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Ocean Thermal Energy Conversion

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Article Outline

Glossary

Baseload The minimum amount of power that a utility must make available to its customers.

Baseload plant An energy plant devoted to the production of baseload supply. Baseload plants typically run at all times through the year (24/7) except in the case of repairs or scheduled maintenance.

CWP Cold water pipe, the pipe used to transport deep ocean water to the OTEC condenser.

Draught (Draft) The depth of a ship's keel below the water surface.

Euphotic zone The upper layer of the ocean in which there is sufficient light for photosynthesis.

Externalities The costs generated by the production of electricity that are not included in the price charged to consumers. These costs manifest themselves through changes in the environment and other societal costs.

Gross power The electrical power generated by the turbine-generator.

Net power The electrical power available for export from the OTEC plant. The difference between gross power and in-plant power consumption needed to run all sweater and working fluid pumps.

Ocean thermal resource Defined by ΔT, the ocean temperature differences between water depths of 20 m (surface water) and 1,000 m.

OTEC Ocean Thermal Energy Conversion, the process of converting the ocean thermal energy into electricity.

OTEC transfer function The relationship between the thermal resource and the electricity generated.

Plantship A ship designed to house an OTEC power plant.

Re-entrainment The mixing of the water already used in the OTEC plant into the incoming warm (surface) water stream.

WOA05 World Ocean Atlas 2005 version.

Definition of the Subject

The vertical temperature distribution in the open ocean can be represented as two layers separated by an interface. The upper layer is warmed by the sun and mixed to depths of about 100 m by wave motion. The bottom layer consists of colder water formed at high latitudes. The interface or thermocline is sometimes marked by an abrupt change in temperature but more often the change is gradual. This implies that there are two reservoirs providing the heat source and the heat sink required for a heat engine. A practical application is found in a system designed to transform the thermal energy into electricity. This is referred to as OTEC for Ocean Thermal Energy Conversion.

At first, OTEC plantships providing electricity, via submarine power cables, to shore stations could be implemented. This would be followed, in 20 to 30 years, with OTEC factories deployed along equatorial waters producing energy-intensive products, like ammonia and hydrogen as the fuels that would support the post–fossil fuel era [2].

Apparently, there are sufficient petroleum resources (≈1400 billion barrels) to meet worldwide current demand (>30 billion barrels/year) for almost 50 years. Production, however, is peaking and humanity will face a steadily diminishing petroleum supply and higher demand due to emerging economies like China, India, and Brazil. Coal and natural gas resources could meet current worldwide demand for 100 to 120 years, respectively.

It seems sensible toconsider OTEC as one of the renewable energy technologies of the future.

Introduction

It has been postulated that the ocean thermal resource, defined as the difference between surface water and water from about 1,000 m depth, could be used to generate most of the energy required by humanity [1]. What is pending, however, are realistic determinations of the costs and the potential global environmental impact of OTEC plants, and this can only be accomplished by deploying and subsequently monitoring operations with first-generation plants.

One might ask: is OTEC renewable energy? The simple answer is: *as long as the sun shines and, if and only if, deep-ocean cold water is provided by the thermohaline circulation, the ocean thermal resource is renewable.*

A pertinent question, however, is: what is the worldwide power resource that could be extracted with OTEC plants without affecting the thermohaline ocean circulation? The estimate is that the maximum steady-state OTEC exportable electrical power is at least 5 TW, e.g., 10,000x 500 MW OTEC plants [3]. This is about twice the amount projected for worldwide electricity consumption by 2025.

OTEC History

Captain Nemo, Jules Verne's alter ego in "Twenty Thousand Leagues Under the Sea" published in 1870, provides the first reference to the idea of producing electricity using the ocean thermal resource:

- "I was determined to seek from the sea alone the means of producing my electricity.". . . "From the sea?". . . "Yes, Professor, and I was at no loss to find these means. It would have been possible, by establishing a circuit between two wires plunged to different depths, to obtain electricity by the difference of temperature to which they would have been exposed. . .."

Although Nemo conceptualized a thermoelectric device, the seeds of the OTEC principle emanated from Verne's pen inspired by ongoing discussions in French academic circles.

Eleven years later, D'Arsonval documented a formal proposal to use the relatively warm (24–30°C) surface water of the tropical oceans to vaporize pressurized ammonia through a heat exchanger (i.e., evaporator) and use the resulting vapor to drive a turbine-generator. The cold ocean water transported (upwelled) to the surface from 800 m to 1,000 m depths, with temperatures ranging from 8°C to 4°C, would condense the ammonia vapor through another heat exchanger (i.e., condenser). D'Arsonaval concept is grounded in the thermodynamic Rankine cycle used to study steam (vapor) power plants. Because the ammonia circulates in a closed loop, this concept has been named closed-cycle OTEC (CC-OTEC).

D'Arsonval's concept was demonstrated in 1979 when the state of Hawaii and a consortium of U.S. companies produced more than 50 kW of gross power, with a net output of up to 18 kW from a small plant mounted on a barge off Hawaii [4]. Subsequently, a 100 kW gross power, land-based plant was operated in the island nation of Nauru by a consortium of Japanese companies. These plants were operated for a few months to demonstrate the concept. They were too small to be scaled to commercial-size systems. Since then, the US Department of Energy [5, 6] and researchers at Saga University in Japan have performed extensive testing of heat exchangers and have proposed the use of an ammonia-water mixture as the working fluid [7].

Forty years after D'Arsonval, Georges Claude, another French inventor, proposed to use the ocean water as the working fluid [8]. In Claude's cycle, the surface water is flash-evaporated in a vacuum chamber. The resulting low-pressure steam is used to drive a turbine-generator, and the relatively colder deep seawater is used to condense the steam after it has passed through the turbine. This cycle can, therefore, be configured to produce desalinated water as well as electricity. Claude's cycle is also referred to as open-cycle OTEC (OC-OTEC) because the working fluid flows once through the system. Claude demonstrated this cycle in Cuba (1930) with a small land-based plant making use of a direct contact condenser (DCC). Therefore, desalinated water was not a by-product. The plant failed to achieve net power production because of a poor site selection (e.g., thermal resource) and a mismatch of the power and seawater systems. However, the plant did operate for several weeks.

Claude, subsequently, designed a 2.2 MW floating plant for the production of up to 2,000 t of ice (this was prior to the wide availability of household refrigerators) for the city of Rio de Janeiro in Brazil. Claude housed his power plant in a ship (i.e., plantship), about 100 km offshore. Unfortunately, he failed in his numerous attempts to install the vertical long pipe required to transport the deep ocean water to the ship (the cold water pipe, CWP) and had to abandon his enterprise in 1935. His failure can be attributed to the absence of the offshore industry, and ocean engineering expertise presently available. His biggest technological challenge was the at-sea installation of a CWP. This situation is markedly different now that there is a proven record in the installation of several pipes during experimental operations [1].

The next step toward answering questions related to operation of OTEC plants was the installation of a small OC-OTEC land-based experimental facility in Hawaii (Fig. 1). The turbine-generator was designed for an output of 210 kW for 26°C warm surface water and a deep water temperature of 6°C. A small fraction (10%) of the steam produced was diverted to a surface condenser for the production of desalinated water. The experimental plant was successfully operated for 6 years (1993–1998). The highest production rates achieved were 255 kWe (gross) with a corresponding net power of 103 kW and 0.4 L/s of desalinated water. These are world records for OTEC [9, 10].

A two-stage OTEC hybrid cycle, wherein electricity is produced in a first-stage (closed cycle) followed by water production in a second-stage, has been proposed to maximize the use of the thermal resource available to produce water and electricity [1]. In the second-stage, the temperature difference available in the seawater effluents from an OTEC plant (e.g., 12°C) is used to produce desalinated water through a system consisting of a flash evaporator and a surface condenser (basically, an open cycle without a turbine-generator). In the case of an open cycle plant, the addition of a second-stage results in doubling water production.

The use of the cold deep water as the chiller fluid in air conditioning (AC) systems was proposed and implemented [11]. It has been demonstrated that these systems providing significant energy conservation independent of OTEC [12].

OTEC energy could be transported via chemical, thermal, and electrochemical carriers. The technical evaluation of nonelectrical carriers lead, for example, to the consideration of hydrogen produced using electricity and desalinated water generated with OTEC technology. The product would be transported from

Ocean Thermal Energy Conversion. Figure 1
210 kW OC-OTEC experimental apparatus (1993–1998)

the OTEC plantship located at distances of about 1,500 km (selected to represent the nominal distance from the tropical oceans to major industrialized centers throughout the world) to the port facility in liquid form to be primarily used as a transportation fuel. A 100 MW-net plantship can be configured to yield (by electrolysis) 1,300 kg/h of liquid hydrogen [13]. Unfortunately, the production cost of liquid hydrogen delivered to the harbor would be equivalent to at least $300 barrel-of-crude-oil (approximately four times present cost). The situation is similar for the other energy carriers considered (e.g., anhydrous ammonia). Presently, the only energy carrier that is cost-effective for OTEC energy is the submarine power cable. This situation would be different in future decades in the post fossil-fuels era.

A number of possible configurations for OTEC plants have been proposed. These range from floating plants to land-based plants, including shelf-mounted towers and other offshore structures. The primary candidate for commercial size plants appears to be the floating plant, positioned close to land, transmitting power to shore via a submarine power cable [1, 2].

Over a decade ago, the detailed evaluation of economic feasibility and financial viability of OTEC revealed that, in general, plants would have to be sized at about 50–100 MW to produce cost-competitive baseload electricity. Smaller plants could be cost effective in some niche markets. It was also concluded that, although experimental work with relatively small plants had unambiguously demonstrated continuous production of electricity [4, 9, 10] and desalinated water [9, 10], it would be necessary to build a pre-commercial plant sized around 5–10 MW to establish the operational record required to secure financing for the commercial size plants [12]. The pre-commercial plant would produce relatively high-cost electricity and desalinated water such that support funding was required from the federal and state governments. Unfortunately, development did not proceed beyond experimental plants sized at less than 0.25 MW [1].

In the mid 1990s, an engineering team in Hawaii designed a 5 MW pre-commercial plant and made the information available in the public domain [14]. However, because the price of petroleum fuels was relatively low and fossil fuels were considered to be abundantly available, government funding for the pre-commercial plant could not be obtained.

Direct extrapolation from the experimental plants to commercial sizes, bypassing the pre-commercial stage, would have required a leap of faith with high technical and economic risks that no financial institution was willing to take. Important lessons learned can be summarized as follows:

- All components must be considered in technical and economic assessments: *OTEC plants consist of several components or subsystems that must be integrated into a system.*
- The entire life cycle must be incorporated into design process.
- Equipment must be manufactured using commercially available practices in existing factories.
- Embellishment leads to negative consequences creating credibility barriers for others and unrealistic expectations from the public.

Ocean Thermal Resources

The vast size of the ocean thermal resource and the baseload capability of OTEC systems remain very promising aspects of the technology for many island and coastal communities across tropical latitudes. For example, OTEC plants could supply all the electricity and potable water consumed in the State of Hawaii throughout the year and at all times of the day. This is an indigenous renewable energy resource that can provide a high degree of energy security and minimize green house gas emissions. This statement is also applicable to all US Insular Territories (e.g., American Samoa, Guam, Northern Mariana Islands, Virgin Islands, and Puerto Rico). With the development of electric vehicles, OTEC could also supply all electricity required to support land transportation. The resource is plentiful enough to meet additional electricity demand equivalent to several times present consumption. Please see section “Site Selection Criteria for OTEC Plants” for further information.

Thermal resource characteristics are used along with the specific OTEC system transfer function to determine electricity production. Ocean thermal resources are defined by ΔT, the ocean temperature differences between water depths of 20 and 1,000 m.

ΔT characterizes extractable OTEC power as long as the local thermal structure is preserved.

The current resource evaluation benefits from high-resolution ocean models. The HYCOM + NCODA (1/12°) model is used by Prof. Gerard Nihous of the University of Hawaii to track changes on a daily basis over a wide area around different locations [15].

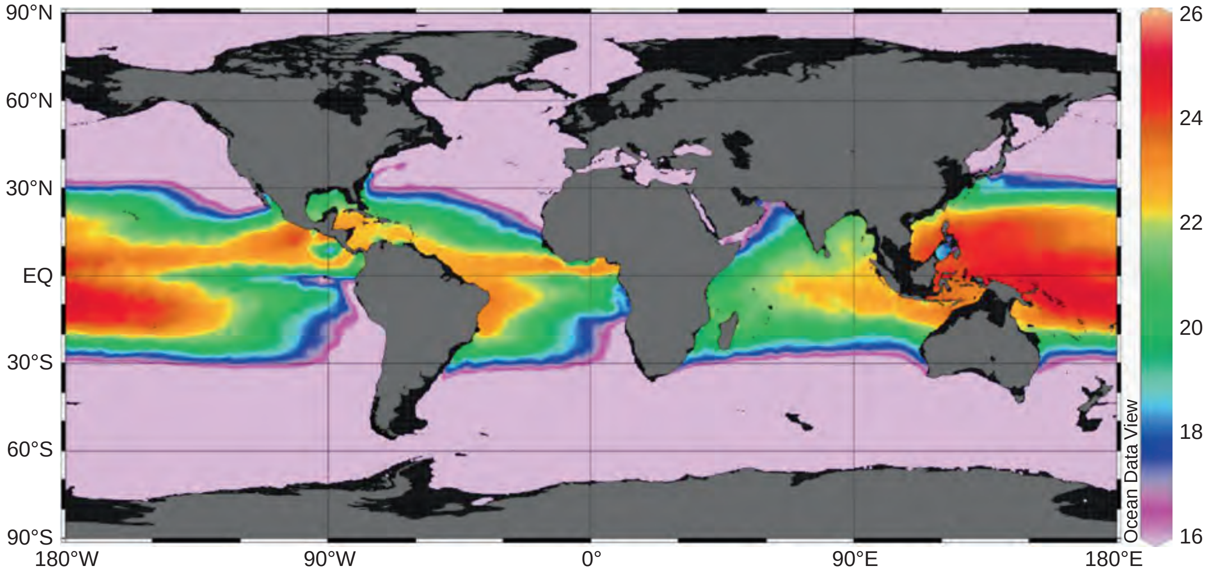
The optimized turbine-generator output P_{gross} varies with the square of ΔT so that for typical values of 20°C, a change of 1°C in ΔT will produce relative fluctuations of about 10% in P_{gross} [3]. Measurements performed during the operation of the *210 kW OC-OTEC Experimental Apparatus* confirmed this point [9, 10]. From a net power perspective, matters are even more sensitive since the in-plant power consumption needed to run all pumps represents about 30% of the reference value of P_{gross}; hence, changes of the order of 10% in P_{gross} approximately translate in 15% variations in net power output, which is the true basis for the determination of electricity production costs [3].

