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*** 2. Cover Letter**

May 20, 2005,

Prof. N. Lior
Editor-in-Chief
School of Engineering and Applied Science
Dept. of Mechanical Engineering and Applied Mechanics
University of Pennsylvania
297 Towne Building
220 South 33rd Street
Philadelphia, PA 19104-6315

Dear Prof. Nior,

The object of this letter is to submit the manuscript entitled "A Preliminary Assessment of Ocean Thermal energy Conversion (OTEC) Resources" for publication in *Energy*.

The paper presents a simple analysis of the potential interaction between very large-scale OTEC operations throughout the tropical oceans and the thermal structure of the tropical water column. Such interaction is found to provide a sustainability limit for OTEC, although at time and space scales that may not practically affect practical implementation.

This study is the second step in a general assessment of OTEC resources. The first cursory examination of the steady-state problem with standard conditions resulted in a publication now in press:

> Nihous, G.C., "An order-of-magnitude estimate of Ocean Thermal Energy Conversion (OTEC) resources," *Journal of Energy Resources and Technology*, in press, 2005.

The present manuscript provides a more sophisticated evaluation of steady-state resources, including a provision for operational adjustment of the OTEC process. More importantly, the basic equations describing the thermal structure of the tropical ocean and OTEC are solved in the time domain.

I hope that you and the editorial staff will find this manuscript of potential interest for the readers of *Energy*, and I thank you for initiating the review process.

Sincerely,

Gérard Nihous, Ph.D.

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Hawaii Natural Energy Institute
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* 3. Manuscript

A PRELIMINARY ASSESSMENT OF OCEAN THERMAL ENERGY CONVERSION (OTEC) RESOURCES

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Abstract

Worldwide power resources that could be extracted from OTEC plants are estimated with a simple one-dimensional time-domain model of the thermal structure of the ocean. Recently published steady-state results are extended by partitioning the potential OTEC production region in one-degree-by-one-degree 'squares' and by allowing the operational adjustment of OTEC operations. This raises the estimated maximum steady-state OTEC electrical power from about 3 TW (10^9 kW) to 5 TW. The time-domain code allows a more realistic assessment of scenarios that could reflect the gradual implementation of large-scale OTEC operations. Results confirm that OTEC could supply power of the order of a few terawatts. They also reveal the scale of the perturbation that could be caused by massive OTEC seawater flow rates: a small transient cooling of the tropical mixed layer would temporarily allow heat flow into the oceanic water column. This would generate a long-term steady-state warming of deep tropical waters, and the corresponding degradation of OTEC resources at

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deep cold seawater flow rates per unit area of the order of the average abyssal upwelling. More importantly, such profound effects point to the need for a fully three-dimensional modeling evaluation to better understand potential modifications of the oceanic thermohaline circulation.

1.0 INTRODUCTION

The concept of Ocean Thermal Energy Conversion (OTEC) was formulated a long time ago as a means to extract some of the solar energy stored in the upper mixed layer of tropical oceans [1, 2]. Typically, an appropriate working fluid would produce mechanical work in a Rankine cycle operated between warm surface seawater and cold deep seawater. Because practical seawater temperature differences are only of the order of 20°C, the cycle thermodynamic efficiency is very low. As a result, OTEC electricity generation would require very large seawater flow rates of the order of several cubic meters per second per megawatt. Such facts have so far prevented OTEC and some of its byproducts from being economically competitive. Interest in the technology understandably surged with the price of oil in the seventies [3, 4]. As energy markets stabilized, however, this enthusiasm waned and the more ambitious existing OTEC R&D programs were completed by the nineties without near-term prospects of commercial implementation. Many involved researchers have continued to advocate the OTEC technology [5-11].

