# Ocean Thermal Energy Conversion (OTEC): Principles, Problems and Prospects

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## *Abstract*

**The concept of OTEC is succinctly reviewed, with an emphasis on the specific aspects of the technology that have hampered its development. Although the ocean thermal resource is abundant, widespread and steady, no commercial OTEC system has yet been deployed. Low thermodynamic efficiencies and the need for large systems at sea result in very capital-intensive projects. This traditionally has deterred investors and the resulting lack of operational OTEC power plants has acted as a powerful negative feedback. The location of OTEC resources in tropical areas may have further limited the interest of wealthy, technologically advanced stakeholders. In spite of engineering, economic and possibly geopolitical hurdles, however, prospects for the deployment of OTEC systems seem better today than at any time in the past two decades. In an age of concerns about global warming and energy security, OTEC is a resource which mankind ignores at its peril.**

## *1. INTRODUCTION*

A number of good comprehensive reviews of Ocean Thermal Energy Conversion (OTEC) have been written over the past decades. Although we may refer to a few [1-4], this list undoubtedly is not exhaustive. While we will fail to give due credit to all who have contributed to the OTEC literature, our greatest challenge is to try to present, under a slightly different light, material that has largely been available. The most essential question, in a sense, is why there isn't any OTEC system operating at sea *today*. This is a particularly timely issue since mankind's energy needs have recently been soaring against the threats of environmental deterioration and declining fossil fuel production. The growing gap between the supply and demand of primary energy sources has spurred a sharp rise in the cost of oil, and such developments have rekindled interest in renewable energies in general. It is therefore likely that we are about to witness a new dawn for OTEC.

This paper is a brief overview of the specific challenges that have made OTEC implementation difficult so far, from thermodynamics and heat transfer to ocean engineering, economics and geopolitics. These fields are in fact intimately connected and, ultimately, converge toward the dual (or alternative) objectives of funding the deployment of OTEC plants through market mechanisms and fostering strong political stewardship to help the OTEC technology reach maturity.

## *2. BASIC THERMODYNAMICS*

### *2.1. OTEC temperature ladder*

The basic thermodynamic principle of OTEC was articulated as early as in 1881 by d'Arsonval [5]. It consists in running an engine that cyclically absorbs heat from warm surface seawater found throughout tropical oceans, and rejects a slightly smaller amount of heat into cold seawater pumped from water depths of 700 to 1000 m. In the process, work is recovered as an auxiliary fluid expands in a turbine. Theoretically, nothing distinguishes an OTEC system from any other heat engine. There are, however, significant practical aspects of the technology that makes it more difficult to implement. An obvious hurdle is the small available temperature difference $\delta T$ of the order of 20ºC between the warm and cold seawater streams. In fact, only a fraction of $\delta T$ can be used in the energy conversion process *per se*, because allowances must also be given for the cooling of the warm seawater, for the warming of the cold seawater and for small temperature differentials needed to drive the exchange of heat between seawater and the working fluid. This gives rises to the OTEC temperature ladder illustrated in Figure 1.

### *2.2. Standard Rankine cycle*

In what follows, OTEC power generation will be conceptually represented as a Rankine cycle where a working fluid is circulated in a closed loop where it alternatively evaporates, expands and condenses before being pumped back. From a historical point of view, the pioneering efforts of Claude [6] and the recent, most comprehensive experimental results obtained for a complete OTEC plant to date [7] were based on the so-called open-cycle instead. With open-cycle OTEC, the working fluid consists of steam that is continuously produced from the warm seawater itself in a low-pressure evaporator. Once it is condensed, the steam is exhausted from the system so that the cycle is not closed indeed. The constraints imposed by the very low open-cycle pressures (2 to 3 kPa) are likely to limit its potential applicability to small power plants of perhaps one to a few megawatts in spite of considerably simpler and more cost effective heat exchangers. Alternatively, a standard condenser in open-cycle systems makes it possible to produce fresh water. This is a significant potential benefit in many tropical areas where fresh water is valuable.

