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Ocean Thermal Energy Conversion (OTEC): Technical Viability, Cost Projections and Development Strategies

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Abstract

Ocean thermal energy conversion (OTEC) is a baseload renewable energy source particularly suited for tropical zones. It uses the temperature difference between the warm surface ocean water and the cold deep ocean water to generate electricity and, if desired, potable water. This alternate energy source does not depend on fossil fuels, is not vulnerable to world market fluctuations, and has less environmental impact than other energy sources. During the 1970's and 1980's R&D projects such as Mini-OTEC and OTEC-1 in Hawaii and the Japanese 100-kW land-based pilot plant at the Republic of Nauru demonstrated the technical viability of OTEC, specifically with a closed-cycle system to generate electric power. Between 1993 and 1998, the Natural Energy Laboratory of Hawaii (NELHA) built and operated a 210-kW open-cycle pilot plant for the co-production of electricity and potable water. The facility was shutdown by the federal government. Today, this facility is used primarily for aquaculture and desalinated bottled Deep Ocean Water. Due to the recent progress in systems design, heat exchangers efficiency, the high costs of fossil fuels experienced in 2008, combined with the fluctuations in the oil world market, several companies have re-evaluated the use of OTEC. At present, a number of projects focused on the commercial implementation of OTEC at various sites are under consideration. Puerto Rico possesses specific conditions that make it an ideal site to implement OTEC.

Conceptual design and capital cost estimates for the proposed 75-MWe closed-cycle plant for Puerto Rico are based on commercially available components and manufacturing practices. A modular and integrated design has been applied which is readily adaptable to other plant sizes. OTEC is a benign and environmentally compatible technology. Its potential impact to the environment can be minimized through proper design and engineering & construction best practices. The first plant would include a periodical program to study long-term environmental effects of OTEC, to optimize the design and operation of future plants. This paper summarizes efforts dedicated to commercial implementation of OTEC in Puerto Rico and other locations, concentrating on the technical and economical viability, and the associated environmental and socio-economical implications.

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^o North and 20^o 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 ^oC. 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 (Avery et al. 1994).

One of OTEC's greatest advantages is that it allows the co-production of potable water, in addition to electric power through desalination. It is possible to produce up to 2 million liters per day (0.5 million gallons per day) for each megawatt of electricity generated (Cohen 1982). Since OTEC does not utilizes fuel, the produced electricity has a fixed cost, thus, it is not susceptible to the volatility of costs that affects other energy sources such as petroleum, coal and natural gas. Moreover, the environmental impact is less than other sources of energy since no products of combustion are generated during the power production process. All of these aspects have caused a revival of interest in OTEC.

Basic Principles

An OTEC plant consists of a heat engine that converts thermal energy into mechanical work through the temperature gradient between a "heat source" and a "heat sink". Although this temperature gradient is relatively small compared to a steam engine, the principle is the same. The OTEC technology is divided into three categories: closed-cycle, open cycle and hybrid-cycle.

In the closed-cycle system, the most common of the three, the temperature difference is used to vaporize (and condense) a working fluid (e.g. ammonia) to drive a turbine-generator to produce electricity. See Figure 1. In the open-cycle system, warm surface water is introduced into a vacuum chamber where it is flash-vaporized. The produced water vapor drives a turbine-generator to generate electricity. The remaining water vapor (essentially distilled water) is condensed using cold water. The condensed water can either return back to the ocean or be collected for the production of potable water. The hybrid-cycle combines the characteristics of the closed cycle and the open cycle, and has great potential for applications requiring higher efficiencies for the co-production of energy and potable water (Avery and Wu 1994). In all of the three cycles, it is required to obtain deep cold water to condense the working fluid, which is normally available at depths of 1,000 meters (3,200 feet), where the temperature of the water is approximately 4 ^{o}C (39 ^{o}F).

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 pre-commercial 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.

Why OTEC Now?