In the following discussion, the ocean thermal resource off the Hawaiian Islands is considered to illustrate the methodology that can be applied to any region of interest. The most recent, 2005 version of the World Ocean Atlas (WOA05) compiled by the National Ocean Data Center (NODC) represents an extremely valuable source of objectively analyzed statistical fields, including ocean temperature [16]. The data includes long-term historical averages of variables that have been determined from all available oceanographic measurements. Monthly averages also are available. The data is provided with a resolution of one-quarter degree latitude by one-quarter degree longitude.

Figure 2 shows a map of the average OTEC thermal resource ΔT from the WOA05 data base plotted with the Ocean Data View software (http://odv.awi.de).

As can be seen in Fig. 2, the Hawaiian Archipelago is very well located from a thermal resource perspective. The volcanic islands have a steep bathymetry that affords good access to deep water. Their isolation and nearly complete dependence on fossil fuels today make any local baseload power-production technology particularly attractive. Additional factors that would hamper other renewable energy technologies in Hawaii, such as limited land availability, pristine reefs, and valuable surf resources, would hardly affect OTEC.

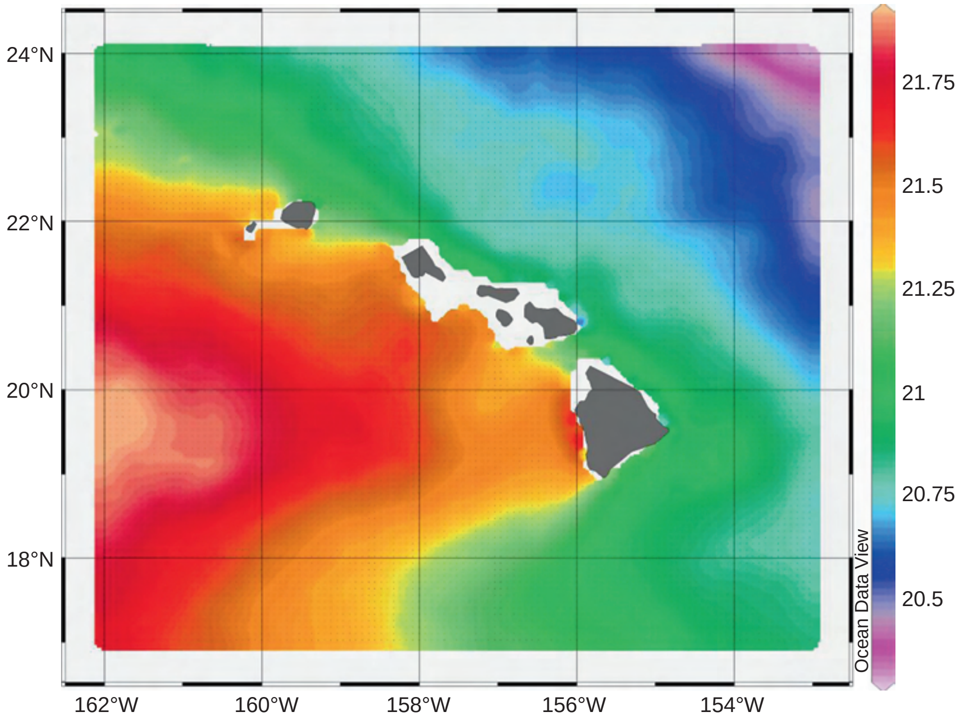
Regarding OTEC thermal resources around the main Hawaiian Islands, a closer look at the WOA05 data in Fig. 2 suggests that such resources are not



Ocean Thermal Energy Conversion. Figure 2
Average ocean temperature differences (between 20 and 1,000 m water depths) from WOA05 data with color palette from 16°C to 26°C (From [15])

enhanced from North to South, as would be intuitive, but roughly from Northeast to Southwest. Recently available predictive tools afford a much more detailed analysis. An ocean model called HYCOM (HYbrid Coordinate Ocean Model), subject to routine data assimilation via the Naval Research Laboratory (NRL)'s Coupled Ocean Data Assimilation (NCODA) protocol, allows daily assessments of ocean variables at a spatial resolution of 1/12° latitude by 1/12° longitude across the water column [17]. NCODA assimilates all available operational sources of ocean observations. The model output essentially should be interpreted as daily averages [15]. This data can be downloaded via public-domain servers such as http://ferret.pmel.noaa.gov/LAS.

Figure 3 shows the average available OTEC thermal resource ΔT over a period of 3 years, from July 1, 2007 through June 30, 2010. Areas that are shallower than 1,000 m are displayed in white to indicate that ΔT is not defined there. Although overall geographic variations in the selected area covering 7° of latitude and 9° of longitude are within 2°C, a prominent wedge can be seen; its apex roughly lies at the eastern tip of the Big Island, and the feature is somewhat symmetric across the latitude of that point; from the apex, a line running along the northeast (windward) coasts of the islands defines the angular overture of the wedge. The emergence of such a feature is likely to be the result of the strong influence the islands exert on large-scale ocean currents [18]. The westward-flowing North Equatorial Current (NEC) forks at the Big Island and gives rise to a branch that follows a northwesterly direction (North Hawaiian Ridge Current). West of the islands, the vorticity of the wind-stress curl associated with the wake of the islands causes a clockwise circulation centered at 19°N and a counterclockwise circulation centered at 20°30′N, with the narrow Hawaiian Lee Counter Current (HLCC) extending between them from 170°W (or from as far as the Dateline) to 158°W. The eastward-flowing HLCC is responsible for the advection of warm water toward the lee of the Hawaiian archipelago [15, 18].



Ocean Thermal Energy Conversion. Figure 3

Average ocean temperature differences (between 20 and 1,000 m water depths) around the main Hawaiian Islands from HYCOM + NCODA (1/12°) data for the period July 1, 2007, through June 30, 2010 (From [15])

Technical Limitations and Challenges

The performance of OTEC cycles is assessed with the same thermodynamics concepts used for conventional steam power plants. The major difference arises from the large quantities of warm and cold seawater required for heat transfer processes, resulting in the consumption of a portion of the power generated by the turbine-generator in the operation of pumps. The power required to pump seawater is determined accounting for the pipe-fluid frictional losses and in the case of the cold seawater for the density head, i.e., gravitational energy due to the differences in density between the heavier (colder) water inside the pipe and the surrounding water column. The seawater temperature rise, due to frictional losses, is negligible for practical designs [1].

The ideal energy conversion for 26°C and 4°C warm and cold seawaters is 8%. An actual OTEC plant will transfer heat irreversibly at various points in the cycle yielding an energy conversion of 3–4%. These values are small compared to efficiencies obtained for conventional power plants; however, OTEC uses a resource that is constantly renewed by the sun.

The thermal performance of CC-OTEC and OC-OTEC is comparable. Approximately 5 m^3/s of warm seawater and 2.5 m^3/s of cold seawater, with a nominal temperature difference of 20°C, are required per MW of exportable or net electricity [1]. To keep the water pumping losses at about 30% of the gross power, an average speed of about 2 m/s is considered for the seawater flowing through the pipes transporting the seawater resource to the OTEC power block. Therefore, a 100 MW-net plant would use about 500 m^3/s of 26 C water flowing through a 17 m inside diameter pipe extending to a depth of 20 m, and 250 m^3/s of 4°C water flowing through a 12 m diameter pipe extending to depths of 1,000 m. Using similar arguments, a 22 m diameter pipe is required for the mixed water return. To minimize the environmental impact due to the return of the processed water to the ocean (mostly changes in temperature), a discharge depth of 60 m is sufficient for most sites considered feasible, resulting in a pipe extending to depths of 60 m.

The design and installation of a cost-effective pipe to transport large quantities of cold water to the surface (i.e., cold water pipe, CWP) presented an engineering challenge of significant magnitude complicated by a lack of evolutionary experience. This challenge was met in the USA with a program relying on computer-aided analytical studies integrated with laboratory and at-sea tests. The greatest outcome achieved has been the design, fabrication, transportation, deployment, and test at sea of an instrumented 2.4 m diameter, 120 m long, fiberglass-reinforced-plastic (FRP) sandwich construction pipe attached to a barge [19]. The data obtained was used to validate the design technology developed for pipes suspended from floating OTEC plants. This type of pipe is recommended for floating OTEC plants.

For land-based plants, there is a validated design for high-density polyethylene pipes of diameter less than about 2 m [20]. In the case of larger diameter pipes offshore techniques used to deploy large segmented pipes made of steel, concrete or FRP are applicable. Pressurized pipes made of reinforced elastomeric fabrics (e.g., soft pipes), with pumps located at the cold-water intake, seem to offer the most innovative alternative to conventional concepts. However, the operability of pumps in 800–1,000 m water depths over extended periods must be verified and the inspection, maintenance and repair (IM&R) constraints established before soft pipes can be used in practical designs.

Other components for OTEC floating plants that present engineering challenges are the position keeping system and the attachment of the submarine power cable to the floating plant. Deep ocean-mooring systems, designed for water depths of more than 1,000 m, or dynamic positioning thrusters developed by the offshore industry can be used for position keeping. The warm-water intake and the mixed return water also provide the momentum necessary to position the surface vessel. The offshore industry also provides the engineering and technological backgrounds required to design and install the riser for the submarine power cable.

The design of OTEC CWPs, mooring systems, and the submarine power cable must take into consideration survivability loads as well as fatigue-induced loads. The first kind is based on extreme environmental phenomena, with a relatively long return period, that might result in ultimate strength failure, while the second kind might result in fatigue-induced failure through normal operations.

OTEC systems are in the pre-commercial phase with several experimental projects having already demonstrated that the technology works but lacking the operational records required to proceeding into commercialization. Adequately sized pilot projects must be implemented to obtain these records. The largest OTEC experimental system was sized at 0.25 MW; however, our analysis indicates that a pilot plant sized at about 5–10 MW is required [2].

Major challenges to OTEC commercialization can be summarized as follows:

- How to overcome the lack of consistent government funding that is required for industry to proceed from concept design to the required OTEC pre-commercial demonstration phase.
- How to streamline the process of obtaining licenses and permits, including the necessary Environmental Impact Statement (EIS). The process is project specific, expensive, and estimated to require at least 2 years for commercial projects in the USA.
- How to evolve into a situation represented by a one-stop-shop (as envisioned in the USA 1980 OTEC Act), where industry can process all documentation stipulated for licensing and permitting under federal, state, city, and county regulations avoiding duplicity, contradictory requirements, and interdepartmental jurisdictional disputes.

In the USA, the proposed location determines the various federal, state, and county agencies and regulations that apply. In addition to the licenses and permits that must be secured from different agencies, the project must comply with several other applicable laws. The 1980 OTEC Act (OTECA) gives the National Oceanic and Atmospheric Administration (NOAA) of the Department of Commerce the authority for licensing the construction and operation of commercial OTEC plants. After the promulgation of OTECA in 1981, licensing regulations were developed by NOAA but, in 1996, NOAA rescinded these regulations and eliminated its OTEC office because no applications had been received. NOAA is currently in the process of developing new licensing regulations. Under OTECA, NOAA is required to coordinate with Coastal States and the US Coast Guard as well, as other Federal Agencies. An EIS would be required for each license. It is expected that the majority if not all federal, state, and local requirements would be handled through the NOAA licensing process.

The original Act gave the Secretary of Energy the authority to exempt Test Plants from NOAA's licensing requirements. A Test Plant was defined as "a test platform which will not operate as an OTEC facility or plantship after conclusion of the testing period." An EIS would be required if "there are other permits to be obtained that are considered a major federal action."

Perhaps a lesson can be learned from the successful commercialization of wind energy that was due to consistent government funding of pilot or pre-commercial projects that led to appropriate and realistic determination of technical requirements and operational costs in Germany, Denmark, and Spain. In this context, by commercialization we mean that equipment can be financed under terms that yield cost competitive electricity. This of course depends on specific conditions at each site.

Environmental Impact

While it is certain that physical, chemical, and biological impacts would occur during the construction and operation of an OTEC facility, the precise magnitude and extent of these impacts are not known. The cumulative or secondary impacts are largely undeterminable without long-term monitoring [21].

These impacts must be evaluated, and all licensing and permitting requirements must be fulfilled. However, it is of extreme importance to understand that the only process that differentiates OTEC from other well-established human activities and industries is the use of ocean water drawn from ~1,000 m depths and its return to the ocean below the photic zone. Given the intricate and dynamic nature of the ocean, it is nearly impossible to determine with a high degree of certainty what would be the effect of such process through basic research or the development of ecological theory. The only way to evaluate the OTEC environmental differentiator is to obtain field data with a pilot plant operating with flow rates corresponding to at least a 5 MW plant. Such plant must be operated and monitored through ongoing and adaptive experience for one to two continuous years, i.e., an adaptive management process.

To better understand the risks that these impacts pose, an environmental baseline is required prior to installation. This site-specific baseline should include monitoring for presence and abundance of large and small biota, as well as the physical and chemical seawater characteristics. For certain impacts, a longer baseline may be desired to capture multi-year variability. Monitoring for changes to the baseline should occur during the installation and operation phase and would provide information on how the facility is impacting the local environment. Physical, chemical, and biological criteria should be monitored, including temperature; salinity; dissolved oxygen; pH; trace metals; and abundance, diversity, mortality, and behavioral changes in plankton, fish, marine mammals, turtles, and other biota [21].

The energy that could be provided by OTEC must be balanced with the impact to the marine environment that would be caused by OTEC plants. The return water from a 100 MW plant would be equivalent to the nominal flow of the Colorado River into the Pacific Ocean. Although river runoff composition is considerably different, providing a significant amount of power to the world with OTEC might have an impact on the environment below the oceanic mixed layer and, therefore, could have long-term significance in the marine environment. However, numerous countries throughout the world could use OTEC as a component of their energy equation with relatively minimal environmental impact. Tropical and subtropical island sites could be made independent of conventional fuels for the production of electricity and desalinated water.

OTEC offers one of the most benign power-production technologies, since the handling of hazardous substances is limited to the working fluid (e.g., ammonia) and no noxious by-products are generated. The carbon dioxide outgassing from the seawater used for the operation of an OC-OTEC plant is less than 1% of the approximately 700 g per kWh amount released by fuel oil plants. The value is even lower in the case of a CC-OTEC plant [1].

