energy source for fossil fuel there will be a significant reduction in global CO_2 emissions. Third, normal operation of the floating OTEC platforms pumps large quantities of slightly cooled warm ocean surface water (and the CO_2 it has captured from the atmosphere) down to the top of the thermocline. This effectively sequesters atmospheric CO_2 into the lower part of the ocean by putting it in contact with the higher nutrient concentrations at the top of the thermocline. The result is a reduction in the density gradient, an increase in photosynthesis and pH, and a reduction in reef damage. Fourth, operation of the OTEC platform will transport slightly warmed cool deep ocean water to the upper portion of the thermocline where the consequences are a reduction in the density gradient and an increase in photosynthesis. None of the other alternative energy systems (wind, photovoltaic, nuclear) have this comprehensive reversal of the detrimental consequences of anthropogenic CO_2 emissions (Energy Harvesting Systems, LLC, 2010).

3.5. *Near-term results*

A group of companies and governmental agencies from several countries are actively discussing the building and deployment of OTEC platforms of various sizes to produce base load electrical power, fresh water and liquefied hydrogen. The technology for these OTEC systems is based on integrating commercially established components including concrete platforms developed by Dr. Alfred Yee of PDC and EHS, the Kalina cycle by Recurrent Engineering and EHS, the CWP by EHS and Intecsea, and integrated engineering design by EHS and Worley Parsons. A 10 MW OTEC platform project to supply power and fresh water for Diego Garcia is being considered with participation by the US Navy and the United Kingdom. This platform would be constructed in Singapore. Discussions have also been initiated for larger scale open ocean OTEC platforms to produce fresh water and liquid hydrogen for Singapore. A multinational project is under active discussion for a 125 MW OTEC platform in the Republic of the Marshall Islands (RMI) to supply power and water to the local population and to the US military facility on Kwajalein as well as supply liquid hydrogen for the world market. Discussions for this RMI project include South Korea. A 60 MW size OTEC platform is being proposed for Guam to supply much of the power requirements for the US military due to the relocation of marines from bases in Japan. Discussions are also ongoing to supply hydrogen for transportation projects in Germany and the USA involving fuel cell cars. Similarly, marine transportation changes from the present diesel-electric to hydrogen fuel cell-electric systems are being discussed. Also, high speed rail projects could very easily and efficiently be powered by alkaline fuel cell systems supplied by large scale OTEC platforms (Energy Harvesting Systems, LLC, 2010)

4. Concluding remarks

There are many other alternative energy solutions being used, such as windmills, wave machines and photovoltaic panels, but none have the potential magnitude as OTEC to replace fossil fuels entirely in producing power required by our growing world-wide population and industries and at the same time have significant positive environmental consequences.

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