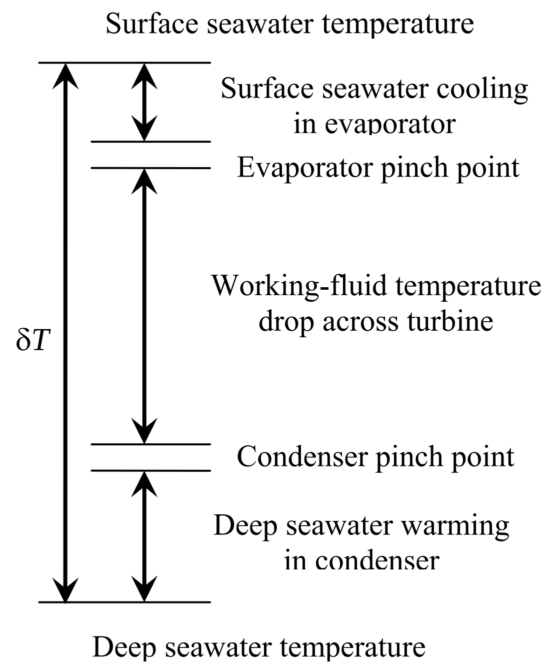


Figure 1. OTEC temperature ladder

The ranges of temperatures for warm surface seawater (e.g., 24 to 28ºC) and for deep cold seawater (e.g., 4 to 8ºC) suggest that closed-cycle OTEC should roughly behave like a typical household refrigeration cycle run in reverse. Hence, fluids used in common refrigeration systems should be adequate. It can be shown that pure substances with relatively steep saturation curves $P_{sat}(T_{sat})$ should be best. Among refrigerants at moderate temperatures, ammonia is a prime candidate; its heat transfer performance is very good as well, and there is vast experience regarding its use.

The isentropic power (work per cycle) $W_{isen}$ that can be produced by an ideal turbine in an OTEC Rankine cycle can be approximated as:

$$W_{isen} \approx m h_{fg} (T_{evap} - T_{cond})/T_{evap} \qquad (2.1)$$

$m$ is the mass flow rate of working fluid, $h_{fg}$ its latent heat of vaporization and $T_{evap} - T_{cond}$ the temperature drop across the turbine (between evaporation and condensation temperatures). This approximation is valid as long as $\varepsilon = c(T_{evap} - T_{cond})/h_{fg} << 1$, where $c$ is the specific heat of the working fluid in the liquid phase.

A simplified heat balance on the OTEC evaporator yields:

$$Q_{evap} \approx m h_{fg}, \qquad (2.2)$$

where once again, the approximation of the heat load $Q_{evap}$ holds as long as $\varepsilon << 1$.

Using the Clausius-Clapeyron relationship away from the critical point, the isentropic power $P_{pump}$ needed to pressurize the working fluid between the condenser outlet and the evaporator inlet can be shown to be negligible since

$$P_{pump} \approx W_{isen} (v_{liq}/v_{vap}), \qquad (2.3)$$

with the ratio of specific volumes in the liquid and vapour phases, $v_{liq}/v_{vap}$, of the order of 1%. Hence, the actual gross power that can be produced in the overall Rankine cycle is very close to:

$$P_{gross} \approx \eta_{tg}\, m h_{fg} (T_{evap} - T_{cond})/T_{evap} \qquad (2.4)$$

$\eta_{tg}$ is a combined turbogenerator efficiency.

Equations (2.2) and (2.4) suggest that, in an overall heat-and-mass balance of the complete cycle, the condenser and evaporator heat loads are practically equal:

$$Q_{evap} \approx Q_{cond}, \qquad (2.5)$$

The above expressions certainly cannot be substitutes for a detailed analysis that would be necessary for specific OTEC plant designs. With the additional specification of some basic heat exchanger characteristics, however, such as effectiveness or heat transfer coefficient, Equations (2.2), (2.4) and (2.5) can be manipulated under the constraints embodied in the OTEC temperature ladder to yield a relatively simple expression of $P_{gross}$ that depends on only three independent variables. This would be expected since the operator of a simple closed-cycle OTEC plant would have exactly three ways to affect $P_{gross}$: by setting the mass flow rates of warm seawater $m_{ww}$, of cold seawater $m_{cw}$, and of working fluid $m$. For mathematical convenience, $m$ can be replaced by another variable, e.g., $(T_{evap} - T_{cond})$. Since the deep cold seawater flow rate typically drives the design of OTEC systems, $m_{ww}/m_{cw}$ can be substituted for $m_{ww}$ as well.

The net power delivered by the OTEC plant to an electrical grid would then be the difference $P_{net}$ between $P_{gross}$ and the power $P_{seawater}$ needed to sustain both seawater flow rates. $P_{seawater}$ is independent of $m$. For a given plant design (heat exchangers, pipes, etc.), $P_{net}$ can be operationally maximized by writing the necessary conditions:

$$\partial P_{net}/\partial m = 0,\ \partial P_{net}/\partial m_{ww} = 0 \text{ and } \partial P_{net}/\partial m_{cw} = 0 \qquad (2.6)$$

The first equality is equivalent to $\partial P_{gross}/\partial m = 0$ (where $m$ may be understood as a suitably chosen proxy variable independent of $m_{ww}$ and $m_{cw}$). Although details are beyond the scope of this paper, the above condition yields the remarkable result that the temperature drop across the turbine is:

$$T_{evap} - T_{cond} \approx \delta T/2 \qquad (2.7)$$

Hence, the Carnot efficiency of a Rankine closed-cycle OTEC system is of the order of 3%. As a result, large and costly heat exchangers are needed for a given power production, i.e., several thousand square meters of heat exchange surface per megawatt of OTEC electricity.