A sustained flow of cold, nutrient-rich, bacteria-free deep ocean water could cause sea surface temperature anomalies and biostimulation if resident times in the mixed layer and the euphotic zone respectively are long enough (i.e., upwelling). The euphotic zone is the upper layer of the ocean in which there is sufficient light for photosynthesis. This has been taken to mean the 1%-light-penetration depth (e.g., 120 m in Hawaiian waters). This is unduly conservative because most biological activity requires radiation levels of at least 10% of the sea surface value. Since light intensity decreases exponentially with depth, the critical 10%-light-penetration depth corresponds to, for example, 60 m in Hawaiian waters. The analyses of specific OTEC designs indicate that mixed seawater returned at depths of 60 m results in a dilution coefficient of 4 (i.e., 1 part OTEC effluent is mixed with 3 parts of the ambient seawater) and equilibrium (neutral buoyancy) depths below the mixed layer throughout the year [22]. This water return depth also provides the vertical separation, from the warm-water intake at about 20 m, required to avoid reingestion into the plant. This value will vary as a function of ocean current conditions. It follows that the marine food web should be minimally affected and that persistent sea surface temperature anomalies should not be induced. These conclusions need to be confirmed with actual field measurements that could be performed with pilot plants [21].

To have effective heat transfer, it is necessary to protect the heat exchangers from biofouling. It has been determined that, with proper design, biofouling only occurs in OTEC heat exchangers exposed to surface seawater [5]. Therefore, it is only necessary to protect the CC-OTEC evaporators by, for example, intermittent chlorination (50–100 parts per billion chlorine for 1 h/day). This amount, for example, is well below what is allowed under current US regulations.

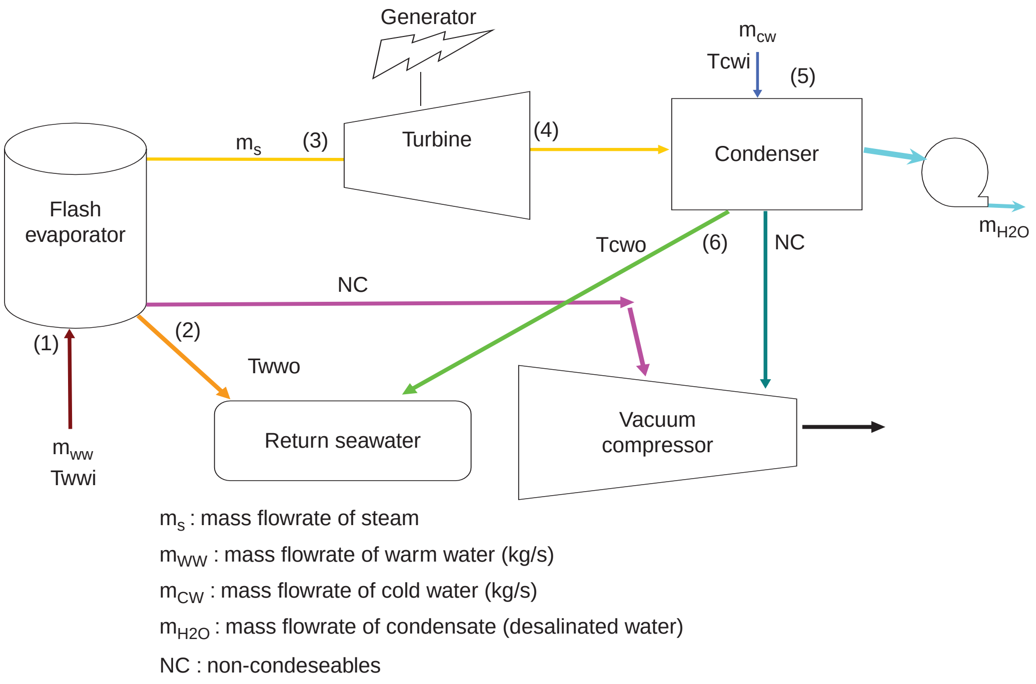
Other potentially significant concerns are related to the construction phase. These are similar to those associated with the construction of any power plant, shipbuilding, and the construction of offshore platforms. What is unique to OTEC is the movement of seawater streams and the effect of passing such streams through the OTEC components before returning them to the ocean [23, 24]. The use of biocides and ammonia are similar to other human activities. If occupational health and safety regulations like those in effect in the USA are followed, working fluid and biocide emissions from a plant should be too low to detect outside the plant sites. Ammonia is used as a fertilizer and in ice skating–rink refrigeration systems. Chlorine is used in municipal water treatment plants and in steam power plants.

OTEC plant construction and operation may affect commercial and recreational fishing. Fish will be attracted to the plant, potentially increasing fishing in the area. However, the losses of inshore fish eggs and larvae, as well as juvenile fish, due to impingement and entrainment and to the discharge of biocides may reduce fish populations. The net effect of OTEC operation on aquatic life would depend on the balance achieved between these two effects. Through adequate planning and coordination with the local community, recreational assets near an OTEC site may be enhanced.

It is essential that all potentially significant concerns be examined and assessed for each site and design to assure that OTEC is an environmentally benign and safe alternative to conventional power generation. The consensus among researchers is that the potentially detrimental effects of OTEC plants on the environment can be avoided or mitigated by proper design and that their impact is less than that of conventional power technologies.

Open-Cycle OTEC

The open cycle consists of the following steps: (1) flash evaporation of a fraction of the warm seawater by reduction of pressure below the saturation value corresponding to its temperature; (2) expansion of the vapor through a turbine to generate power; (3) heat transfer to the cold seawater thermal sink, resulting in condensation of the working fluid; and (4) compression of the noncondensable gases (air released from the seawater streams at the low operating pressure) to pressures required to discharge them from the system. These steps are depicted in Fig. 4. In the case of a surface condenser, the condensate (desalinated water) must be compressed to pressures required to discharge it from the power generating system. The evaporator, turbine, and condenser operate in partial vacuum ranging from 3% to 1% atmospheric pressure. This poses a number of practical concerns that must be addressed. First, the system must be carefully sealed to prevent in-leakage of atmospheric air that can severely degrade or shut down operation. Second, the specific volume of the low-pressure steam is very large compared to that of the pressurized working fluid used in closed cycle OTEC. This means that components must have large flow areas to ensure that steam velocities do not attain excessively high values. Finally, gases such as oxygen, nitrogen, and carbon dioxide that are dissolved



Ocean Thermal Energy Conversion. Figure 4
Open-cycle OTEC process flow diagram

in seawater (essentially air) come out of solution in a vacuum. These gases are not condensable and must be exhausted from the system.

In spite of the aforementioned engineering challenges, the Claude cycle enjoys certain benefits from the selection of water as the working fluid. Water, unlike ammonia, is nontoxic and environmentally benign. Moreover, since the evaporator produces desalinated steam, the condenser can be designed to yield fresh water. In many potential sites in the tropics, potable water is a highly desired commodity that can be marketed to offset the price of OTEC-generated electricity.

Flash evaporation is a distinguishing feature of open cycle OTEC. Flash evaporation involves complex heat and mass transfer processes. In the configuration tested with the *210 kW OC-OTEC Experimental Apparatus* [9, 10] warm seawater was pumped into a chamber through spouts designed to maximize the heat-and-mass-transfer surface area by producing a spray of the liquid. The pressure in the chamber (2.6% of atmospheric) was less than the saturation pressure of the warm seawater. Exposed to this low-pressure environment, water in the spray began to boil. As in thermal desalination plants, the vapor produced was relatively pure steam. As steam is generated, it carries away with it its heat of vaporization. This energy comes from the liquid phase and results in a lowering of the liquid temperature and the cessation of boiling. Thus, as mentioned above, flash evaporation may be seen as a transfer of thermal energy from the bulk of the warm seawater to the small fraction of mass that is vaporized to become the working fluid. Approximately 0.5% of the mass of warm seawater entering the evaporator is converted into steam.

A large turbine is required to accommodate the relatively large volumetric flow rates of low-pressure steam needed to generate any practical amount of electrical power. Although the last stages of turbines used in conventional steam power plants can be adapted to OC-OTEC operating conditions, existing technology limits the power that can be generated by a single turbine module, comprising a pair of rotors, to about 2.5 MW. Condensation of the low-pressure working fluid leaving the turbine occurs by heat transfer to the cold seawater. This heat transfer may occur in a Direct-Contact-Condenser (DCC), in which the seawater is sprayed directly over the vapor, or in a Surface Condenser (SC) that does not allow contact between the coolant and the condensate. DCCs are relatively inexpensive and have good heat transfer characteristics due to the lack of a solid thermal boundary between the warm and cool fluids. Although SCs for OTEC applications are relatively expensive to fabricate, they permit the production of desalinated water. Desalinated water production with a DCC requires the use of fresh water as the coolant. In such an arrangement, the cold seawater sink is used to chill the fresh-water coolant supply using a liquid-to-liquid heat exchanger.

Effluent from the low-pressure condenser must be returned to the environment. Liquid can be pressurized to ambient conditions at the point of discharge by means of a pump or, if the elevation of the condenser is suitably high, it can be compressed hydrostatically. Noncondensable gases, which include any residual water vapor, dissolved gases that have come out of solution, and air that may have leaked into the system, must be pressurized with a compressor. Although the primary role of the compressor is to discharge exhaust gases, it usually is perceived as the means to reduce pressure in the system below atmospheric. For a system that includes both the OC-OTEC heat engine and its environment, the cycle is closed and parallels the Rankine cycle. Here, the condensate discharge pump and the noncondensable gas compressor assume the role of the Rankine cycle pump.

The analysis of the cycle yields (Fig. 4):

Heat (added) absorbed from seawater (J/s)	$q_w = \dot{m}_{ww} Cp\,(T_{wwi} - T_{wwo})$
Steam generation rate (kg/s)	$\dot{m}_s = q_w / hfg$
Turbine work (J/s)	$w_T = \dot{m}_s (h_3 - h_4)$ $= \dot{m}_s\, \eta_T\, (h_3 - h_{4s})$
Heat (rejected) into seawater (J/s)	$q_c = \dot{m}_{cw} Cp\,(T_{cwo} - T_{cwi})$

where

$\dot{m}_{ww}$ is the mass flow rate of warm water; Cp the specific heat; T_{wwi} and T_{wwo} the seawater temperature at the inlet and outlet of the heat exchanger; hfg the heat of evaporation; and the enthalpies at the indicated points are given by h, with the subscript s referring to constant entropy. The turbine isentropic efficiency is given by η_T. The subscript cw refers to the cold water.

The 210 kW OC-OTEC Experimental Apparatus

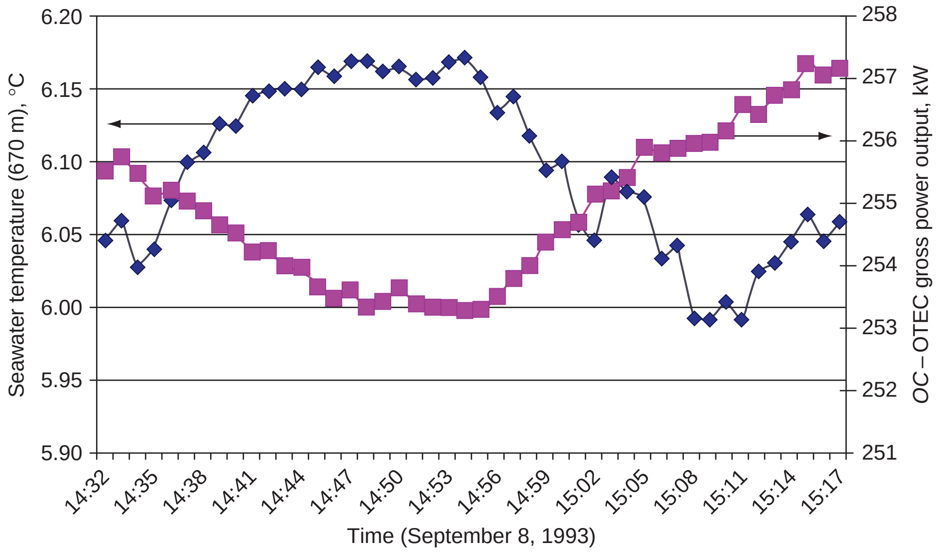
The *210 kW OC-OTEC Experimental Apparatus* was conceived to answer questions related to operation of OTEC plants (Fig. 1). The apparatus was operated for 6 years (1993–1998), providing valuable data and pointing the way for future modifications and improvements in the OC-OTEC process. The turbine-generator was designed for an output is 210 kW for 26°C warm surface water and a deep water temperature of 6°C. A small fraction (10%) of the steam produced was diverted to a surface condenser for the production of desalinated water. The highest production rates achieved were 255 kW (gross) with a corresponding net power of 103 kW and 0.4 l/s of desalinated water. It must be noted that the net power was not optimized because pumping losses were relatively high due to the use of a seawater system that was already available. It is expected that for a commercial size plant the ratio of net to gross power will be about 0.7 [9, 10].

The relationships between power production and the system control parameters were established experimentally. From the perspective of the overall system, the control parameters are the flow rate of warm water; the flow rate of cold water; and the compressor subsystem setting as given, for example, by the inlet pressure. The other control parameters are set by seasonal variations of seawater temperature and cannot be set by the operator.

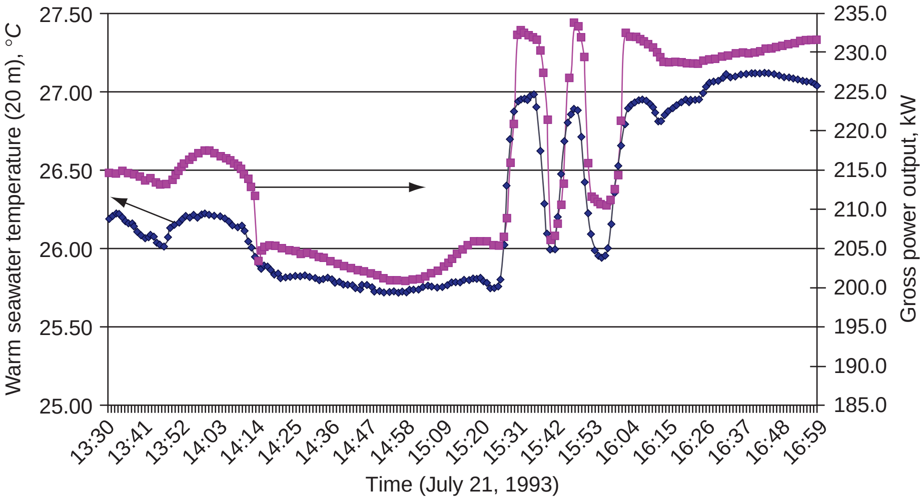
Figure 5 depicts the effect in gross power output as the cold-water temperature varies. The power increases as the temperature decreases with all other control parameters constant. The somewhat unexpected oscillation in cold-water temperature depicted in the figure is induced by internal waves of periods in the order of 1 h (with corresponding wave lengths of approximately 3,500 m) and 50 m height. These internal waves were present in the majority of the time history records.