Recent concerns about secure energy supplies as well as strong demand-based increases in the cost of primary energy have rekindled enthusiasm for renewable energy. In particular, the vast baseload OTEC resource seems attractive again, at least in some special niches. Since the OTEC technology has yet to be implemented, the theoretical question of the size of the OTEC resource never received too much attention. This issue was recently investigated [12] and a literature survey revealed a wide range of estimates, from 10 to 1000 TW. The high-end values generally were derived from the amount of solar radiation absorbed by tropical oceans, while the low-end figures were quoted without details. As a reference, worldwide electrical power consumption, which represents for the most part secondary energy from power plants using fossil fuels, is projected to grow from 1.5 TW in 2001 to 2.7 TW in 2025. Installed capacity for electricity production was 3.5 TW in 2002 (http://www.eia.doe.gov/aer/txt/ptb1117.html). A steady-state one-dimensional analysis of the potential interaction between OTEC seawater flow rates and the thermal structure of the water column was then conducted under moderately conservative standardized conditions. It was concluded that the order-of-magnitude of steady-state OTEC resources might not exceed 3 TW. While this would represent an enormous amount of electrical power, it nevertheless falls short of previous estimates.

The following study has several objectives. The first goal is to refine the recent estimate of steady-state (sustainable) OTEC resources [12] by better accounting for the geographic distribution of tropical ocean temperatures, as shown in Figure 1, and by allowing some flexibility in the operation of the OTEC process. The second goal is to solve the problem of OTEC implementation in the time domain to get a sense of the time scales involved. In the next Section, a simplified OTEC process and a one-dimensional model of the vertical structure of oceanic temperature are presented. Results from the proposed algorithms are discussed next before concluding remarks are offered.

2.0 MODEL DESCRIPTION

2.1 Standard OTEC Process

A standard OTEC process was proposed by Nihous [12] for modeling purposes, with little loss of generality. The available OTEC temperature difference between surface and deep ocean waters, ΔT, is distributed between the major components of a power plant: one half across a power producing turbine, as suggested from simple optimization procedures [7], and the balance to allow surface seawater to cool down in an evaporator, and deep seawater to warm up in a condenser. Included in this 'temperature ladder' illustrated in Figure 2, a minimum approach (pinch) temperature $\Delta T/16$ (of the order of 1 °C) in either evaporator or condenser is imposed to maintain the exchange of heat. The thermodynamic efficiency of such a typical OTEC power cycle is $\varepsilon_{tg}\Delta T/(2T)$, where T is the surface water temperature and ε_{tg} the turbo-generator efficiency possibly as high as 0.85. The small amount of energy extracted through the OTEC process is often negligible, e.g. when defining the OTEC 'temperature ladder' in an overall enthalpy balance of the seawater streams.

In his formulas for OTEC power, Nihous [12] used the warm seawater flow rate Q_{ww} as a reference; yet, it is more intuitive to adopt the deep seawater flow rate Q_{cw} instead, since deep seawater is 'less accessible.' This latter convention will be followed henceforth, with the ratio γ representing Q_{ww}/Q_{cw}. Also, γ will be allowed to vary as a matter of operational flexibility. The gross electrical power P_g is written as the product of the evaporator heat load and the thermodynamic efficiency:

$$P_g = \frac{Q_{cw}\rho c_p 3\gamma\varepsilon_{tg}}{16(1+\gamma)T}\Delta T^2 \quad (1)$$

where ρ is an average seawater density, say 1025 kg/m^3, and c_p is the specific heat of seawater, about 4 kJ/kg-K.

Next, the net power P_{net} must be estimated, since it takes a considerable power consumption to drive the large seawater flow rates through an OTEC plant. Most OTEC plant configurations typically require about 30% of P_g at design conditions [14, 15]. With a fixed seawater flow ratio (γ= 2), and a fairly constant absolute surface seawater temperature ($T \approx T_{design}$, in K), the effect of this parasitic power was represented [12] as a decrease of {0.30 ΔT_{design}^2} imposed on ΔT^2 in Eq. (1). Here, a distinction is made between fixed parasitics (e.g. to sustain a given deep seawater flow rate), e.g. 18% of P_g at design, and those that would vary if γ is adjusted, e.g. {0.12 $(\gamma/2)^{2.75}$} times P_g at design. The choices embodied in the above expressions are typical, for example with the exponent 2.75 representative of friction and other flow losses. It can be verified that at design conditions, the net power P_{net} given below is maximal near the design value γ= 2 as γ varies:

$$P_{net} = \frac{Q_{cw}\rho c_p \varepsilon_{tg}}{8T} \{\frac{3\gamma}{2(1+\gamma)}\Delta T^2 - 0.18\,\Delta T_{design}{}^2 - 0.12\,(\frac{\gamma}{2})^{2.75}\Delta T_{design}{}^2\} \qquad (2)$$

In what follows, Eq. (2) will be used as a basis to evaluate OTEC resources. It corresponds to a total seawater flow rate intensity of 7.3 m^3/s per MW (net) at design conditions with γ= 2.

2.2 One-Dimensional Model of Ocean Temperature

A fundamental assumption is that OTEC operations take place over an area A_{OTEC} of the same order of magnitude as the total oceanic surface A so that the effect of horizontal inflow and outflow at the margins can be overlooked. From Figure 1, the area where the annual temperature difference between a 75 m surface mixed layer and 1000 m deep water exceeds 18°C is 136 million km^2 or 37% of A (more precisely, it represents 42% of the oceanic area where water depths are at least 1000 m). Hence, a one-dimensional model of ocean temperature is adopted. The oceanic water column extends from the seafloor (at $z = 0$) to the bottom of a mixed layer of thickness h_m (at $z = L$). With little loss of generality, seawater density and specific heat are kept constant at this preliminary modeling stage. The transport of heat results from vertical diffusion and advection. These phenomena are characterized by constant coefficients, K and w, respectively, although more complex parametrizations are possible. Without extensive flow perturbations from large scale OTEC operations, a partial differential equation for the water-column temperature $\theta(t, z)$ can be obtained from a heat balance on an elementary slab of thickness dz:

$$\frac{\partial \theta}{\partial t} = K \frac{\partial^2 \theta}{\partial z^2} - w \frac{\partial \theta}{\partial z} \tag{3}$$

The seafloor boundary condition represents the renewal of deep water from downwelling at the polar margins[1]; it is expressed as a flux:

$$-K \frac{\partial \theta}{\partial z}(t, 0) + w\theta(t, 0) = wT_p \tag{4}$$

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[1]The polar regions receive an advective heat flux wT from the mixed layer; this water cools, downwells and spreads over the ocean floor, inducing an upward advective heat flux wT_p in the one-dimensional model.

where T_p is the temperature of the downwelled polar water, taken for example as 0°C. Eq. (3) also must satisfy a continuity condition with the mixed layer at temperature T:

$$\theta(t, L) = T(t) \tag{5}$$

Before considering the flow resulting from large scale OTEC operations, the initial (unperturbed) condition may be derived from the steady-state form of Eqs. (3-5):

$$\theta(0, z) = T_p + \{T_0 - T_p\} \exp\{w \frac{z - L}{K}\} \tag{6}$$

where T_0 is the initial mixed layer temperature $T(0)$.

The choice w = 4 m/yr is made throughout this study and is typical for one-dimensional models of the ocean [16, 17]. In his steady-state analysis, Nihous [12] chose T_0 = 25°C and a value K = 2300 m^2/yr selected to yield a temperature of 5°C at a targeted OTEC deep water withdrawal depth of 1000 m (z_{cw} = 3075 m with L = 4000 m and a mixed layer 75 m thick). In other words, he considered an initial OTEC resource ΔT_{design} = 20 K; accordingly, A_{OTEC} was taken equal to 100 million km^2. Finally, he opted for a neutrally-buoyant OTEC mixed effluent discharge; on the basis of temperature, this yielded a depth of 253 m (z_{mix} = 3822 m) with γ = 2. Whenever 'standard conditions' are mentioned henceforth, the values just summarized are understood. Otherwise, the procedure to choose K is to fit an observed initial value of ΔT between a 75 m thick mixed layer and a water depth of 1000 m according to Eq. (6); in turn, the value of z_{mix} is estimated from matching the temperature of OTEC mixed effluents with the profile from Eq. (6). In general, vertical eddy diffusion coefficients K thus obtained are smaller than in early references [17], but in good agreement with the findings of recent and more elaborate models [18].