Both $P_{gross}$ and $P_{seawater}$ increase with the seawater flow rates, but the latter term has a much stronger dependence (for a fixed process system). Hence, a net power maximum does exist and expressing the two remaining conditions in Equations (2.6) would complete the net power maximization exercise. For typical designs, it is found that the flow rate ratio $m_{ww}/m_{cw}$ is larger than unity (say, 1.5 to 2), which simply reflects the fact that surface seawater is more accessible. As expected from the large OTEC heat loads, seawater needs are substantial, with $m_{cw}$ corresponding to volume flow rates of about 2.5 to 3 $m^3/s$ per net megawatt.

Interestingly, the simple power maximization scheme outlined here is quite robust. If the assumption expressed in Equation (2.5) is removed and terms of order $\varepsilon$ are kept in Equations (2.1) and (2.2), results hardly change because of compensatory effects.

### 2.3 Variable thermal resource

Along with Equation (2.7), the optimization of $P_{gross}$ also means that the maximum OTEC gross power is proportional to $(\delta T)^2$. This would occur as long as an active operator (or some automated control algorithm) could adjust the plant flow rates, within practical limits, to relatively significant variations in the available thermal resource. If the plant were left unattended instead, with all flow rates fixed, heat loads in the evaporator and condenser as well as $P_{seawater}$ would remain essentially the same. In such a case, changes in $\delta T$ would be entirely absorbed in the temperature drop across the turbine and $P_{gross}$ would vary linearly with $\delta T$. Since ($T_{evap}$ - $T_{cond}$) ≈ 10ºC and by virtue of Equation (2.4), a rule of thumb is that $P_{gross}$ varies by 10% whenever $\delta T$ changes by 1ºC. This would correspond to relative net power changes typically as large as 15%. Clearly, optimization would improve plant performance beyond what this simple rule suggests, with more power produced or less power lost depending on whether $\delta T$ increases or decreases. While such optimal control can easily be achieved using modern micro processors, it is undeniable that the performance of OTEC systems is very sensitive to the quality of the thermal resource.

### 2.4. Beyond the Rankine cycle

There have been recent efforts to improve the low efficiency of OTEC Rankine cycles by using a mixture of ammonia and water through the heat exchangers. This concept is embodied in the proprietary Kalina cycle. The rationale is that at a given pressure, the mixture evaporates or condenses over a range of temperatures rather than at a single temperature. If applied correctly, this fact results in a better match of heat loads during heat transfer since the temperatures of working fluid and seawater can remain closer. A plant based on this cycle requires additional hardware, i.e., a separator before the turbine inlet and an absorber after the turbine outlet because only ammonia flows through the turbine. Also, the heat carried by the water in the mixture can be partly recuperated through a regenerator. The Kalina cycle reportedly can boost the Carnot efficiency of an OTEC system by 50% or so, but it also imposes increased demands on the evaporator and condenser [4, 8]. This issue has been partly addressed by fine-tuning the cycle at the expense of further complications, but more importantly, by proposing much more efficient plate type heat exchangers [8]. Hence, the viability of OTEC cycles departing from the standard Rankine cycle may very well hinge on the availability of much better heat exchangers. Claims that such improved systems may approximately require only 60% of the seawater demand associated with classical designs certainly is tantalizing [8], but they warrant careful scrutiny. At the same time, the greatest technological (and credibility) challenges facing OTEC probably remain in the realm of ocean engineering.

## 3. HARSH LESSONS AT SEA

With practical limits on pumping velocities (say, not much greater than 2 m/s), the volume flow rates of deep cold seawater that maximize OTEC net power effectively correspond to Cold Water Pipe (CWP) diameters (in m) of about 1.2 to 1.4 times the square root of $P_{net}$ (expressed in MW). To date, OTEC is the only technology that requires such large pipelines reaching water depths of the order of 1000 m.

Not surprisingly, OTEC field experimentation has critically depended on whether a CWP could be deployed and how long it could survive. In the late 1930s, Claude pioneered these efforts in Cuba [6, 9] with innovative concepts such as single-length deployment and controlled submergence. A large (oversized) conduit, 1.6 m in diameter and made of corrugated steel sections with rubber joints, was installed along the steep seafloor after three failures. The first two attempts, that involved towing the entire air-filled pipe, did not succeed due to rough seas and inaccurate positioning. The deployment strategy was then updated by placing the CWP on a rail track onshore and pulling only one end to sea; human error resulted in the loss of one pipe when controlled submergence was erroneously initiated from the offshore end. Within weeks, the operating CWP was severely damaged by a tropical storm. Today's operators of oil and gas platforms in the Gulf of Mexico are quite familiar with hurricane damage. Claude's later OTEC project to demonstrate a floating plant concept off of Rio de Janeiro proved to be too challenging, as bad weather and technical problems to attach the CWP to the supporting buoy finally bankrupted him [10]. Claude was basically ahead of his time; the construction materials, analysis techniques, weather forecasting and vessel positioning capabilities available to him were not fit for the task.