The power output as a function of warm-water temperature, with all other control parameters constant is shown in Fig. 6. The relationship depicted in Fig. 6 is obvious. It is interesting to note that the temperature variations shown, by means of the 1 min averages of surface water temperature (20 m depth) sampled once per second, are apparently caused by a warmer water mass intrusion that could have been driven by an ocean gyre of the kind observed in coastal regions close to channels (in this case the Alenuihaha Channel between Maui and the Big Island of Hawaii).

Data records like these were used to establish that the variation of power output with seawater temperature is approximately 34 kW/°C at power levels of about 200 kW. It was also determined that the variation



Ocean Thermal Energy Conversion. Figure 5
210 kW OC-OTEC experimental apparatus: Power output variation as a function cold-water temperature



Ocean Thermal Energy Conversion. Figure 6
210 kW OC-OTEC experimental apparatus: Power output variation as a function warm-water temperature

of power with vacuum pumps inlet pressure, with all other control parameters kept constant, is given by 0.2 kW/Pa such that for an inlet pressure lowering of 5 Pa, an extra 1 kW of power is realized. The minimal inlet pressure achievable is dictated by the pumps' capability. This type of information is used to design of the controls for OTEC systems.

The data and experience obtained demonstrated that the OC-OTEC process is technically feasible for the production of base load electricity and desalinated water. This has been used as the basis for the design of a 50 MW OC-OTEC plant housed in a ship-shaped platform [25].

The most significant and exciting lessons learned were those which were fundamental new insights into the OC-OTEC process. The two main discoveries were the unstable synchronous generator output, and the violent outgassing of seawater in the heat exchangers. The most annoying problem was the frequent failures of the grease-lubricated bearings of the centrifugal pumps used for the vacuum and exhaust system. In retrospect, this was due to a major design oversight. Equipment operating at speeds higher than approximately 27,000 rpm should, in general, not use grease-lubricated bearings. It was concluded that high-speed centrifugal pumps with, for example, magnetic bearings can be used in future OC-OTEC systems to achieve extended life cycles, relatively low power consumption and, therefore, optimum net power.

Other significant lessons learned (or relearned) and observations from the perspective of an operator of the OTEC experimental or pilot plant facility were:

- Specifications should be written to emphasize the particulars of the job excluding "boiler plate" information.
- Make the plant "user friendly" from the standpoint of troubleshooting, maintenance, repair and modification.
- Include technical field support from suppliers of major equipment but be prepared to solve most problems on your own.
- Select equipment with excess capacity. It was appropriate to optimize design point performance, but there will always be off-design operations requiring additional capacity.
- Mechanical equipment specifically designed for OTEC must be instrumented to measure temperatures and pressures in as many locations as possible. For example, measurements performed with sensors installed, in the field, to estimate temperatures around the bearings of the high-speed centrifugal pumps revealed that they were failing because of two main causes: (1) deterioration of the bearing's lubricant grease due to high temperatures and/or (2) differential expansion of the outer and inner rings, resulting in squeezing of the ball bearings.

- If equipment has moving parts evaluate the bearing system and ask potential supplier to provide references of successful application of their design before purchase.
- Consider the corrosive saltwater, condensate, and the typically harsh environment of OTEC sites when making design decisions, especially material selection and placement of mechanical and electrical equipment.
- Concrete was an excellent material for the vacuum structures required for OC-OTEC.
- Avoid metal components, but if unavoidable, use the hot-dip-galvanized process from a factory with proven quality control procedures.
- Fresh Water, instead of seawater, should be used as the Coolant for the intercoolers used with the vacuum compressors.

The *210 kW OC-OTEC Experimental Apparatus* was also used to demonstrate that frequency control in the island mode is achieved with either a load-diversion-governor (LDG) or with the vacuum compression system. OTEC plants installed in isolated tropical locations would require some means of controlling turbine-generator speed to maintain 60 Hz (or 50 Hz) under varying conditions of power production and load demand. They would not have the line frequency, from an established electrical grid, to fix their turbine-generator speed. Such a stand-alone power plant is referred to as operating in an island mode or being islanded.

Alternating current (AC) power is produced by either a synchronous or induction generator. The 60 Hz AC comes from a two pole synchronous generator turning at 3,600 rpm or a four pole synchronous generator turning at 1,800 rpm, like the one used with the *210 kW OC-OTEC Experimental Apparatus*. A synchronous generator produces its own magnetic field through self-excitation and so can operate islanded without grid connection. An induction motor becomes an induction generator when driven slightly faster than synchronous speed (1,800 or 3,600 rpm) but requires VAR's (volt-amp-reactive) from the utility to produce its magnetic field. Therefore, an induction generator can never operate islanded.

Either type of generator connected to an infinitely stiff grid (very large power capacity compared to the generator size) is slaved to the grid frequency and must follow any variations in it. Because a synchronous generator operating islanded cannot depend on the grid for frequency regulation, a method of speed control is required. Without it, generator speed and AC frequency will remain constant only when its power output exactly matches that required by the load. If there is the slightest mismatch, the generator will slow down when the load increases or speed up when it decreases and thus the frequency will change.

Frequency control is referred to as governing and is accomplished with a device called a governor. Diesel generators, for example, have mechanical or electronic governors that regulate fuel flow. Likewise, steam or gas turbines have governors that control steam or fuel flow. A CC-OTEC ammonia turbine can be governed by adjusting the turbine inlet nozzles as was done in 1979 aboard the Mini-OTEC barge islanded offshore [4]. For OC-OTEC plants flow control, as done in conventional steam and ammonia turbines, is difficult due to the relatively large volumes of low density cold steam.

Large hydroelectric plants can be governed similarly to CC-OTEC. Small plants, however, are commonly allowed to run at full power and an electronic device called a load diversion governor (LDG) diverts (shunts) excess power to resistive water-heating elements to maintain 60 Hz frequency. A LDG was installed on the *210 kW OC-OTEC Experimental Apparatus*, and this control method was found to give appropriate frequency regulation. Gross control of power output is possible by regulating water flows, but this does not provide the precise frequency regulation required. This leaves process control via the vacuum compressor system as the only other alternative. Frequency control using modulation of the vacuum compressor system (i.e., varying the vacuum pumps speed to vary the condenser outlet pressure and, therefore, the power output) was also demonstrated to work.

Any islanded OC-OTEC plant would probably consist of multiple modules for purposes of redundancy and reliability, and because of limitations on the maximum size of a single module. Thus, it would be possible to bring online or drop offline modules as load demand varies. It might be possible to design the plant such that some modules could be operated as base load units without precise frequency control but slaved to units controlling the frequency.

Frequency control could be a combination of gross regulation via water flows, tuning of the process via modulation of the vacuum system, and precise control with a LDG. Being an electronic device, the LDG might present problems of reliability. Furthermore, it seems likely that the LDG would be sized to shunt only a small portion of the total power output for purposes of trimming the total load for precise frequency control. From the standpoint of plant wear and tear, it seems unlikely that a control module would be run at full capacity all the time with a large LDG wasting excess power, as with a small hydroelectric plant.

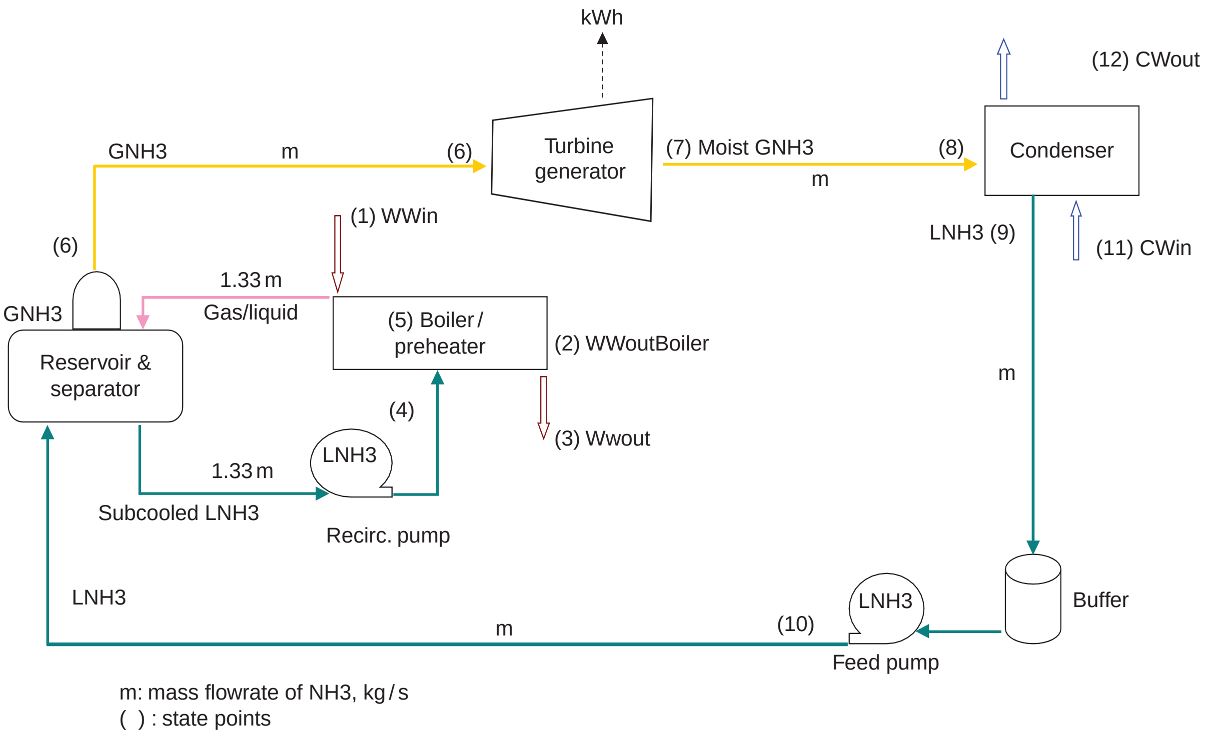
OC-OTEC Control Parameters

The OC-OTEC control parameters are: (1) mass flow rate of warm water, (2) mass flow rate of cold water, (3) vacuum compressor inlet pressure, (4) warm-water temperature, and (5) cold-water temperature. The gross power output from an OC-OTEC power plant can be controlled only with the first three parameters, while the water temperatures are dictated by natural processes. During operations with the *210 kW OC-OTEC Experimental Apparatus*, gross power output was controlled by varying the water stream flow rates with the water pumps and the inlet pressure with the vacuum pumps [9].

Closed-Cycle OTEC

The operation of a closed-cycle OTEC plant, using anhydrous ammonia as the working fluid, is modeled with the saturated Rankine cycle. Figure 7 shows the process flow diagram of the CC-OTEC cycle. The analysis of the cycle is straightforward. Based on a unit mass flow rate of ammonia vapor (kg/s) in the saturated cycle

Heat Added (J/kg)	$q_A = h_6 - h_5$
Turbine Work (J/kg)	$w_T = h_6 - h_7$
Heat Rejected (J/kg)	$q_R = h_8 - h_9$
Pump Work (J/kg)	$W_P = h_5 - h_9$
Cycle Net Work (J/kg)	$\Delta W_{net} = (h_6 - h_7) - (h_5 - h_9)$
Thermal Efficiency	$\eta th = \Delta W_{net}/q_A$



Ocean Thermal Energy Conversion. Figure 7
Closed-cycle OTEC flow diagram

where, h is the enthalpy at the indicated state point. It follows that the heat-added plus the pump-work is equal to the heat-rejected plus the turbine-work. Please see section "State of the Art 10 MW CC-OTEC Pilot Plant" for further information.

Evaporator Performance (CC-OTEC)

Relatively cold liquid ammonia (LNH_3) is fed to the evaporator system (encompasses the preheater and boiler) from the separator/reservoir tank with the recirculating pump. The preheater warms the LNH_3 to a temperature approaching the saturation temperature corresponding to the boiler's pressure. This is followed by the actual "boiling" of the ammonia into a wet vapor.

Conservation of energy, considering a control volume enclosing the entire evaporator system and neglecting the relatively small enthalpy difference between the liquid ammonia at the inlet and outlet, yields:

$$Cp\ dMww/dt\ \Delta\ Tww\ =\ hfg\ dMGNH_3/dt$$

where

Cp, the specific heat of seawater at constant pressure is 4 kJ/kg-°C under OTEC conditions
dMww/dt, the mass flow rate of warm seawater (kg/s)
ΔTww, the seawater temperature drop across the evaporator (°C)
hfg, is the latent heat of vaporization at the evaporator exit (kJ/kg)
$dMGNH_3/dt$, the mass flow rate of the ammonia gas at the evaporator exit (kg/s)

The water-side heat duty is given by the left-hand side of the equation and the ammonia-side heat duty by the right-hand side.

The overall heat transfer coefficient Uo ($kW/m^2\ K$) can be estimated by equating the heat duty to [Uo A LMTD], where A is the effective heat transfer area and the log-mean-temperature-difference (LMTD) is defined such that:

$$UoA\ = Cp\ dMww/dt\ Ln\ [(Twwin - Tsat)/(Twwout - Tsat)]$$

where, Ln is the natural logarithm and Tsat is the saturation pressure at Pevpout. It must be noted that taking Tsat as the saturation temperature corresponding to the average ammonia pressure in the Evaporator increases the UoA estimate by a factor of approximately 1.35. This must be taken into consideration when comparing different types of evaporators.

Another parameter of importance in the evaluation of performance is the quality (χ) of the ammonia vapor leaving the evaporator. Quality is the ratio of the gas-mass flow rate to the total mass flow rate. That is, the ratio of the mass of ammonia flowing into the turbine to the mass flow rate into the boiler. This is estimated by the ratio of the flow rate measured downstream of the feed pump to the flow rate measured in the recirculating flow loop.