The recent world events have created a new interest in OTEC (Tellado 2008). First, the price of oil has increased vertiginously, reaching as high as $148 per barrel in 2008. There are serious concerns in regards to the stability of oil production in highly conflictive areas such as the Middle East and the possibility of the world oil production to reach its peak (also known as "Hubbert's Peak", which some commentators have announced for the period between 2000 and 2010). 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). Both the United States and the European Union have seriously discussed the imposition of taxes on greenhouse gas emissions. Another significant problem is the "Energy-Water Nexus": to produce energy, large quantities of water are required; and to produce and distribute water, large quantities of energy are required. All of these factors have caused the interest in OTEC to revive since it doesn't use fossil fuel or nuclear energy, is available practically all the time (compared to availability factors of 30% for wind energy and the 40% factor for solar energy), and permits the co-production of potable water, if desired. For the first time, the high cost of oil and its volatility and fluctuations in the world market have created the conditions to make an OTEC plant commercially viable, without the need of government subsidies. Offshore Infrastructure Associates has presented a proposal for the construction and operation of an OTEC plant in Puerto Rico, to generate electric power only, based on private financing. Figure 2 shows the proposed facility.

Technical Viability

Since Claude's first attempt to demonstrate the viability of the OTEC technology at his plant in Cuba back in 1930, 78 years of accumulative experience (and more than $500 MM invested in R&D) is available to us today in the form of engineering data, equipment development, environmental studies, conceptual & preliminary designs, and technical information, to finally build the first commercial OTEC plant in the world. There have been many discussions over the past two decades among the OTEC community as to what the right development path is for OTEC and how this technology can be seriously inserted into the widely-accepted renewable energy portfolio. One of the fundamental discrepancies has been whether a pre-commercial plant (between 2-10 MWe sizes) is required before a full-scale commercial plant (above 40 MWe) can be considered to be feasible, both technically and financially. Offshore Infrastructure Associates firmly believes that with the correct technical and financial strategy, a middle step is not necessary for OTEC to be commercialized on a short-term period to become a real alternative for various countries and/or territories to address their energy needs.

Much has been said about the “alleged traditional handicaps” that some skeptics use as their basis to state that OTEC is not a mature technology and that more R&D is needed, or at least a pre-commercial step, before it can be fully commercialized. Thus, it is very important to differentiate, among all the potential development options available for OTEC, which ones have the necessary elements for short-term commercialization and which options require further work.

OTEC has the potential to contribute to the supply of basic needs or commodities that ranges from electric power and potable water, to areas such as air conditioning and mariculture products. In addition, energy produced using OTEC technology can be in the form of electric power or in the form of chemical energy. For these reasons, a development strategy needs to consider which of these opportunities may be commercially attractive based on all the available data and information, and the potential sites that possesses the natural resources to make OTEC viable and the socio-economic conditions that will allow the consumption of the OTEC products desirable (Avery and Wu 1994; Cohen 1982).

For the countries and/or territories located in regions such as the Caribbean and the Pacific, where the thermal resource exists on a continuous basis (temperature gradient greater than 20 ^{o}C) and deep cold ocean water is near the shore, OTEC plants may be land-based, shelf-mounted or off-shore (moored platform). Particularly for sites like Puerto Rico and Hawaii, where power transmission to shore from a moored floating platform is practical and electric power demand on these two sites is substantial, an OTEC plant of cost-effective/commercial size is feasible (Avery and Wu 1994; Cohen 1982).

The first OTEC commercial plant (40-MWe size or higher) should be for electric power generation only. In addition to the reasons mentioned above, co-generation of potable water and/or on-site production of chemicals such as ammonia, hydrogen or methanol, add more variables and potential unknowns during the design phase, resulting in a significant increase in the overall technical risk of the project. More importantly, most of the R&D, tests, studies and design completed during the past seven decades focused on the Rankine closed-cycle system, with ammonia as the working fluid (Avery and Wu 1994). Specifically, the pilot plant tests conducted during the late 1970’s and early 1980’s (Mini-OTEC, 1979; OTEC-1, 1980; and Nauru, 1981 – Freon as working fluid) demonstrate that an OTEC closed-cycle system is ready for commercial scale-up (Cohen 1982; George and Richards 1980; Avery and Wu 1994) and that enough data is available to complete a detailed design package for construction (thermodynamic performance, heat engine design, heat exchangers configuration, materials and cost, working fluid design, various conceptual and preliminary designs, etc.).