A half century later, Claude's ideas were revived when the next efforts to test OTEC at sea were initiated. Improved weather forecasting and depth charting, as well as the availability of plastic materials provided very significant advantages. This led to the installation of several high density polyethylene (HDPE) deep water pipelines for small land-based OTEC pilot projects. Most notably, two conduits of 0.45 m (18") and 1 m (40") in diameter, respectively, were deployed in the early 1980s at the Natural Energy Laboratory of Hawaii Authority (NELHA) in Kailua-Kona, Hawaii. The smaller of these CWPs was installed using Claude's rail track configuration, as can be seen in Figure 2; the larger item was towed to sea from a distant harbour before final assembly and controlled submergence on site, i.e., much as Claude had initially envisioned such operations (Figure 3). In the process, however, further innovations were conceived to better handle local seafloor steepness and irregularities: a dual anchor-pendant system for the 0.45 m diameter CWP and a long inverse catenary for the offshore portion of the 1 m diameter CWP. Benefiting from the experience and knowledge acquired at NELHA, Makai Ocean Engineering, Inc. was able to design and deploy the largest CWP to date (55", i.e., 1.4 m in diameter, and 2.8 km long) to a depth of 900 m in 2001.

Figure 2. Deployment of a 0.45 m (18") diameter CWP (photo courtesy of Makai Ocean Engineering, Inc.)

Figure 3. Deployment of a 1 m (40") diameter CWP (photo courtesy of Makai Ocean Engineering, Inc.)

Despite the remarkable outcome of these modern undertakings, it should be mentioned that a 1.2 m diameter CWP was lost under tow in Hawaiian waters in 1987, and that the most recent deployment of the 1.4 m diameter pipe had to be temporarily reversed (by refloating the partially submerged conduit) because of a broken holding line [11]. A similar HDPE CWP (0.7 m in diameter), feeding a small land-based pilot plant built by Tokyo Electric and Toshiba on the island of Nauru in 1981, got severely damaged in a storm after a few months of operation.

The few success stories outlined above apply to small land-based systems. The large-scale future of the OTEC technology, however, lies in the exploitation of vast remote offshore areas. Accordingly, different designs have to be envisioned since plants would be sited on floating platforms with, eventually, CWPs of much greater sizes. Offshore systems pose specific challenges. Positioning, power transmission and, more critically, the necessity of a sound connection between the platform and its deep seawater pipeline are issues that have to be dealt with.

The easiest transition to offshore plants would be to use the same type of relatively small HDPE conduits that have been deployed successfully for land-based designs. This strategy was successfully applied with a 0.60 m CWP during a short closed-cycle OTEC experiment conducted in 1979 in sheltered Hawaiian waters [12]. A year later, another offshore system was launched in the same area. While funding restrictions limited the scope of the overall project to a mere heat exchanger test at sea, without power production, the ocean engineering aspect of this venture was more ambitious. Its CWP consisted of a bundle of three 1.2 m diameter HDPE conduits topped with a buoyancy collar (Figure 4).

Figure 4. The upper portion of the "OTEC 1" CWP being pulled into Kawaihae Harbor, Hawaii

Although those were relatively small steps in demonstrating the feasibility of offshore OTEC, it would be naïve to believe that even such limited operations at sea do not remain risky today. The National Institute of Ocean Technology (NIOT) of India failed twice in its efforts to deploy a floating OTEC system using a 1000 m long, 1 m diameter HDPE CWP in February 2001, and again in early 2003 [13]. This led NIOT to reduce the scope of the project to a desalination system in shallower waters. Such ill-fated attempts unfortunately have further deterred funding agencies or investors from OTEC. It is believed that many past failures could have been avoided by engaging the skills, resources and experience of the oil and gas offshore contracting industry.

While it has been recognized that HDPE CWPs are ideal for small megawatt-class systems, any move to OTEC plants of much greater capacity would have to rely on other choices. In addition, the bundling of HDPE pipes does not represent a practical option since significantly greater pumping power losses would be incurred. In this respect, the most ambitious program designed to resolve ocean engineering problems specific to large floating OTEC plants remains the comprehensive effort carried out under the leadership of the U.S. National Oceanic and Atmospheric Administration (NOAA) in the late 1970s and early 1980s. This remarkable undertaking included the development of computer simulation tools, model basin tests of potential platforms and pipes, and an at-sea test of a 120 m long, 2.5 m diameter CWP suspended from a small barge. The pipe was made of two layers of fibreglass-reinforced plastic (FRP) separated by syntactic foam. Manufactured in Washington State, it was shipped to Hawaii in 24 m sections (Figure 5). A double-gimbal connection decoupling the CWP from the roll and pitch motions of the barge was selected (Figure 6). The field experiment took place for three weeks in the spring of 1983 off of Honolulu (Figure 7).

The short length of the pipeline which was intended to be at least three times longer for a representative 1/3 scale test, is symptomatic of the end of political support for OTEC in the United States after the 1980 presidential election. In essence, the project administrators used all the funds that were left to perform as meaningful an at-sea test as possible. Only three weeks of data were collected in rather mild seas and currents. Although a longer record collected under more challenging environmental conditions would have been better, the existing data from strain gauges along the CWP was sufficient to calibrate predictive computer codes [14] and to validate the overall design methodology.