For optimum performance, the ammonia vapor at the exit of the evaporator must be relatively wet. As shown in Fig. 7, a closed-cycle OTEC system needs a device between the evaporator and the turbine to separate the gas from the liquid (i.e., a separator).

Condenser Performance (CC-OTEC)

Relatively dry ($\chi > 98\%$) ammonia vapor, exiting the turbine, flows into the condenser system. The relatively warm ammonia vapor flowing inside the condenser panels is cooled by cold seawater, flowing between the panels, and begins to condense. The heat released by the ammonia during the condensation process is absorbed by the cold seawater.

Conservation of energy, considering a control volume enclosing the entire condenser system and neglecting the relatively small enthalpy difference between the liquid ammonia at the inlet and outlet, yields:

$$Cp\ dMcw/dt\ \Delta Tcw = hfg\ \chi\ dMGNH_3/dt$$

where

Cp, the specific heat of seawater at constant pressure is 4 kJ/kg under OTEC conditions
dMcw/dt, the mass flow rate of cold seawater (kg/s)
ΔTcw, the seawater temperature drop across the condenser (°C)
hfg, is the latent heat of condensation at the condenser inlet pressure (kJ/kg)
$dMGNH_3/dt$, the mass flow rate of the ammonia gas at the evaporator exit (kg/s)
χ is the quality of the ammonia vapor at the inlet.

The left-hand side of the equation gives the water-side heat duty and the right-hand side the ammonia-side heat duty.

The overall heat transfer coefficient Uo (kW/m^2 K) can be estimated by equating the heat duty to [Uo A LMTD], where A is the effective heat transfer area and the log-mean-temperature-difference (LMTD) is defined such that:

$$\text{UoA} = \text{Cp dMcw/dt Ln}\;[(\text{Tsat} - \text{Tcwin})/(\text{Tsat} - \text{Tcwo})]$$

where, Ln is the natural logarithm and Tsat is the saturation pressure at Pcndin. It must be noted that taking Tsat as the saturation temperature corresponding to the average ammonia pressure in the condenser increases the UoA estimate by a factor of approximately 1.28. This must be taken into consideration when comparing different types of condensers.

CC-OTEC Control Parameters

The CC-OTEC control parameters are: (1) mass flow rate of warm water, (2) mass flow rate of cold water, (3) working fluid (e.g., NH3) mass flow rate and recirculating to feed flow ratios, (4) warm-water temperature, and (5) cold-water temperature. The gross power output from a CC-OTEC power plant can be controlled only with the first three parameters while the water temperatures are dictated by natural processes.

State of the Art 10- MW CC-OTEC Pilot Plant

The concept presented in this Section is based on state-of-the-art manufacturing and practices and could be designed, purchased, and installed to represent a complete scaled version of a commercial-size OTEC plant.

An optimized plant with flow rates of 27.7 m^3/s (28,450 kg/s), 4.5°C cold water drawn from a depth of 1,000 m; and, 52.8 m^3/s (54,000 kg/s) 26°C warm water drawn from a depth of about 20 m, would yield 16 MW at the generator terminals (P_{gross}) with 5.3 MW (P_{loss}) required to pump seawater and the working fluid (e.g., anhydrous ammonia) through the plant. The net output (P_{net}) would be 10.7 MW. To keep pumping losses at ~30% of P_{gross}, an average speed of less than 2 m/s is considered for the seawater flowing through the pipes transporting the seawater resource to the OTEC power block.

OTEC design parameters can be generalized as follows:

- In-house or parasitic electrical loads P_{loss} represent about 30% of P_{gross}, such that the exportable power (P_{net}) is about 70% of P_{gross};
- A cold-water flow rate (Q_{cw}) of 2.6 m^3/s is required per MW_{net};
- The optimal warm-water flow rate (Q_{ww}) is about $1.9 \times Q_{cw}$.

P_{gross} is proportional to the square of the temperature differential (ΔT) and the seawater flow rate, such that:

$$P_{net} = P_{gross} - P_{loss} = \beta Q_{cw}(\Delta T)^2 - P_{loss}$$

where β and P_{loss} are system specific. Considering nominal values, it can be shown that a 1°C change in ΔT leads to a change of approximately 15% in P_{net}. This generalization compares favorably with the site-specific heat and mass balance presented below.

A number of configurations for OTEC plants have been proposed. These include moored plants, grazing plants, land-based plants, shelf-mounted towers, guyed-tower, and tension leg plant concepts. Large and small waterplane platforms have been considered. In general, the former (ship shape) is considered cost effective in most commercial application studies. Moored OTEC configurations transmit electrical power to shore via a submarine power cable. The grazing plant operates as a self-contained factory ship on which an energy-intensive product like ammonia or hydrogen is produced. The main advantage of this design is that the plant, with its mobility, can cruise or graze around the tropical waters and is essentially decoupled from land [1].

The plant presented in this section would be housed in a 26,000 t deep draft ship moored 10–20 km offshore. The 1,000- m long 3.9 m i.d. fiber-reinforced-plastic (FRP) sandwich construction CWP is attached to a gimbal at midship. The mooring system consists of a single-point mooring system, including a power (electrical) swivel. The Aluminum plate-fin heat exchangers can be manufactured in existing factories.

The electricity is transmitted to shore via a commercially available submarine power cable (~10 cm diameter).

Major subsystem	10 MW pilot plant
Floating platform	Ship shaped: 90 m (LBP) × 32 m (beam) × 16 m (Height) with operational draft at 9 m
Mooring positioning and control	Single Point Moor (e.g., FPSO platforms) with dynamic positioning thrusters and power (electrical) swivel
Heat exchangers	Compact Al plate/fin installed below main deck
NH_3 turbine-generators	Installed on main deck
CWP	FRP Sandwich manufactured on-shore; horizontal tow and upended
Submarine power cable	34.5 kV, AC ethylene-propylene rubber insulation

The final design will have to integrate the following:

- Platform hull and structures
- Propulsion and positioning
- Land support system
- Seawater pipes and pumps
- Pipe/hull connection
- Deployment and attachment of seawater pipes to the platform
- The power block consisting of the evaporator, turbine-generator, and condenser along with the ammonia system and instrumentation and controls
- The electrical transmission system consisting of the submarine power cable and the power swivel connection

Design Environment

The design-oriented analysis of an OTEC system must consider both survivability design loads and operational/fatigue loads. The first kind are based on extreme environmental phenomena, with a long return period, that might result in ultimate strength failure, while the second kind result in fatigue-induced failure through normal operations. The meteorological, sea surface, water column, and sea floor description required to determine both kinds of loading for each major subsystem are established by considering the design processes.

Environmental loading conditions corresponding to a generic and somewhat extreme (e.g., relatively high surface current) site are considered as applicable until the specific site is identified (Table 1). Seafloor conditions are not considered at this stage of the design.

The operational environment for the pilot plant is given by up to 3.7 m (12′) significant wave height (7.5 s period) and surface currents below 1.5 m/s. The conditions used to determine survivability design loads are given by: 20 m/s winds, 1.5 m/s surface currents, 6.1 m (20′) significant wave height (9.6 s period) head seas. For environmental conditions exceeding these values, the vessel would release the CWP and the single-point mooring (with submarine power cable) and move away from the storm track. The CWP and single-point mooring attachment sequences must be designed to be reversible.

Power Cycle

A simplified block diagram of the power cycle is shown in Fig. 7. Given a surface water temperature range of 24–28°C and a 1,000 m deep ocean water temperature ranging from 4°C to 5°C, the design values were selected as 26°C and 4.5°C. Output would be ≈15,900 kW at the generator terminals with a corresponding net production of ≈10,600 kW.

Ocean Thermal Energy Conversion. Table 1 Baseline design environment for the 10 MW pilot plant

Ocean surface temperature:	26°C (Annual average) 24–28°C range
Ocean temperature at 1,000 m depth:	4.5°C (Annual average) 4–5°C range
Operational limit waves:	3.7 m significant wave height/ 7.5 s period
Survival conditions:	6.1 m significant wave height/ 9.6 s period 20 m/s wind (~40 knots) 1.5 m/s ocean current (~3 knots)

For the temperature range considered, the gross power output varies as a function of surface water temperature by ≈1,600 kW/°C such that for temperatures of 28°C and 4.5°C, a gross power output of ≈19,100 kW is sufficient to produce 13,800 kW-net with an in-plant consumption of 5,300 kW. In the case of the lower surface temperature, the net output would be 7,400 kW.

The facility would employ 550 kg/s of anhydrous ammonia (NH_3) as the working fluid with the power extracted through a commercially available turbine-generator and aluminum heat exchangers for the evaporator and condenser units. The design seawater flow rates are:

- 52.8 m^3/s (54,050 kg/s) of warm water
- 27.7 m^3/s (28,450 kg/s) of cold water

The flow rates of warm and cold seawater are optimization to maximize net power in the electricity production mode under the baseline conditions.

The process illustrated in Fig. 7 can be further described as follows. Warm seawater is drawn in from sumps by submersible pumps into the evaporator. The evaporator is designed to withstand extended exposure to seawater and ammonia. Pressurized liquid ammonia is fed into the evaporator through a system of pumps and valves. The evaporator includes a “preheater” to provide liquid ammonia to the “boiler” at the saturation temperature. Energy transferred from the warm seawater evaporates the ammonia, and the vapor that is produced rises up through a low-pressure-drop mist eliminator. The mist eliminator is included in the flow path of the wet vapor to separate the liquid ammonia and to ensure minimal carry-over of entrained liquid ammonia into the turbine. The separated liquid ammonia flows by gravity to the recirculation pump shown in Fig. 7.

The ammonia vapor exiting the evaporator flows past a series of stop and control valves before expanding through a single-flow axial turbine coupled to a synchronous electrical generator. A short diffuser downstream of the turbine stage is employed to recover some kinetic energy. The exiting vapor passes down into a second heat exchanger (condenser), where it is condensed using cold seawater brought up from a depth of 1,000 m. Several submersible pumps are used to draw the cold water from a sump connected to the CWP.

The pressure of the ammonia condensate is increased, and the liquid is transferred to the evaporator by means of a feed pump before beginning the cycle again. The ammonia power system flow loop is connected to an on-site ammonia storage and purification system. The purification system removes any water or solids which may have entered the working fluid.

Ammonia is used extensively in industry, and relevant codes, standards, and practices have been established (e.g., in the USA) for the construction and operation of ammonia systems. Temperatures and pressures encountered in the present application fall well within the ranges of practical experience. It is not anticipated that any significant safety risk will be entailed during normal operation of this facility if standard procedures are followed.

A chlorination unit will be included to minimize biofouling of the evaporator passages. It has been determined that biofouling from cold seawater is negligible and that evaporator fouling can be controlled effectively by intermittent chlorination (50–100 parts per billion chlorine for 1 h/day). Monitoring of the effluent water for elevated concentrations of ammonia or chlorine would be performed on a regular basis.

The volumetric space requirements for the heat exchangers and the turbine-generators are summarized in Table 2. It is understood that considerable design work would be required to develop the detailed engineering design. However, these global volumetric dimensions can be used to size the plantship.

Turbine-generator (TG) units required for the 10 MW-net plant are commercially available. It is understood that the maximum size available *off-the-shelve* is rated at about 15 MW-gross. Herein, it is assumed that 4 × 4 MW-gross units would be used. The overall dimensions of a 4 MW unit are 17 m (length) × 4 m (width) × 4 m (height), including the lube-oil-skid.

All seawater effluents are mixed together and returned to the ocean at a depth of 60 m by means of two 5.5 m inside diameter FRP pipes (or alternative one a 7.8 m i.d. pipe). This return depth meets the most stringent environmental standards.

Ocean Thermal Energy Conversion. Table 2 Power cycle heat exchangers and TG: Global volumetric space requirements

Unit	Core dimensions	4 MW-gross assembly w/flanges	Global volumetric space per 4 MW assembly, including seawater and NH_3 piping
NH_3/ seawater evaporator (Plate-fin)	6.1 m (L) 1.0 m (W) 4.6 m (H)	6.1 m (L) 4.0 m (W) 7.0 m (H)	Lower decks: 14 m (L) 10 m (W) 14 m (H)
NH_3/ seawater condenser (Plate-fin)	6.1 m (L) 1.0 m (W) 4.6 m (H)	6.1 m (L) 4.0 m (W) 7.0 m (H)	Lower decks: 14 m (L) 10 m (W) 14 m (H)
NH_3 turbines with lube oil skid	Not applicable	17 m (L) 4 m (W) 4 m (H)	Main deck: 17 m (L) 4 m (W) 4 m (H)

Electrical Interface

It is expected that the OTEC pilot plant would be operated in parallel with the local utility system. The plant will be equipped with the required protective devices (relays, circuit breaker, etc.), metering equipment, and synchronizing equipment called for in the interconnect agreement. A synchronous generator unit would be used which includes the required voltage and frequency relays to trip the tie breaker or generator breaker in the event of a fault. Supervised synchronizing would be employed.

Plantship, Mooring, Propulsion, and Position Control

The objectives for the ship-shaped baseline platform (i.e., plantship) for the pilot plant are:

- Develop a floating platform of sufficient size, and with adequate structural arrangements to support large OTEC components and seawater piping systems for normal operations, as well as for maintenance and repair procedures.
- The platform shall meet international regulatory body requirements for stability and damage subdivision and be reasonably sea-kindly for the safety and comfort of personnel in severe open sea conditions.
- Ensure that OTEC components are located for ease of accessibility rather that optimum power production and system efficiency.
- The platform construction shall be cost effective and based on “state-of-the-art” tanker construction procedures.
- In addition, the mooring, propulsion, and position control systems must:
  - Maintain platform position within a predetermined watch circle with acceptable loading on the seawater pipes and the power transmission cable while exposed to the operational environment.
  - Maintain vessel deck motions within allowable values for the operation of power cycle components.
  - Provide adequate propulsive power to depart site after CWP detachment, prior to extreme environment occurrence.

The platform for the OTEC pilot plant consists of a straight-walled 26,000 ton barge fitted with semicircular ends, 90 m long, and 32 m beam with an operating draught of 9 m and 16 m height. A 1,000- m-long pipe would be suspended from the vessel via a double gimbal joint, which effectively decouples the two structures in roll and pitch. The electricity produced would be transmitted to shore via a submarine power cable through a power (electrical) swivel.

The overall plantship dimensions given in Table 3 provide the space required for the heat exchangers (HXs), turbine-generators (TGs), and pumps with associated sumps. The HXs are located below the main deck with the TGs on the main deck. Figures 8 and 9 provide the side view and top view of the pilot plantship.