Extensive research and development has been conducted to determine the optimum configuration, design basis and material of construction for the heat exchangers required for an OTEC process. Mini-OTEC and OTEC-1 provided the basis for the development of design methods for commercial-scale heat exchangers. Lessons learned in these experiences have been applied to the development of heat exchangers which are being used for other applications today.

Since large heat exchangers are expected for a commercial size plant (due to the large amounts of water required for the process), design and selection should be based on two factors: optimum heat transfer rate and low unit cost (compact size). In addition, the material selection should be based on durability, compatibility with the working fluid and life-cycle cost. Based on these criteria, the leading candidates are stainless-steel plate and aluminum-brazed heat exchangers, both of which are commercially available from several major suppliers (Cohen 1982; George and Richards 1980; Avery and Wu 1994). Both alternatives offer the advantage of modular design allowing full integration with the rest of the power block subsystems. This provides a significant opportunity to increase the system’s performance and reduce costs during the design phase of the project. Moreover, due to the recent advances in their design and fabrication, aluminum-brazed (Al-Bz) heat exchangers allow for a reduction in platform size due to their compact configuration and higher efficiency, compared to plate heat exchangers (PHE). See Figures 3 and 4. It has been estimated that platform size could be reduced by 20 to 30% if Al-Bz heat exchangers are used instead of the PHE’s. The same principle is applied to the total parasitic power, which could be reduced also by 20 to 30% if compact and highly efficient heat exchangers are selected for the first commercial plant (Avery ad Wu 1994; Cohen 1982).

Biofouling in OTEC heat-exchangers was identified as a potential obstacle for commercial implementation during the early stages of the US R&D program in the 1970’s, because it can significantly reduce the efficiency of an OTEC process. However, efforts at the Argonne National Laboratory (Panchal et al. 1983), led to the development of effective and practical control measures, such as intermittent low dosing of oxidants that have been found to be very effective in preventing degradation of heat exchanger performance during sustained system operation.

Ammonia is the preferred working fluid, due to its superior thermodynamic and thermal characteristics over other substances (Cohen 1982; George and Richards 1980; Avery and Wu 1994). An OTEC closed cycle system is essentially a reversed refrigeration cycle, and there is substantial operational experience with ammonia refrigeration in commercial and industrial applications.

Another key component of the OTEC power block is the turbine-generator. These are commercially available for other applications and only require minor modifications for use in OTEC plants. The same concept applies to the seawater pumps (for both the warm and cold water streams). It is important to add that the design strategy for an OTEC commercial plant needs to integrate all of the subsystems and subcomponents, including the platform, in order be cost-effective and minimize the technical risk.

The selection of a floating platform for an OTEC commercial plant raises a number of questions regarding its construction and operation that fortunately have been answered in a satisfactory manner (Avery and Wu 1994). First, the design of the platform itself needs to address the concerns associated to the typical challenges of construction, operation and maintenance of at-sea facilities. The available data shows that a platform with a barge design/configuration made of reinforced or post-tensioned concrete or steel can be constructed and deployed for an OTEC plant size of at least 100-MWe with existing technology and construction techniques used in marine and offshore oil industries, as long as the plant subsystems are integrated into the overall design in an efficient manner. Mini-OTEC and OTEC-1 projects showed that an OTEC plant can be operated from a moving floating platform (Cohen 1982). In addition, and very importantly, the platform can be designed to have an operating life of at least 30 years and with the ability to withstand the severe storms which occur in sites such as Puerto Rico and Hawaii.