Figure 5. A 24 m section of the 2.5 m diameter FRP CWP tested off of Honolulu in 1983

Figure 6. The double-gimbal connection between the CWP and the barge tested off of Honolulu in 1983

Figure 7. A flotilla of barges and tugboats leaving Honolulu Harbor for the 1983 CWP at-sea test

## *4. ECONOMIC CONSIDERATIONS*

The large size of OTEC components and the demands imposed by offshore environments on equipment survival and power production logistics result in high projected capital costs. From an economic point of view, this is exacerbated by relatively low power outputs so that standard analyses based, for example, on the levelized cost of electricity generation have consistently resulted in uneconomical projects. Such an approach essentially leaves the responsibility of technology development to the private sector and relies on market mechanisms. For renewable energy systems in general, and the more capital-intensive ones in particular, the levelized cost of electricity generation is essentially determined by the capital cost burden to construct the plant. This is in sharp contrast to fossil-fuel power plants for which the investment burden is relatively low (≈ $2000/kW) while fuel expenditures over the life of the plant may be considerable. Hence, as the price of primary energy commodities has been sharply increasing over the past few years, the cost-effectiveness gap between OTEC and at least the most expensive fossil-fuel power generation technologies (e.g., oil) has steadily declined. OTEC market penetration, however, has not yet succeeded.

On the basis of available OTEC plant designs proposed by the early 1990s, Vega [15] published estimates of the capital cost per unit power for OTEC systems as a function of rated power. One noticeable trend is a considerable expected economy of scale as one would move from small pilot plants to larger commercial units. Because of a lack of experimental and operational data in running OTEC systems, however, taking advantage of this purported economy of scale has been one of the biggest challenges facing OTEC development. A common strategy has been to identify niche markets where the local cost of electricity would be sufficiently high and the overall power demand sufficiently low to make OTEC potentially competitive at the modest power outputs better suited for first-generation projects (e.g. 1 to 10 MW). Unfortunately, these niche markets often present additional logistical difficulties (remoteness, lack of appropriate infrastructure etc.) that may further deter investors.

Vega's results were recently updated [16] and are shown in Figure 8. Interestingly, applying an average inflation rate of 3% over 18 years on the early 90s' estimates brings them well within the updated range. Given a high Avoided Energy Cost (AEC) of nearly 20 ¢/kWh in Maui and Hawaii, as reported by the local utilities in late 2007, Vega noted that a 50 MW OTEC plant should be attractive there, at projected costs of less than 13500 $/kW (upper curve). Yet, no such project is currently being considered while other renewable technologies such as wind power now represent a significant portion of the local power generation portfolio. This state-of–affairs calls for several remarks. An obvious one is that OTEC projects are not immune to inflation. Moreover, when rises in the costs of fossil primary energy sharply outpace background inflation, OTEC not only competes with traditional fossil-fuel power generation systems, but with other renewable technologies as well. This usually favours mature ones. More fundamentally, if OTEC fails to penetrate niche markets where electricity costs are as high as 50 ¢/kWh and the power demand is less than 10 MW (e.g., Pohnpei, Micronesia [17]), in spite of substantial expected returns on investment, it may very well mean that the standard economic analysis does not properly reflect risks perceived by potential investors. In other words, the hope of securing loans at interest (discount) rates of a few percents for small OTEC projects that may still cost $100 million to $300 million is quite unrealistic. Instead, it appears as if the capital recovery factor that typical investors would accept is weighted upward by a risk function that grows sharply with capital cost. The consensus among many OTEC proponents that a meaningful OTEC pilot plant for scaling purposes should be in the 5 to 20 MW range actually suggests that a risk-weighted curve of predicted capital cost per unit power should have a minimum in that range, as illustrated in Figure 8. This essentially sets the cost-effectiveness threshhold much higher in a market-driven environment.

The above arguments highlight a vicious circle of sorts for OTEC, or, in more technical language, the existence of a strong negative feedback between OTEC deployment and the current lack of deployed OTEC systems. To break this "Catch 22" deadlock, risks that deter investors have to be lowered by building a few meaningful pilot systems and by operating them for a few years. While it is possible that, following Claude's example, exceptionally strong private companies or consortia may be able and willing to carry out such a program, it is more likely to be implemented with public