The conceptual position control system consists of two subsystems: a single-point moor to maintain position, within a given watch circle, during OTEC operations (~99% of the time) and up to the site departure condition; and four propulsion and position control thrusters to assist in directional positioning

Ocean Thermal Energy Conversion. Table 3 OTEC plantship baseline dimensions

Mode	LBP (m)	B beam (m)	D ops draught (m)	H height (m)	Displacement (t)
CC-OTEC 10 MW pilot plant	90	32	9	16	26,000
100 MW OTEC H_2 plantship [13]	250	60	20	28	285,000
"Typical" double-hull tanker	180	32.2	11.2	19.2	≈63,000
"Typical" double-hull container	205 LOA: 217	32.2	10.5	20.3	≈68,000
Panamax limits	≤294.1 (LOA)	≤32.3	≤12		

Displacement: LBP × B × D × ρ × Cb; *LBP* length-between-perpendiculars
ρ, density seawater 1,022 kg/m^3; Cb, block coefficient ≈0.95

(weather vaning) during operations and to provide the propulsive power required to depart the site. The baseline single-point mooring subsystem is commercially available. The four propulsion thrusters are rated at ≈2,500 kW each and would be used minimally during operations.

The position control requirements during operations are equivalent to having an annual thruster power of less than 1,500 kW. Thruster requirements are dominated by the current loading on the OTEC pipes under this somewhat extreme conditions with surface currents as high as 1.5 m/s. The actual schedule for thruster usage would be developed during the final design phase.

The SOA mooring system includes a power swivel linked to the OTEC plant at a turntable. This system provides a minimal-thruster-power-consumption means of holding the OTEC platform in position. The system provides mooring cable riser tension sufficient to limit the platform watch circle radius to about 25% of water depth; the attachment decouples the power transmission cable from the platform motions; and the power cable experiences minimum movement across the sea floor.

Auxiliary power diesel generators would be available to operate the thrusters during transit and departure, as well as in situ when OTEC power is not available.

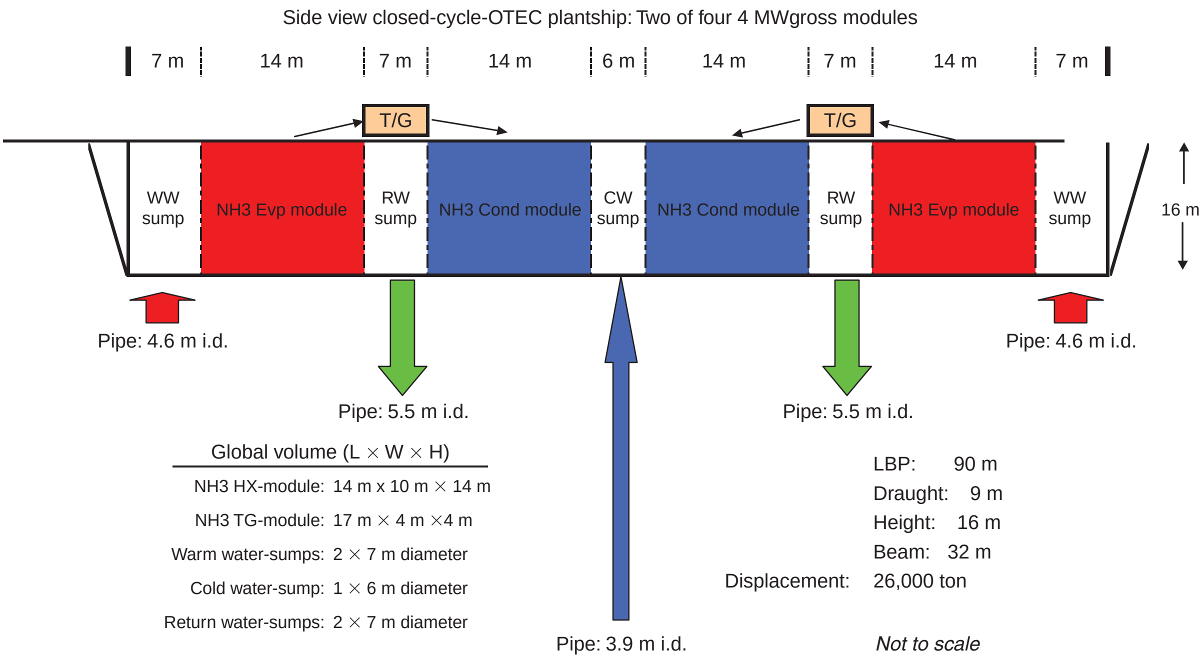
Seawater Components

The OTEC seawater system consists of the pipes and pumps required to supply warm and cold seawater streams to the OTEC HXs and allow for the return of effluents to the ocean. Baseline parameters are summarized in Table 4. The concept considered for the cold water pipe (CWP) is a 3.9 m i.d. glass-fiber-reinforced plastic (FRP) sandwich pipe suspended from the OTEC platform to a depth of 1,000 m. Warm seawater would be drawn in through two 4.6 m i.d. pipes from a depth of about 20 m. The mixed effluent would be returned through two 5.5 m i.d. FRP pipe at a depth of 60 m. This return depth has been selected to minimize the environmental impact.

There is one 6-m-diameter cold-water sump and two 7-m-diameter sumps each for warm water and mixed effluent return water with appropriate distribution piping and pumps. Each of the five sumps has sufficient volume to sustain the head necessary for pumping during start-up and normal operations. The warm- and cold-water sumps house the submersible pumps envisioned for the pilot plant.

The CWP is attached to the platform with a gimbal located on the platform's inner bottom structure. Cold water in the sump is free to flood to the 9 m operating waterline of the platform. The deep-well pumping system located on centerline draws water up through the well and into a manifold that distributes cold water.

This pumping system supplies power for the flow of cold water from the pipe inlet to its discharge through the mixed effluent return pipes. The mixed effluent return from all of the condensers and evaporators is discharged from the mixed effluent sumps through two 5.5 m diameter by 50-m-long pipes. The return water pipes are attached to the inner bottom structure of the platform via a spherical head and inner bottom ring socket.



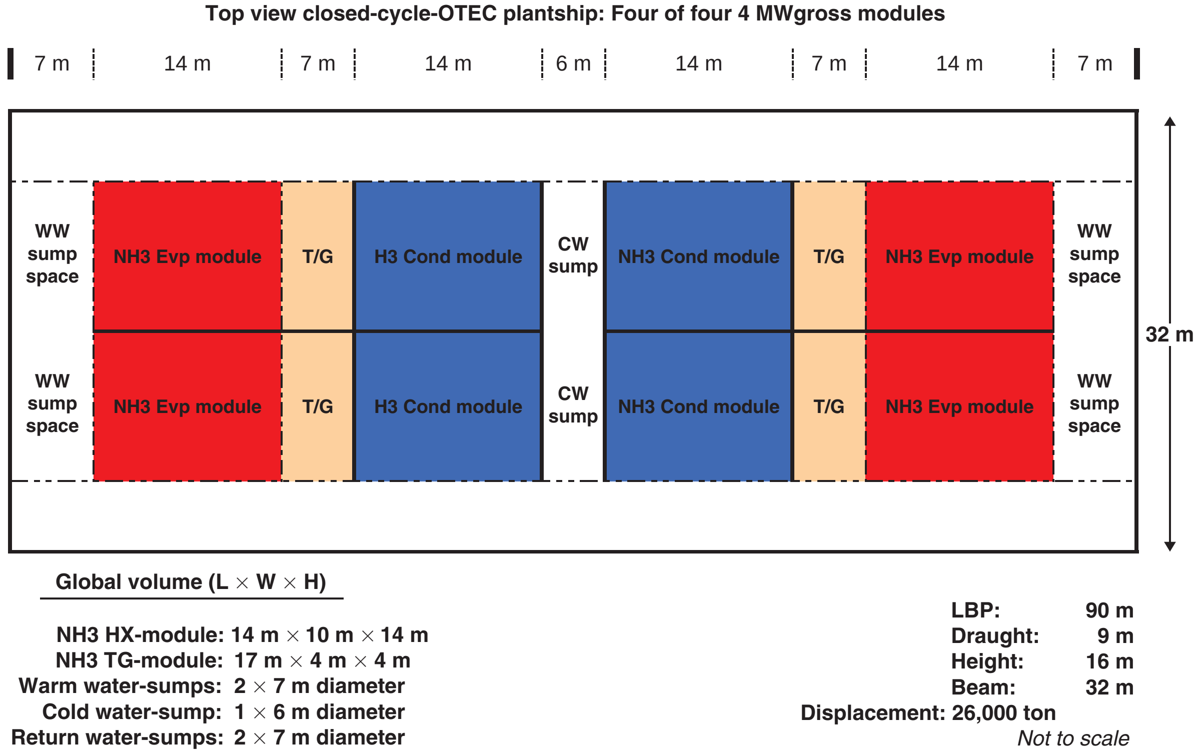
Global volume (L × W × H)

NH3 HX-module: 14 m x 10 m × 14 m
NH3 TG-module: 17 m × 4 m ×4 m
Warm water-sumps: 2 × 7 m diameter
Cold water-sump: 1 × 6 m diameter
Return water-sumps: 2 × 7 m diameter

LBP: 90 m
Draught: 9 m
Height: 16 m
Beam: 32 m
Displacement: 26,000 ton

Ocean Thermal Energy Conversion. Figure 8

10 MW-net OTEC pilot plantship: *Side view*. *Broken lines* indicate space overlap



Global volume (L × W × H)

NH3 HX-module: 14 m × 10 m × 14 m
NH3 TG-module: 17 m × 4 m × 4 m
Warm water-sumps: 2 × 7 m diameter
Cold water-sump: 1 × 6 m diameter
Return water-sumps: 2 × 7 m diameter

LBP: 90 m
Draught: 9 m
Height: 16 m
Beam: 32 m
Displacement: 26,000 ton

Ocean Thermal Energy Conversion. Figure 9

10 MW-net OTEC pilot plantship: *Top view*. *Broken lines* indicate space overlap

Ocean Thermal Energy Conversion. Table 4 Seawater system baseline parameters

Water system		
Cold water to condenser:	439,100	gpm
Cold-water volumetric rate:	27.7	m^3/s
Cold-water density:	1.0269	kg/l
Cold-water mass rate:	28,445	kg/s
Cold-water temperature:	4.5	°C
Cold-water pipe i.d.	3.9	m
Cold-water average speed:	2.3	m/s
Cold-water pump efficiency:	0.72	
Warm water to evaporator:	837,600	gpm
Warm-water volumetric rate:	52.8	m^3/s
Warm-water density:	1.0229	kg/L
Warm-water mass rate:	54,049	kg/s
Warm-water temperature:	26	°C
Warm-water pipes i.d.	2 × 4.6	m
Warm-water average speed:	1.6	m/s
Warm-water pump efficiency:	0.72	
Warm-to-cold-water ratio	1.9	
Combined return pipes i.d.	2 × 5.5	m

Ocean Thermal Energy Conversion. Table 5 Cold-water pipe structural properties

Parameter	Value
Inside diameter	3.9 m
Laminate (facesheet) thickness	14 mm
Core (syntactic foam) thickness	50 mm
Laminate density	1,714 kg/m^3
Outside diameter	4.056 m
Core density	670 kg/m^3
Dry (air) weight	1,010 kg/m
Wet (submerged) weight	33 kg/m
Flexural rigidity, EI	1.7×10^{10} N m^2 (4.2×10^{10} lb-ft^2)
Laminate modulus of elasticity	20,600 MPa (3×10^6 psi)
Core modulus of elasticity	2,360 MPa (0.34×10^6 psi)

Cold Water Pipe

The cold water pipe (CWP) structural properties are summarized in Table 5. The selected CWP walls consist of a sandwich construction, with two 14 mm thick cross-plied unwoven FRP facesheets separated by a 50 mm syntactic foam layer (thus, the outer diameter of the CWP is 4.06 m). The load-bearing FRP provides structural strength, whereas the foam filler allows for the adjustment of wet weight and flexural bending stiffness, as well as for load transmission. The syntactic foam uses glass microspheres and milled fiber to achieve a density of 670 kg/m^3 for buoyancy control. The facesheets are helically wound using 450 yield strand interspersed with 20 oz unidirectional roving and a minor amount of chopped strand. The wind angle is 60° for the helical layers. The pipe is wound in a rotating mandrel. A vinylester resin is used.

The strength of the FRP facesheets is almost comparable to that of steel, with a modulus of elasticity E equal to 20,600 MPa (3×10^6 psi). The longitudinal bending stiffness EI is about 1.7×10^{10} N m^2. Eighty 12.5-m-long CWP segments would be fabricated to facilitate land transportation and butt-connected via splice joints near the launching site (harbor). The 150-mm-deep FRP ring stiffeners, located every 6 m, would provide enhanced lateral buckling capability to resist differential (suction) loads across the CWP walls. It is expected that pipe construction would require about 12–14 months.

Several different types of CWP/Hull platform attachment (gimbal) have been proposed. This is required to decouple the pipe from the roll and pitch of the platform and minimize bending moments at their interface. The attachment system must provide a water seal at the cold-water sump to insure the quality of the cold-water resource. The gimbal should provide ease of attachment of the CWP to the platform at sea. The gimbal system selected is based on the OTEC 1 design tested in Hawaii [13, 14].

CWP deployment procedures suggested for the various configurations proposed in different suspended CWP designs have been of two generic types: (1) horizontal tow of a full-length pipe with subsequent upending at the deployment site or (2) vertical deployment, by sections, through the OTEC platform or an adjacent work platform. Most designs have proposed transporting the pipe to the deployment site independently of the platform because combined movement may result in excessive loads and untenable vessel handling problems. The deployment method selected is basically a function of material selection and CWP buoyancy characteristics. In general, configurations which are buoyant or neutrally buoyant would employ the upending technique, while designs that are fabricated from materials that are considerably denser than seawater would utilize the vertical, sectional approach, in which the CWP is actually assembled during the deployment process. A successful deployment scenario must ensure a minimum exposure time at sea, define weather windows clearly and be somewhat reversible [14]. This is especially important for the attachment of the CWP to the barge since detachment must be allowed before extreme events (e.g., hurricanes).