Second, a platform will be required to have the appropriate pipe technology to supply the deep cold water necessary for the OTEC process. There is enough theoretical and experimental data to predict the design, construction and deployment requirements for a commercial-scale cold water pipe (CWP) for a floating platform. Mini-OTEC and OTEC-1 validated the use of suspended cold water pipes in a floating platform. Light-weight concrete with flexible joints and fiberglass-reinforced plastic are considered to be viable options and are commercially available for the length and diameter associated with plants of 100-MWe capacity. Specifically, available studies demonstrate that a barge platform design with suspended-installed CWP is fully feasible (constructability, deployment, maintenance and cost) with current methods and techniques used in the marine engineering/naval architectural as well as the offshore oil drilling industries (Avery and Wu 1994).

Third, technology for the underwater power cable (with a total length of at least 6 miles or 10 km for sites such as Puerto Rico and Hawaii) to transfer the OTEC electric power to shore is commercially available and currently used at many sites around the world. For the characteristic conditions found in the Caribbean and in the Pacific where an OTEC moored platform would be located, cables such as cross-linked polyethylene (XLPE) rated 400-kV AC and similar have been demonstrated to be technically and economically feasible (Avery and Wu 1994).

Fourth, the mooring and anchoring system required for the floating platform, as well as the necessary anchoring system for the CWP and the submarine power cable are commercially available, too. As mentioned before, these systems are currently employed in the offshore oil drilling industry.

Thus, an OTEC commercial plant to generate 50-100 MWe of electric power only, with a modular design approach for the power block, compact stainless steel or aluminum heat exchangers, and other critical components such as the CWP and the submarine cable, can be designed, constructed, deployed and operated in a cost-effective manner under present conditions and circumstances. For some cases, such as Puerto Rico and Hawaii, proximity of the deep cold water to shore also make land-based plants feasible. The Nauru closed-cycle project (Mitsui et al 1983) as well as the NELHA open-cycle project (Daniel 1999) proved the validity of the electrical and mechanical design and the underwater pipeline laying method for land-based plants. In addition, installation techniques for large diameter pipes have been developed for ocean outfall projects. Thus, land-based commercial plants can be a feasible alternative.

Environmental Impact

In general, OTEC is a benign technology from the environmental point of view. It does not use fuel, there are no air emissions of conventional pollutants, it does not generate solid or toxic waste, and effluents are essentially similar to the receiving waters. Nevertheless, OTEC is not free of environmental impact.

During the construction phase, several zones will be temporarily impacted such as the area where the plant and its seawater piping system (in the case of a land-based plant), are to be built, the electric grid interconnection facilities and the submarine power cable (in the case of the floating platform). It is important to avoid areas that are considered environmentally sensitive when selecting a site for an OTEC plant.

In terms of air emissions, there will not be any release of pollutants associated to the combustion process of fossil fuels. In an open-cycle or hybrid-cycle plant, gases dissolved in seawater will escape to the atmosphere, resulting in emissions of CO2. Nevertheless, these are significantly lower than the emissions generated from the combustion of a fuel to generate an equivalent amount of energy.

In closed or hybrid cycle plants, there are legitimate concerns about the possible effects of releases of the working fluid to the environment. In the past, substances such as chlorofluorocarbons (CFC’s), which are not immediately dangerous to human health, were proposed as working fluid. However, CFC's have adverse effects on the ozone layer and have been identified as potential contributors to global warming. For this reason, most recent designs have considered ammonia as the working fluid, due to its superior thermal and thermodynamic characteristics. Ammonia has been in use as a refrigerant for more than 100 years, and there is vast experience in the design, operation, maintenance, storage, use and distribution of such systems (Cohen 1982; George and Richards 1980; Avery and Wu 1994). Although ammonia has toxic effects, history has demonstrated that systems using it as a working fluid can be operated safely and with high reliability, if basic precautions are taken during design, construction and operation. Most large commercial and industrial refrigeration systems use ammonia as the working fluid.