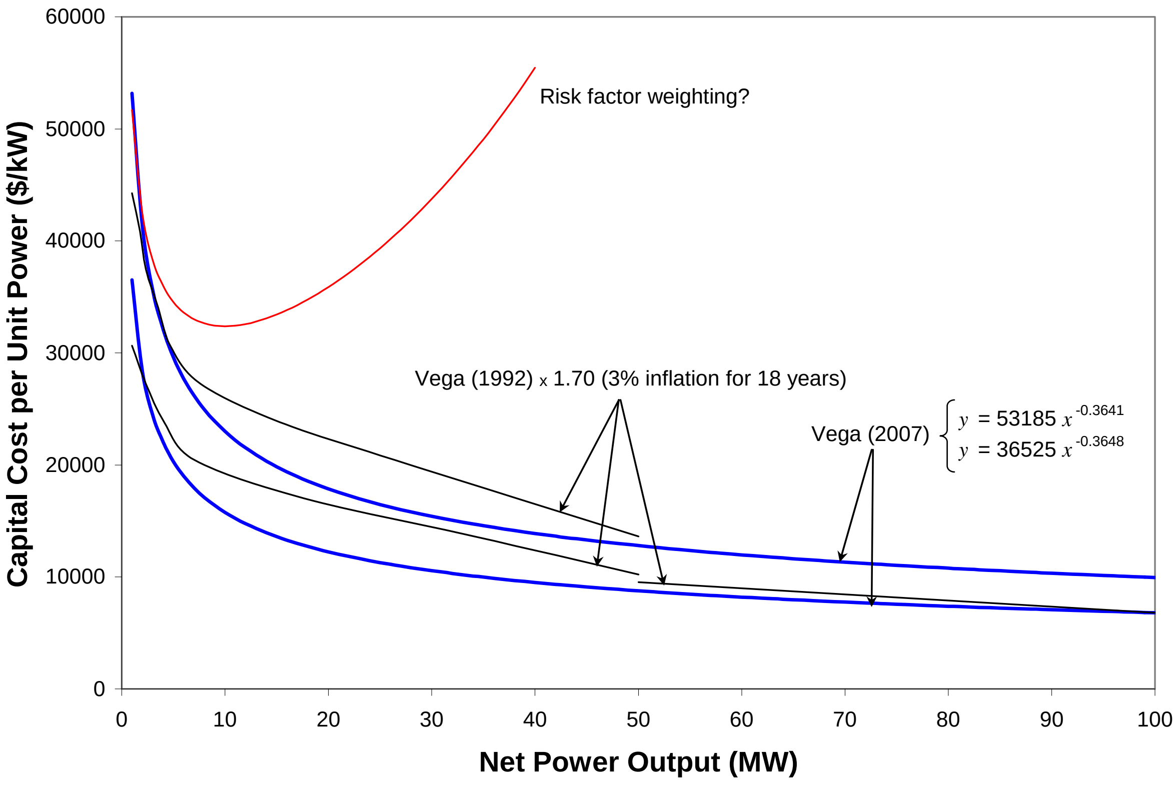


Figure 8. Projected capital cost per unit power for OTEC plants

funds from interested governments (another way to look at this issue is to consider a government as a very large group of investors i.e., taxpayers, for whom the risk in such ventures is individually very low). In essence, the efforts that were initiated in the late 1970s , most notably by the U.S. government after the price of oil sharply increased, but that were abandoned in the 1980s as the economic and political contexts became less favourable toward renewable energy development, have to be completed.

## *5. GEOPOLITICAL ASPECTS*

A map of the worldwide annual average OTEC resources is shown in Figure 9. The reference depth for the cold seawater intake is 1000 m and the warm seawater temperature is represented by an average taken over an arbitrary 75 m mixed layer. This latter convention makes the determination of available OTEC temperature differences slightly conservative. A low $\delta T$ threshold for OTEC power generation is set at 18ºC (dark blue) and contours are 1ºC apart. The area of interest for OTEC thus covers a little more than one third of the total oceanic area, i.e., about 140 million $km^2$. While favourable OTEC regions are considerable, they are, for the most part, far offshore from any land. This is not a cause for much concern until the most accessible sites have been developed. Those may be defined by the Exclusive Economic Zone (EEZ) of countries, to an extent of 200 nautical miles. As a matter of fact, this probably defines a practical reach for large power cables.

In a more distant future, a systematic development of remote OTEC regions would likely require the manufacture of energy vectors rather than direct power transmission to shore. This was one of Claude’s many innovative ideas for OTEC when he designed the ill-fated ice-making barge “La Tunisie” deployed off of Rio de Janeiro in 1935. Today, liquid fuels almost certainly would be considered such as hydrogen and methanol. While this would not reduce the high projected capacity factors of OTEC plants, it could somewhat weaken the argument that OTEC is a potential baseload technology for those remote systems not directly connected into an electrical grid. Moreover, the legal framework for the exploitation of very remote offshore areas would have to be specified. From a commercial perspective, the potential absence of taxes to pay to national governments is particularly attractive.

In the meantime, a more complicated issue arises from the distribution of OTEC resources that may hinder the technological development of OTEC further than dictated solely from economic considerations. Strikingly, most wealthy and technologically developed countries today are located far away from the tropical regions where OTEC systems could be deployed. Notable exceptions may be Brazil and Taiwan, while the Gulf of Mexico could provide the U.S. with a sufficient incentive.