For the concept selected herein, the former procedure applies with the CWP transported awash (filled with water). Towing of the pipeline awash would be acceptable if the confidence of the deployment team in keeping the CWP reasonably well aligned with the dominant wave direction, or in short-term (≈48 h) weather forecasts, is high. Alternatively, submerging the CWP about one diameter deeper would theoretically provide a significant safety factor in reducing bending stresses through less favorable marine environmental conditions.

The conceptual CWP proposed herein will have to be reevaluated after the specific site in selected. Experience indicates bending stresses induced by platform motions as the most critical operational loads. Other concerns are fatigue failure and transportation (towing) bending stresses. A shell analysis of the CWP to quantify hoop stresses and confirm the pipe lateral buckling capability and load evaluation during CWP handling and attachment to the platform is left for the final design.

Submarine Power Cable

A submarine power cable is required to transmit the electricity produced by the 10 MW-net OTEC plant from the floating platform to shore. The baseline is a commercially available AC configuration with an ethylene- propylene rubber (EPR) insulation operating at a voltage of 34.5 kV. This voltage makes EPR insulation a prime choice since other types of insulation, which may be competitive for land-based applications, usually require the addition of a watertight metallic sheath in the marine environment. EPR insulation lends itself to the use of three-core power cables.

The submarine power cable would have an outside diameter of ≈10 cm. and it would be attached to the single point mooring system described above.

Inspection, Maintenance, and Repair (IM&R)

From the perspective of inspection, maintenance, and repair (IM&R), three general areas may be identified throughout the OTEC Platform:

- The components onboard the plantship, such as heat exchangers, turbine-generators, and pumps
- The platform hull and appendages
- The deep water components, such as CWP, submarine power cable, and mooring devices

Onboard the plantship, with adequate layout of the OTEC components, IM&R requirements should be comparable to those stipulated for onshore power plants. IM&R tasks are naturally more cumbersome for the platform itself because of the presence of seawater, and of possibly disturbing platform motions during rough weather. Diver operations and instrumentation/tool deployment from the platform decks should remain relatively easy most of the time. Moreover, the OTEC platform is not fundamentally different from other seagoing structures.

IM&R is challenging for the deep water components of the floating OTEC plant because the depths at stake place those components out of divers' reach. A failure of the mooring system could break the power cable, although thrusters are believed to provide excess redundancy in positioning the platform if the single-point moor fails.

Strict quality control procedures must be applied at the fabrication, shipping, and assembly stages before the structures are finally deployed at sea.

Site Selection Criteria for OTEC Plants

The search for renewable energy resources has resulted in OTEC's second revival. As it is well known, the concept utilizes the differences in temperature, ΔT, between the warm tropical surface waters, and the cold deep ocean waters available at depths of about 1,000 m, as the source of the thermal energy required.

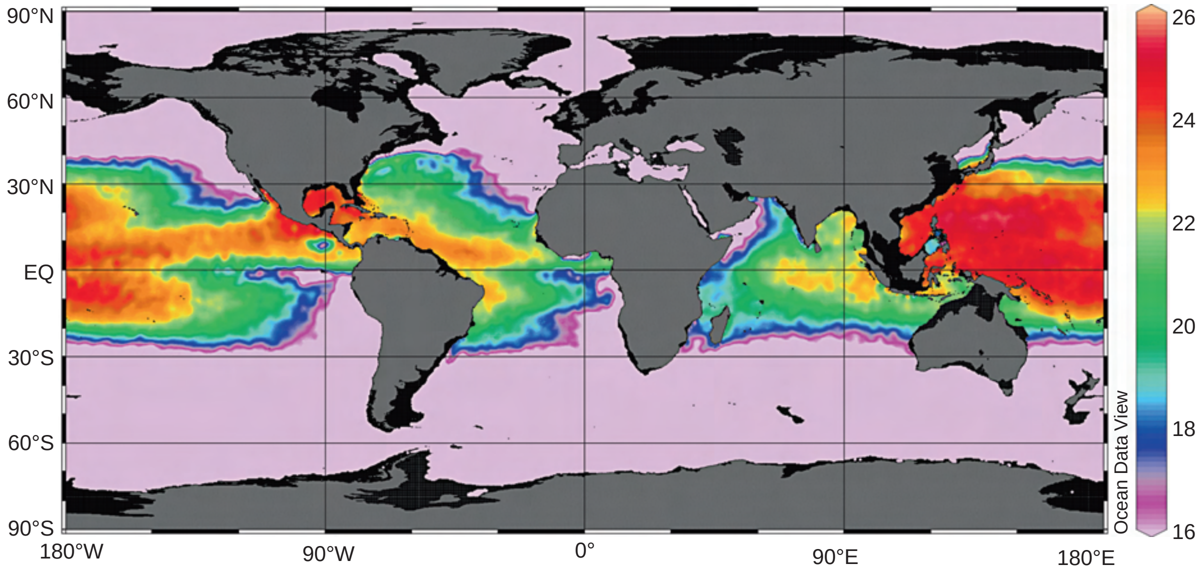
The historical monthly averages of ΔT for February and August are depicted in Figs. 10 and 11, respectively. Values are color coded as indicated in the right-hand side of the figures. The values were obtained from the National Ocean Data Center's World Ocean Atlas [16]. Deep seawater flows from the Polar Regions. These polar water, which represents up to 60% of all seawater, originates mainly from the Arctic for the Atlantic and North Pacific Oceans, and from the Antarctic (Weddell Sea) for all other major oceans. Therefore, T_{cw} at a given depth, approximately below 500 m, does not vary much throughout all regions of interest for OTEC. It is also a weak function of depth, with a typical gradient of 1°C per 150 m between 500 and 1,000 m. These considerations may lead to regard T_{cw} as nearly constant, with a value of 4–5°C at 1,000 m [3].

A desirable OTEC thermal resource of about 20°C requires typical values of T_{ww} of the order of 25°C. Globally speaking, regions between latitudes 20°N and 20°S are adequate. Some definite exceptions exist due to strong cold currents: along the West Coast of South America and to a lesser extent for the West Coast of Southern Africa. Moreover, T_{ww} varies throughout the year and, sometimes, exhibits a significant seasonal drop due to the upwelling of deeper water induced by the action of the wind: such are the cases of the West Coast of Northern Africa in the southern hemisphere winter (Fig. 11).

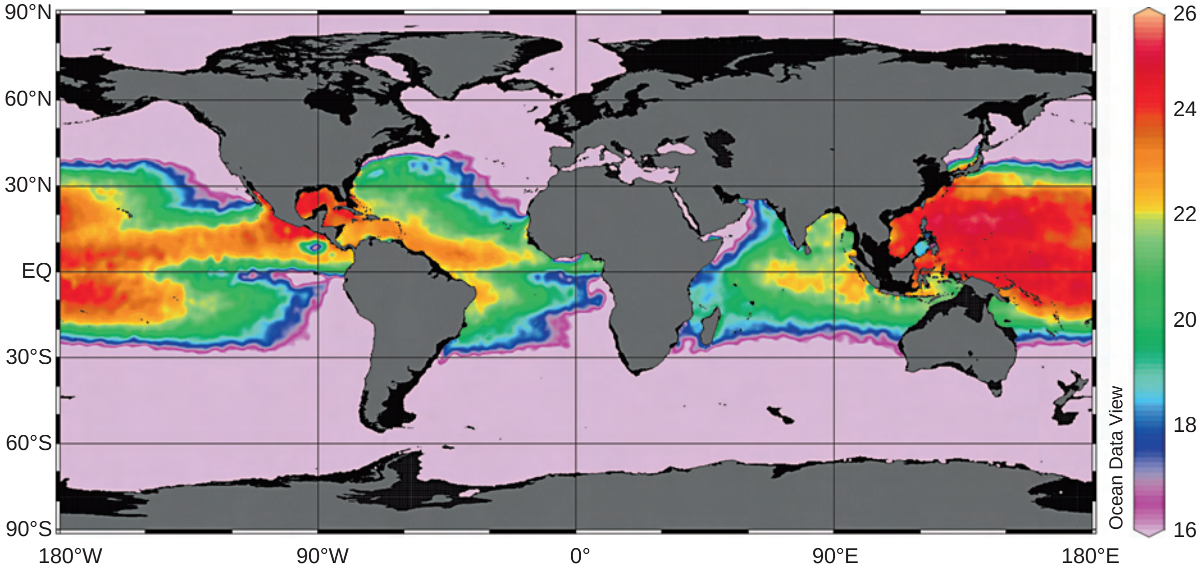
The following summarizes the availability of the OTEC thermal resource throughout the World:

- Equatorial waters, defined as lying between 10°N and 10°S, are adequate, except for the West Coasts of South America and Southern Africa.
- Tropical waters, defined as extending from the equatorial region boundary to, respectively, 20°N and 20°S, are adequate, except for the West Coasts of South America and of Southern Africa; moreover, seasonal upwelling phenomena would require significant temperature enhancement for the West Coast of Northern Africa, the Horn of Africa, and off the Arabian Peninsula.

The accessibility of deep cold seawater represents the most important physical criterion for OTEC site selection once the existence of an adequate thermal resource has been established. In the case of a floating plant, the issue of cold seawater accessibility is only relevant inasmuch as submarine power cables, and,



Ocean Thermal Energy Conversion. Figure 10
Historical monthly average of ΔT during February from WOA05 (From [15])



Ocean Thermal Energy Conversion. Figure 11
Historical monthly average of ΔT during August from WOA05 (From [15])

maybe, a desalinated water hose is needed to transfer the OTEC products to shore. For the grazing plantship, with energy intensive products like hydrogen or ammonia as the product, the distance is important from the perspective of the transit time for the vessels that would transport the product to shore.

Many other points must be considered when evaluating potential OTEC sites, from logistics to socioeconomic and political factors. One argument in favor of OTEC lies in its renewable character: it may be seen as a means to provide remote and isolated communities with some degree of energy independence and to offer them a potential for safe economic development. Such operational advantages, however, are often accompanied by serious logistical problems during the plant construction and installation phases: if an island is under development, it is likely to lack the infrastructure desirable for this type of project, including harbors, airports, good roads, and communication systems. Moreover, the population base should be compatible with the OTEC plant size: adequate manpower must be supplied to operate the plant, and the electricity and fresh-water plant outputs should match local consumption in orders of magnitude.

Another important point to consider is the preservation of the environment in the area of the selected site, inasmuch as preservation of the environment anywhere is bound to have positive effects elsewhere. As outlined in the section “Environmental Impact”, OTEC is one of the most benign power-production technology since the handling of hazardous substances is limited to the working fluid (e.g., ammonia), and no noxious by-products are generated; OTEC merely requires the pumping and return of various seawater masses, which, according to preliminary studies, can be accomplished with virtually no adverse impact. This argument should be very attractive for pristine island ecosystems as well as for already polluted and overburdened environments. For example, the amount of CO_2 released from electricity-producing plants (expressed in gram of CO_2 per kWh) ranges from 1,000, for coal-fired plants, to 700, for fuel-oil plants, while for OC-OTEC plants it is at most ~1% of the amount released by fuel oil plants. The value is much lower in the case of a CC-OTEC plant.

Ninety-eight nations and territories with access to the OTEC thermal resource within their 200 nautical mile exclusive economic zone (EEZ) were identified in the 1980s. A partial list is provided in Table 6. For the majority of these locations, the OTEC resource is applicable only to floating plants. Unfortunately, now as then, there is no OTEC plant with an operational record available. This still remains the impediment to OTEC commercialization.

Ocean Thermal Energy Conversion. Table 6 List of nations with appropriate ocean thermal resource within their 200 nautical miles exclusive economic zone. From [12]

Geographical area	Mainland		Island	
Americas	Mexico	Guyana	Cuba	Guadeloupe
	Brazil	Suriname	Haiti	Martinique
	Colombia	French Guiana	Dominican	Rep. Barbados
	Costa Rica	Nicaragua	Jamaica	Dominica
	Guatemala	El Salvador	Virgin Is.	St. Lucia
	Honduras	Belize	Grenada	St. Kitts
	Panama	USA	St. Vincent	Barbuda
	Venezuela		Grand Cayman	Montserrat
			Antigua	The Grenadines
			Puerto Rico	Curacao
			Trinidad & Tobago	Aruba
			Bahamas	
Africa	Nigeria	Gabon	Sao Tome & Principe	
	Ghana	Benin	Ascension	
	Ivory Coast	Zaire	Comoros	
	Kenya	Angola	Aldabra	
	Tanzania	Cameroon	Madagascar	
	Congo	Mozambique		
	Guinea	Eq. Guinea		
	Sierra Leone	Togo		
	Liberia	Somalia		
Indian/Pacific Ocean	India	Australia	Indonesia	American Samoa
	Burma	Japan	Philippines	Northern Marianas
	China	Thailand	Sri Lanka	Guam
	Vietnam	Hong Kong	Papua New Guinea	Kiribati
	Bangladesh	Brunei	Taiwan	French Polynesia
	Malaysia		Fiji	New Caledonia
			Nauru	Diego Garcia
			Seychelles	Tuvalu
			Maldives	Wake Is.
			Vanuatu	Solomon Is.
			Samoa	Mauritius
			Tonga	Okinawa
			Cook Is.	Hawaii
			Wallis & Futuna Is.	

OTEC Economics

An analytical model is available to assess scenarios under which OTEC might be competitive with conventional technologies [12]. First, the capital cost for OTEC plants, expressed in $/kW-net, is estimated. Subsequently, the relative cost of producing electricity ($/kWh) with OTEC, offset by the desalinated water production revenue, is equated to the fuel cost of electricity produced with conventional techniques to determine the scenarios (i.e., *fuel cost and cost of fresh-water production*) under which OTEC could be competitive. For each scenario, the cost of desalinated water produced from seawater via reverse osmosis (RO) is estimated to set the upper limit of the OTEC water production credit. No attempt is made at speculating about the future cost of fossil fuels. It is simply stated that if a location is represented by one of the scenarios, OTEC could be competitive.

Two distinct markets were previously identified: (1) industrialized nations and (2) small island developing states (SIDS) with modest needs for power and fresh water. OC-OTEC plants could be sized at 1–10 MW, and 450,000 to 9.2 million gallons of fresh water per day (1,700–35,000 m^3/day) to meet the needs of developing communities with populations ranging from 4,500 to 100,000 residents. This range encompasses the majority of SIDS throughout the world [12].

Floating plants of at least 50 MW capacity would be required for the industrialized nations. These would be moored or dynamically positioned a few kilometers from land, transmitting the electricity to shore via submarine power cables. The moored vessel could also house an OC-OTEC plant and transport the desalinated water produced via flexible pipes.