OTEC requires moving large amounts of water. This brings up three important concerns: (1) marine organisms entrainment and impingement through the water current; (2) the effect of chemicals used to reduce/control biofouling buildup inside the seawater pipes and heat exchangers; and (3) the effect known as "upwelling", or rise of the deep cold water to the surface. All three problems can be controlled and mitigated during system design and/or through preventive measures during operation (Cohen 1982; George and Richards 1980; Avery and Wu 1994).

The entrainment and impingement of marine organisms occurs mainly in the ocean warm water surface. Studies have shown that the entrainment of marine organisms is minimal in the deep cold water (Avery and Wu 1994). Nevertheless, proposed commercial designs incorporate mechanisms to divert these organisms and prevent their entrance into the system, minimizing potential harm.

To control biological growth in the system it is necessary to apply chemical agents. Uncontrolled use of these agents may cause serious harm to the environment. Nevertheless, studies show that intermittent low dosages of oxidants are enough to control biofouling under acceptable levels (Panchal et al 1983). To reduce even more this effect, in a commercial plant composed of multiple modules, these agents would be applied to one module at a time, hence, diluting the residual in the effluent by a considerable factor, to probably undetectable levels.

Potential effects of "upwelling" have been a true concern associated to the OTEC operation. Deep ocean water is rich in nutrients and low in pathogens. This could cause an accelerated growth of phytoplankton, which would have stimulating effect along the marine food chain. Another possible effect is the difference in temperature between the effluent and the receiving waters. Design of modern plants takes into consideration the required measures to reduce these effects. One of these measures is to discharge the effluents at a depth where sunlight penetration is minimal. See Figure 2.

Some OTEC proponents have suggested that both upwelling and cooling are beneficial since both can increase biological productivity and create fishing resources. Nevertheless, both could alter natural environmental balance, and it is prudent to incorporate measures in design aimed at minimizing their potential effects. In the case of land-based plants, like in the case of the experimental plants in Hawaii, the deep ocean water can be recovered and used to breed valuable species such as cold water lobsters and micro-algae.

Since there is no data from a long-term operation of an OTEC commercial plant it is desirable to include a program to study environmental effects during the operation of the first plants. This way, the magnitude of any impacts can be determined with certainty, to optimize the operation and the design of future plants.

Socio-Economic Impact

Many nations and/or territories, such as Puerto Rico, Guam or the Dominican Republic, among others, completely depend on imported fuels for their energy needs. This condition makes them vulnerable to the volatility of the prices of fuel, and to any event that decreases or impacts the world market supplies, even when it occurs in other parts of the world and the affected nation doesn't have anything to do with the event.

Between January 2007 and July 2008, the price of petroleum increased from $54.63 to $137.11 per barrel. This generated a global economic crisis, which consequences are still felt today. It has been estimated that incidents such as a new war in the Middle East (e.g. Israel and Iran), or prolonged interruptions in flow through the BTC oil pipe between the fields of Baku, Georgia and Turkey (was endangered during the recent conflict between Russia and Georgia), could increase price of oil to unprecedented levels (above $200 per barrel), having severe effects on the global economy. The lack of control over the cost of energy discourages productive activities and investment, increasing the economic impact and creates a collective socio depression that extends through out the society as a whole.

OTEC offers these countries or territories, currently dependent on foreign oil, the real possibility of energy autonomy and the elimination of vulnerability to disruptions in fuel supplies. In addition, construction of OTEC plants provides a stimulus to the local economy. More importantly, one 75-MWe OTEC plant would save approximately one million barrels of oil per year. Money paid for these fuels currently goes to oil producers. Nevertheless, the money used to pay for the energy generated by an OTEC plant, financed with private funds, would return to the local economy of the country that builds the plant, particularly in the cases of locations such as Puerto Rico and Hawaii.

Cost Projections

The design strategy for OTEC commercial plants should focus on process optimization, systems integration and parasitic power minimization, to achieve the lowest capital cost per kWe and obtain the lowest cost of electricity for a given plant size. The objective is to minimize capital cost, so as to provide an attractive return to the investor.