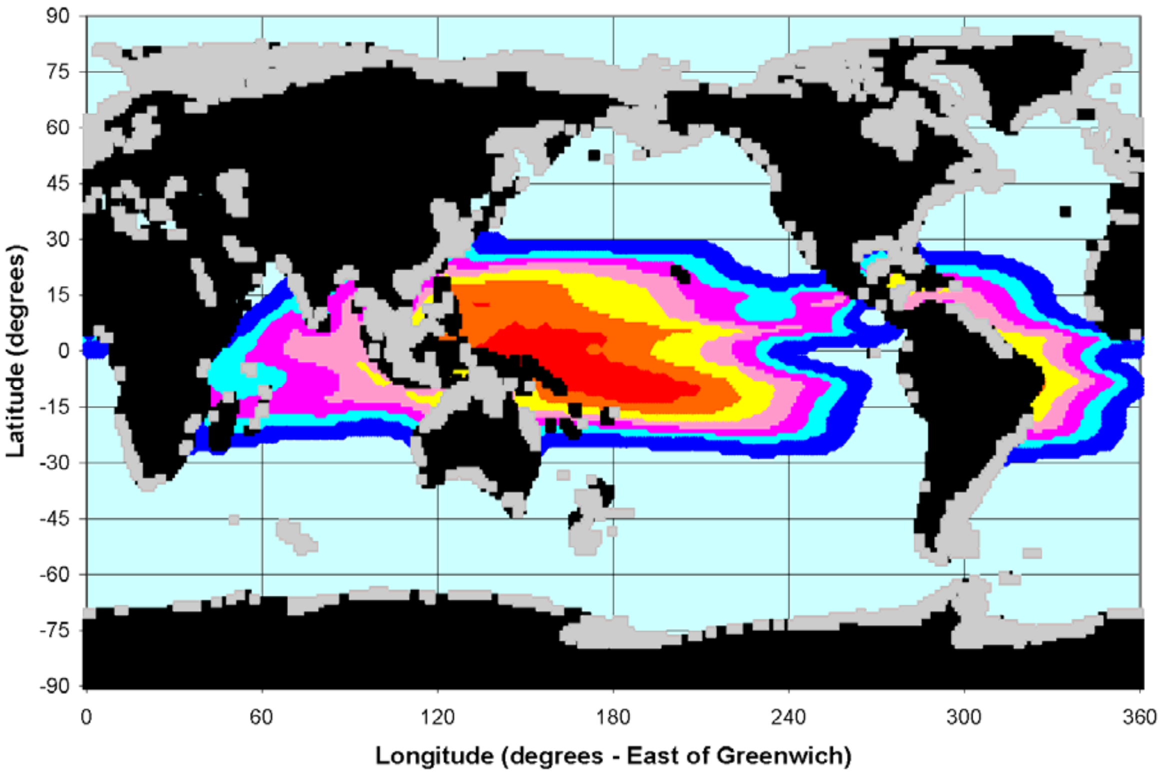


Figure 9. A map of the OTEC resource : average temperature differences between a 75 m mixed layer and 1000 m deep water (from [18]); color contours are 1ºC apart from 18ºC (dark blue) to 24 ºC (red) and grey areas are shallow water

Otherwise, the resource is abundant for countless small islands as well as for some large, sometimes heavily populated island nations that may not easily bear the burden of developing risky capital-intensive technologies (e.g., Indonesia, the Philippines, Papua New Guinea). Other renewable energies based on wind, solar and wave power conversion devices appear to be much more accessible to those stakeholders that could best promote OTEC, but may choose to tap those more reachable alternatives instead.

## 6. CONCLUDING REMARKS

The low thermodynamic efficiency of OTEC systems requires very efficient heat exchangers and large amounts of seawater through the power plant to generate net electrical power. Because pumping losses should not be too great, large diameter pipelines are necessary down to water depths of the order of 1000 m, i.e., hardware that defines a technological frontier even today. These ingredients result in very capital-intensive designs in the harsh marine environment, where corrosion, fatigue and the occurrence of major storms have to be dealt with. The combination of high capital needs and high risk has been self-defeating in the marketplace since only operational experience (with deployed systems) can reasonably lower risk! With the recent sharp rise in the price of primary energy in general and of oil in particular, the few companies that have kept an interest - or that have just managed to stay involved - in OTEC activities over the past decades have redoubled their efforts to achieve OTEC market penetration. Yet, the OTEC glass ceiling has proved hard to break.

Improvements in the OTEC technology that have been aggressively promoted by a number of companies, such as Xenesys, Inc. and OCEES International Inc. deal with the use of Kalina cycles (or their derivatives, such as the Uehara cycle [8]) instead of the standard Rankine cycle. Relative boosts in the Carnot efficiency exceeding 50% (i.e., in absolute terms, from 3% to 5%) have been reported from laboratory tests and computations. In addition, promising claims about heat exchangers have been made. If confirmed, such advances should allow a reduction in OTEC seawater requirements. The proprietary nature of these new designs makes their evaluation somewhat more difficult. In addition, the greatest technological risks associated with OTEC still stem from ocean engineering challenges, as has been demonstrated time and time again from Claude's groundbreaking field tests to NIOT's recent misfortunes.