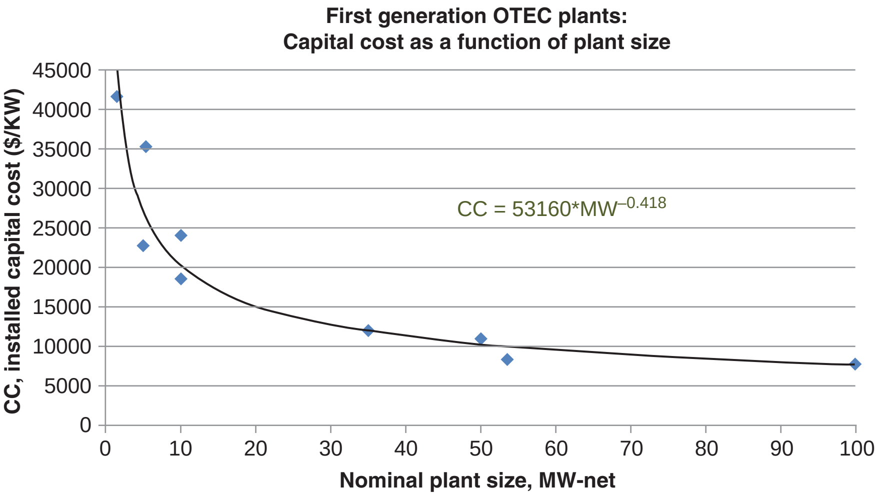
It was also established that OTEC-based mariculture operations and air-conditioning systems could only make use of a small amount of the seawater available; and therefore, could only impact small plants. The use of energy carriers (e.g., Hydrogen, Ammonia) to transport OTEC energy generated in floating plants, drifting in tropical waters away from land, was determined to be technically feasible but requiring increases in the cost of fossil fuels of at least an order of magnitude to be cost effective.

Presently, the external costs of energy production and consumption are not included in the determination of the charges to the consumer. Considering all stages of generation, from initial fuel extraction to plant decommissioning, it has been determined that no energy technology is completely environmentally benign. The net social costs of the different methods of energy production continue to be a topic under study. Estimates of costs due to: corrosion, health impacts, crop losses, radioactive waste, military expenditures, employment loss, subsidies (tax credits and research funding for present technologies) are found in the literature. The range of all estimates is equivalent to adding from $80/barrel to over $400/barrel. Accounting for these externalities might eventually help the development and expand the applicability of OTEC but, in the interim, the scenarios that were identified in the original report should be considered again [12].

Industry did not take advantage of the information because in the 1990s, the prices of oil fuels and coal were such that conventional power plants produced cost-effective electricity (excluding externalities). Moreover, the power industry could only invest in power plants whose designs were based on similar plants with an operational record. It was concluded that before OTEC could be commercialized,

Ocean Thermal Energy Conversion. Table 7 First-generation OTEC plant capital cost estimates: (1) extrapolated archival estimates (1–50 MW) and current estimates (10–100 MW) in $/kW-net

Nominal plant size (MW-net)	Installed capital cost ($/kW)	Land/ floater	Source (extrapolated)
1.4	41,562	L	[12]
5	22,812	L	[26]
5.3	35,237	F	[14]
10	24,071	L	[12]
10	18,600	F	[26]
35	12,000	F	[26]
50	11,072	F	[12]
53.5	8,430	F	[26]
100	7,900	F	[26]



Ocean Thermal Energy Conversion. Figure 12
Capital cost estimated for first-generation OTEC plants

Ocean Thermal Energy Conversion. Table 8 Levelized COE (US-cents/kWh) for CC-OTEC plants with capital costs (CC) amortized through an 8%/15 year loan and annual inflation at 3%, considering US labor rates (O&M) and first-year repair and replacement cost (R&R) as indicated. First two entries are Land Based with lower O&M

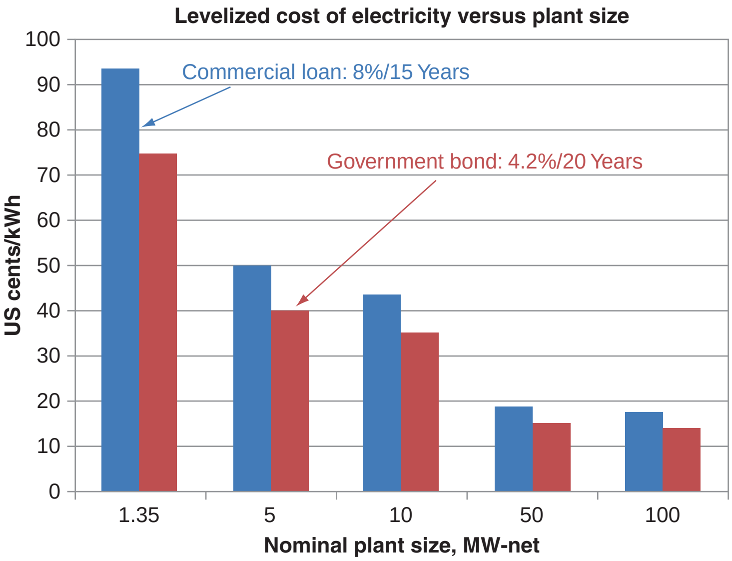
Identifier nominal size (MW)	Capital cost ($/kW)	O&M ($M/year)	R&R ($M/year)	COEcc (c/kWh)	COE$_{OMR\&R}$ (c/kWh)	COE C/kWh
1.35	41,562	2.0	1.0	60	33.7	94.0
5	22,812	2.0	3.5	33	17	50.0
10	18,600	3.4	7.7	26.9	16.8	44.0
53.5	8,430	3.4	20.1	12.2	6.7	19.0
100	7,900	3.4	36.5	11.4	6	18.0
						8% 15 years

a prototypical plant must be built and operated to obtain the information required to design commercial systems and to gain the confidence of the financial community. Conventional power plants pollute the environment more than an OTEC plant would, and the fuel for OTEC is vast and free, as long as the sun heats the oceans; however, it is futile to use these arguments to convince the financial community to invest in an OTEC plant without operational records.

OTEC Capital Costs

OTEC archival information can be converted to present day costs using the USA 20-year average for equipment price-index inflation. Current technical specifications for 10, 50, and 100 MW OTEC plants have been used to solicit budgetary quotes [26]. All estimates are summarized in Table 7 and in Fig. 12.

These estimates are applicable for equipment purchased in the USA, Europe, or Japan and with installation by US firms. Deployment and installation costs are included. One might speculate, based on the implementation of similar technologies, that later-generation designs might reach cost reductions of as much as 30%. However, the premise herein is to indicate that first-generation plants can be cost effective



Ocean Thermal Energy Conversion. Figure 13

Cost of electricity (*Capital Cost Amortization + OMR&R Levelized Cost*) production for first-generation OTEC plants as a function of plant size with loan terms (*interest and term*) as parameter. Annual inflation assumed constant at 3%

under certain scenarios if the cost estimates presented here are met.

Figure 12 illustrates that OTEC capital cost ($/kW) is a strong function of plant size (MW). For convenience and future reference, a least-squares curve fit is provided:

$$\mathrm{CC}(\$/\mathrm{kW}) = 53,000 \times \mathrm{MW}^{-0.42}$$

A 100 MW OTEC plant, for example, could be housed in a floating platform stationed less than 10 km offshore and would have the capability of delivering 800 million kilowatt hour to the electrical grid every year. Budgetary quotes from potential equipment suppliers indicate that the installed cost would be $790 million using state-of-the-art components (Table 7).

The annual costs for operations and maintenance are estimated at $40 million (Table 8) such that under realistic financing terms (15 year loan at 8% annual interest and 3% average annual inflation), electricity could be produced at a levelized cost of less than 0.18 $/kWh such that a realistic power-purchase-agreement from the utility at around 0.20 $/kWh would include ample return on investment. It is interesting to note that if the plant could be funded via government bonds at a realistic rate of 4.2% over 20 years, the COE would be 0.14 $/kWh (Fig. 13).

Future Directions: OTEC

The major conclusion continues to be: *there is a market for OTEC plants that produce electricity and desalinated water*; however, operational data must be obtained by building and operating demonstration plants scaled down from sizes identified as potentially cost effective. OTEC systems are in the pre-commercial phase with several experimental projects having already demonstrated that the technology works but lacking the operational records required to proceeding into commercialization. Adequately sized pilot projects must be operated in situ and for at least one continuous year to obtain these records. A pilot (or pre-commercial demonstration) plant sized at about 10 MW must be operated prior implementation of 50–100 MW commercial plants.

Accounting for externalities in the production and consumption of electricity and desalinated water might eventually help the development and expand the applicability of OTEC. Unfortunately, it is futile to use these arguments to convince the financial community to invest in OTEC plants without an operational record.

The major challenge continues to be the requirement to finance relatively high capital investments that must be balanced by the expected but yet to be demonstrated low operational costs. Perhaps, a lesson can be learned from the successful commercialization of wind energy due to consistent government funding of pilot or pre-commercial projects that led to appropriate and realistic determination of technical requirements and operational costs in Germany, Denmark, and Spain. In this context, by commercialization, we mean that equipment can be financed under terms that yield cost competitive electricity. This of course depends on specific conditions at each site.

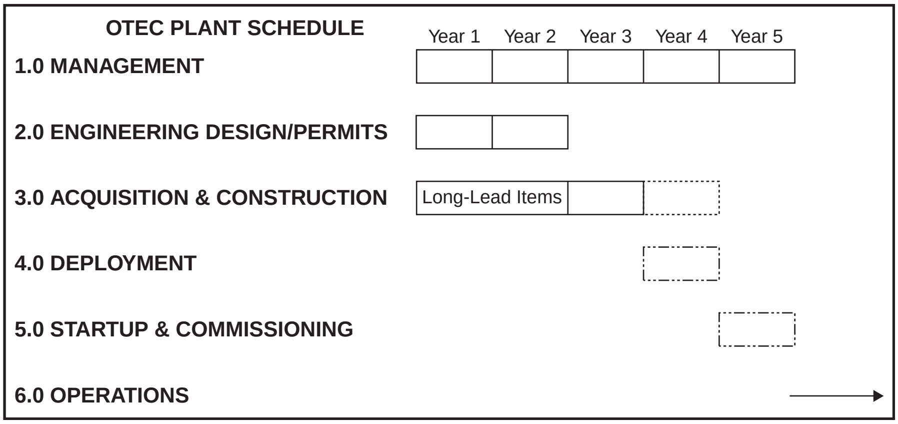
In discussing OTEC's potential, it is important to remember that implementation of the first plant would take about 5-years after order is placed. This is illustrated with the baseline schedule shown in Table 9. Completion of the engineering design with specifications and shop drawings would take 1-year. Presently, it is estimated that the licensing and permitting process through NOAA (in accordance with the OTEC Act) would take at least 1 year for commercial plants with the provision of exemptions from the licensing process for plants considered to be *test plants* because of the limited duration of the operational phase.

A survey of factories that can supply the required equipment indicates that no technical breakthroughs are required but that some components would require as long as 3-years to be delivered after the order is placed. The solicitation of equipment quotes based on technical specifications indicates that long-lead items would require from 18 months to 36 months to be delivered. Based on experience with offshore projects of similar size, it is expected that 1 year would be required to complete the deployment with a second year set aside for commissioning.

As stated above, there are sufficient petroleum resources (≈1,400 billion barrels) to meet worldwide current demand (>30 billion barrels/year) for almost 50 years. Production, however, is peaking, and humanity will face a steadily diminishing petroleum supply and higher demand due to emerging economies like China, India, and Brazil. Coal and natural gas resources could meet current worldwide demand for 100–120 years, respectively.

Given that it takes decades for new energy technologies to reach maturity, it seems sensible to consider the ocean thermal resource as a renewable fuel for the future. At first, OTEC plantships providing electricity, via submarine power cables, to shore stations would be

Ocean Thermal Energy Conversion. Table 9 First-generation OTEC plantship implementation schedule



Ocean Thermal Energy Conversion. Table 10 OTEC implementation program required in preparation for the post–fossil fuel age

USA OTEC DEVELOPMENT		←	YEARS	→		
	1 to 5	6 to 10	11 to 15	16 to 20	21 to 25	26 to ∞
Pre-Commercial Plant (> 5 MW)		Ops				
Electricity (Desal Water) Plants in Hawaii and USA Territories: ~20 × 100 MW Plants	Prelim Design	Ops		Ops	→	→
NH3/H2 Plantships Supplying all States				Prelim Design	Ops	→

implemented. This would be followed, in 20–30 years, with OTEC factories deployed along equatorial waters producing energy intensive products, like ammonia and hydrogen as the fuels that would support the post-fossil fuels era.

The following Development Schedule (Table 10) can be used as an outline of the activities required to implement ocean thermal resources as a major source of energy for our post-fossil-fuels future. A pre-commercial plant would be implemented with government funding. The plant would be operational (supplying electricity to the distribution grid) within 5 years and would be operated for a few years to gather technical, as well as environmental impact information. Some of the valid questions regarding potential environmental impacts to the marine environment can only be answered by operating plants that are large enough to represent the commercial-size plants of the future.

The design of the first commercial plant sized at 50–100 MW would be completed and optimized after the first year of operations with the pre-commercial plant. This would be followed, for example, with the installation of numerous plants in Hawai'i and US Insular Territories for a cumulative total of about 2,000 MW over 15-years. As indicated in Table 10, the design of the grazing factory plantships that would produce the fuels of the future (e.g., hydrogen and ammonia) could be initiated as early as 15-years after the development program is implemented.

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Oceanic Fate and Transport of Chemicals

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Article Outline

Glossary

Anthropogenic Produced by or derived from human-related activities.

Biogeochemical cycling The overall transport of chemicals through the ocean waters as modified by chemical, physical, and biological processes.

Chemical inputs The external sources of chemicals to the ocean from the atmosphere or from deep ocean environments or from rivers and other terrestrial sources.

Chemical sinks All elements and compounds can be removed from the ocean by various processes. The relative ratio of their input to their removal provides an indication of how they are distributed in the ocean, and whether human activity has increased their ocean concentration.

Major ions and nutrients Those chemicals present in the ocean at high concentrations and the major nutrients (nitrogen, phosphorous, and silica).

Metalloid An element in the periodic table that acts both as a metal and a nonmetal, depending on the chemical environment.

Micronutrients and trace elements Those chemicals present in the ocean at low concentrations but which still have an important impact of ocean biological productivity, either because they are