If total parasitic power is minimized, overall thermal efficiency is increased, which has a direct effect on the cost of electricity (more electric power will be available to the Utility's grid). Some areas that represent an opportunity to minimize parasitic power include reduction of friction losses in pipes, low pressure drop and high heat transfer rate across the heat exchangers, and highly efficient pumps and turbo-generators. A similar principle is applied to the total equipment footprint, since when minimized, the total plant capital cost is reduced. See Figures 3 and 4. All of these objectives can be achieved by design optimization and systems integration.

Table 1 shows the cost breakdown (as a percentage of total capital cost) for a 75-MWe plant, based on conceptual design data. As mentioned before, opportunity areas for cost reduction should focus on heat exchangers configuration and efficiency, platform footprint reduction and cold-water pipe design optimization. These three components represent approximately 75% of the total estimated capital cost proposed for the Puerto Rico OTEC plant.

The fact that the OTEC process has a low efficiency as compared to other similar power generation processes does not mean a commercial plant will not be cost effective, as some people believe. Evaluation of OTEC as a commercial option should focus on the following points: (1) OTEC uses no fuel; (2) equipment for closed cycle system is commercially available; (3) the plant can operate safely with minimal environmental impacts; (4) the plant offers a reliable operation with minimum maintenance, similar to industrial refrigeration systems; (5) the platform construction/deployment is similar to the marine industry; and (6) the low pressures and temperatures characteristic of the OTEC process represent a lower equipment cost compared to high pressures and temperatures for similar processes (Cohen 1982; Avery and Wu 1994).

Investment requirements and associated operating costs for a 40-MWe OTEC plant were completed by APL/JHU as part of their baseline design for a moored floating plant in Puerto Rico (George and Richards 1980). This data, as well as data from other valuable studies and conceptual designs, have been used as a starting point to estimate the capital cost for the proposed OTEC commercial plant. Initial units are expected to be competitive with $60 to $80 a barrel of oil, with future units becoming competitive with $40 to $50 a barrel of oil. It is estimated that an initial 75-MWe commercial floating plant located 6 miles off Punta Tuna in Puerto Rico will cost approximately $600 MM and be able to produce 600 million kWh of electricity annually for about $0.15 per kWh.

Conclusions

Bringing renewable energy sources to market is of global importance. The ability to develop OTEC can be enhanced by recent advances in ocean technology, systems integration and heat exchanger improvements. The combination of these developments and the available data and information from previous R&D and demonstration plants makes OTEC commercially viable and financially attractive. A 75-100 MW OTEC closed-cycle moored floating plant located in tropical areas like Puerto Rico is feasible today based on commercially available components and manufacturing practices. Its successful implementation will also depend on the correct technical approach and the appropriate financial strategy. OTEC is a benign technology and its environmental impact is significantly less than other energy sources, specifically, compared to fossil fuel combustion and nuclear power. All the identified environmental concerns can be mitigated through proper planning and design. In addition, OTEC offers the opportunity to contribute to the energetic independence and economic development for the countries and territories where the technology is found suitable.

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Tables

Table 1. 75-100 MW OTEC Plant Conceptual Cost Breakdown (Percentage of Total Capital Cost)

Moored Platform	**30%**
Heat Exchangers	**25%**
Cold Water Pipe	**20%**
Other Components - **Turbine-Generators** - **Controls** - **Working Fluid System** - **Seawater Pumps** - **On-shore Electrical Facility** - **Mooring/Anchoring** - **Submarine Power Cable** - **Others**	**25%**