This gives a definite edge to those involved in the successful deployment of the deep pipelines used in seawater air conditioning (SWAC) or multi-purpose deep ocean water applications (DOWA) such as the NELHA conduits. In fact, SWAC provides an economical (and perhaps psychological) bridge toward OTEC by demonstrating that deep cold water may be a practical resource immediately. At the forefront in this group is Makai Ocean Engineering, Inc. Also noteworthy is a recent commitment from Lockheed-Martin, a large company earlier involved in OTEC [12], to revive research and development efforts related to this technology. Yet, the ultimate move to offshore platforms with very large CWPs is necessary to realize the greater potential of OTEC. This remains a quantum leap of sorts, even for the more experienced OTEC protagonists.

A potential development which could see a practical demonstration of the required sea-water systems may be provided by a deepwater tropical ocean FPSO (Floating Production Storage and Offloading) unit. These oil and gas processing facilities are now routinely moored in water depths greater than 1000 m. In tropical oceans, the processing efficiency of these units can be substantially improved by making use of the cold and relatively biologically inert, deep ocean water. Figure 10 gives an indication of how such a system might be configured and additional information about potential savings is provided in [19]. Such savings look particularly attractive for a gas to liquids (GTL) FPSO. In many tropical areas remote from population centers, utilizing gas is difficult. However, flaring the gas is obviously wasteful and unwise from an environmental perspective. Thus, it is desirable to convert it to a liquid so it can be more easily transported.

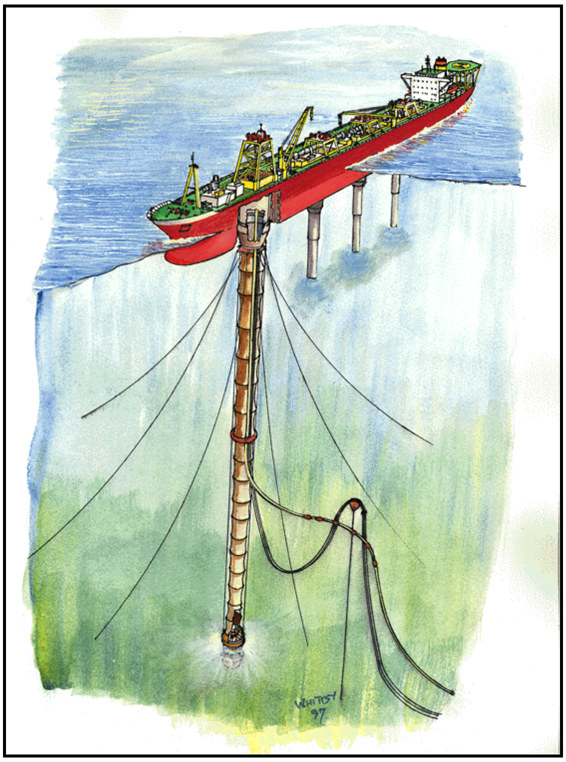

Figure 10. Example of deep water cooling for a tropical oil and gas FPSO

Another strategy to increase investor confidence has been to seek power purchase agreements (PPAs) with local utilities in niche markets where electricity is relatively costly. Memoranda of understanding (MOUs) with local political authorities also have been touted in the media, e.g., by Xenesys Inc. in Palau (2001) and in French Polynesia (2008). This approach is valid since it may secure the revenue-side of a project or facilitate the local permitting process, but it may not suffice to convince investors. Moreover, electricity consumers have started complaining about high PPAs when mature renewable energy technologies with lower production costs are available.

Given the heavy financial outlay and persisting high risks associated with any significant OTEC development, a strong commitment from interested governments still seems necessary (at least to accelerate and guide the development process). In this respect, however, the geopolitical location of most of the OTEC resource may not readily provide incentives for such a commitment.

Finally, if and when the OTEC technology is developed on a scale commensurate with available OTEC resources, issues that may appear somewhat academic for the moment will demand close attention. These questions hinge on the fact that moving very large flow rates of water from one ocean depth to another could affect the OTEC resource itself, at least in a local sense. Providing as much electrical power with OTEC as is being consumed today, i.e. about 2 TW, would correspond to combined intake (or discharge) flows of the order of 10 Sv (1 Sv = $10^6$ $m^3/s$). This is more than an order of magnitude greater than the combined flow of all the world's rivers estimated to be 0.7 Sv [20]. While the careful design of isolated single plants may easily prevent any problem such as effluent recirculation, clusters of plants definitely would be subject to a maximum deployment density beyond which an excessive degradation of the vertical thermal gradient may occur. On a grander scale, this may place a limit on the actual amount of OTEC power that can be produced worldwide [18, 21-22].

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