Figures

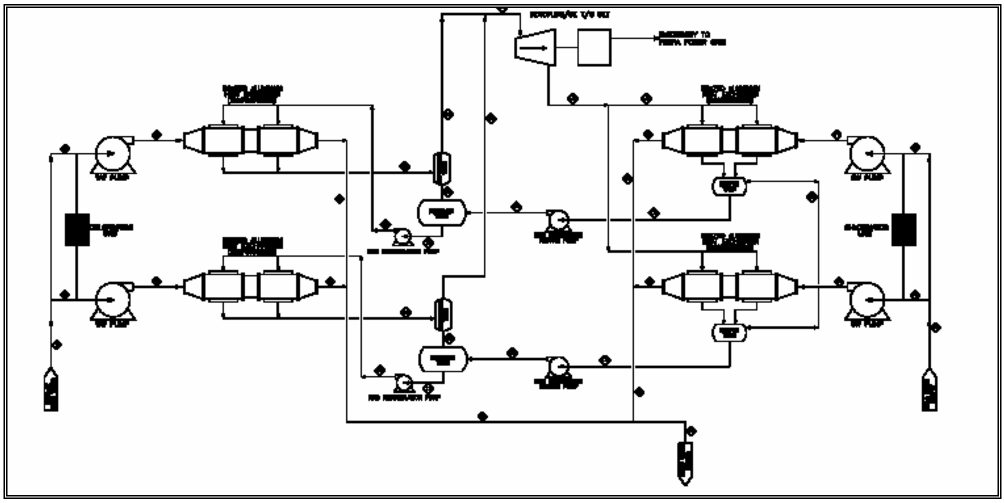
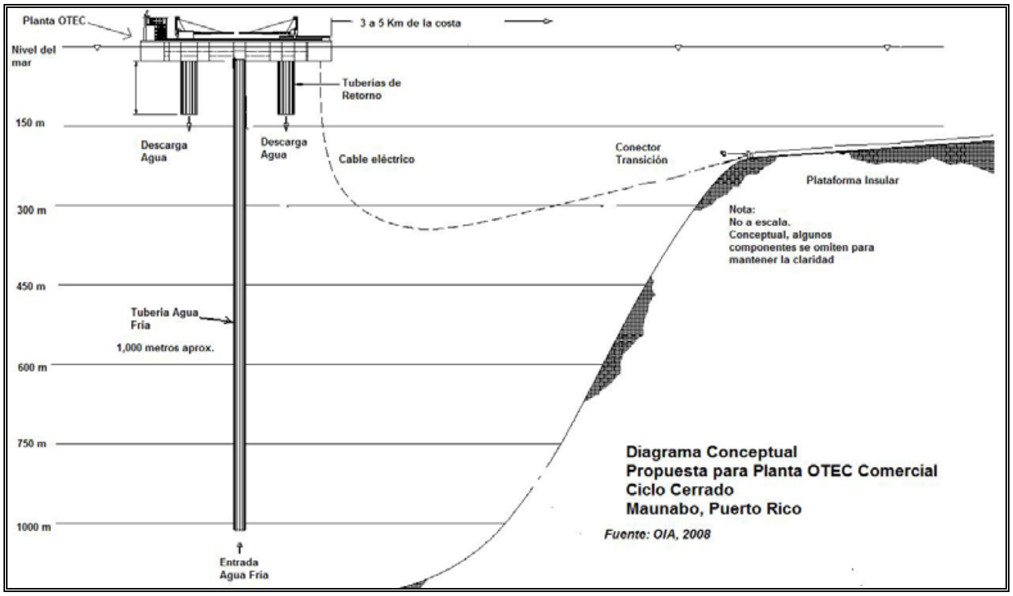


Figure 1. OTEC Closed-Cycle System Schematic



Nota:
No a escala.
Conceptual, algunos componentes se omiten para mantener la claridad

Diagrama Conceptual
Propuesta para Planta OTEC Comercial
Ciclo Cerrado
Maunabo, Puerto Rico

Fuente: OIA, 2008

Figure 2. Proposed OTEC Commercial Plant for Puerto Rico

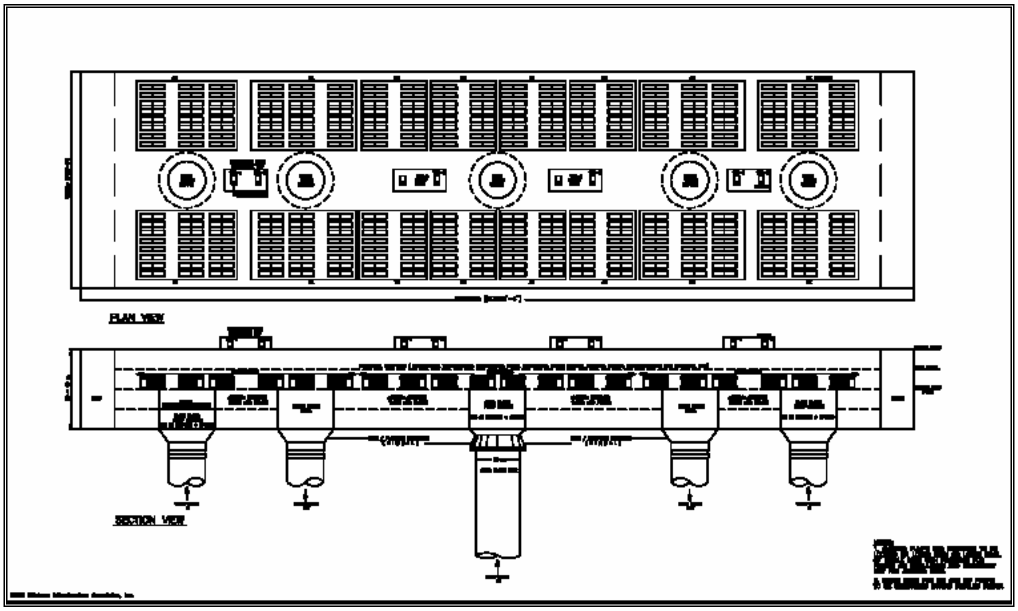


Figure 3. Proposed OTEC Conceptual Platform Layout for Puerto Rico

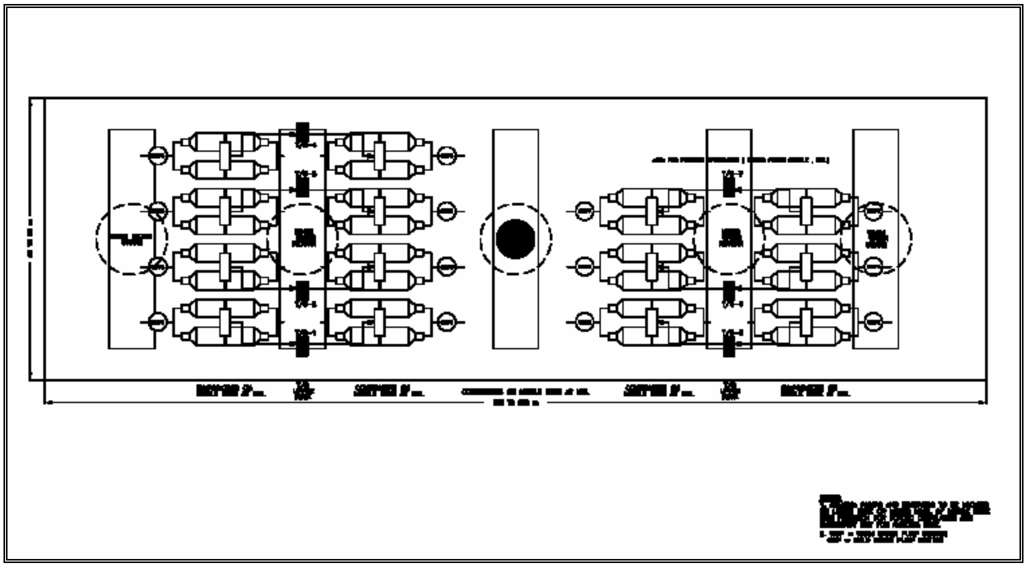


Figure 4. Alternative OTEC Platform Design Layout for Puerto Rico