The effect of massive OTEC operations is now examined. With an incompressible one-dimensional model, the flow field from any perturbation is determined from mass conservation alone (the momentum equation would provide information on pressure gradients). Large-scale OTEC operations can schematically be represented by a sink of (flow) strength γQ_{cw} in the mixed layer, a sink of strength Q_{cw} at the deep water withdrawal depth z_{cw}, and a source of strength $(1 + \gamma)Q_{cw}$ at the effluent discharge depth z_{mix}. These elementary singularities result in discontinuous vertical velocities through the water column which can be partitioned into three regions: from the seafloor to z_{cw} there is no flow change; between z_{cw} and z_{mix}, there is an additional velocity $-Q_{cw}/ A_{OTEC}$ (downward); and between z_{mix} and the mixed layer, there is an additional velocity $\gamma Q_{cw}/ A_{OTEC}$ (upward). Accordingly, three coupled Initial Boundary Value Problems (IBVPs) must be solved.

Between the seafloor and z_{cw}, Eqs. (3-4) still apply with a temperature continuity condition at z_{cw}. In the region $z_{cw} > z > z_{mix}$, the partial differential equation to be solved is:

$$\frac{\partial \theta}{\partial t} = K \frac{\partial^2 \theta}{\partial z^2} - (w - \frac{Q_{cw}}{A_{OTEC}}) \frac{\partial \theta}{\partial z} \tag{7}$$

with temperature continuity conditions at z_{cw} and z_{mix}. Finally, from z_{mix} to the mixed layer, the new partial differential equation is:

$$\frac{\partial \theta}{\partial t} = K \frac{\partial^2 \theta}{\partial z^2} - (w + \frac{Q_{ww}}{A_{OTEC}}) \frac{\partial \theta}{\partial z} \tag{8}$$

Once more, a temperature continuity condition is enforced at z_{mix}, and Eq. (5) still applies.

The three IBVPs are well defined, but there remain three unknowns: $\theta(z_{cw})$ and $\theta(z_{mix})$and T. It can be shown that expressing the heat flux discontinuity from the OTEC sink at z_{cw} results in a continuity condition for the temperature gradient; in other words, simple withdrawal of seawater does not affect the local smoothness of the temperature profile. The known heat flux discontinuity at z_{mix} provides an additional equation; if the small amount of energy extracted by OTEC plants is neglected, this flux jump is $Q_{cw}\ [\gamma T + \theta(z_{cw})]/\ A_{OTEC}$. Finally, a differential equation is needed for the heat balance of the mixed layer:

$$\frac{dT}{dt} = -\frac{(T - T_0)}{\tau} + \frac{1}{h_m}\{-K\frac{\partial\theta}{\partial z}(L) + w(T_0 - T_p)\} \qquad (9)$$

where τ is a characteristic mixed-layer radiative cooling time, of the order of 4 years. The first term on the right-hand-side of Eq. (9) embodies the net thermal effect of all stable radiative processes (changes in these processes, e.g. from enhanced greenhouse forcing, would necessitate additional terms in the equation [19]). With or without perturbations from OTEC operations, all advective heat fluxes affecting this one-dimensional mixed layer cancel out; the second term on the right-hand-side of Eq. (9) represents any transient imbalance in the diffusive heat flux at the bottom of the mixed layer.

3.0 RESULTS AND DISCUSSION

The one-dimensional model of the oceanic thermal structure developed in Section 2.2 allows one to calculate the potential temperature perturbation generated by massive seawater flows. In turn, if such flows are necessary to sustain large-scale OTEC operations, Eq. (2) yields the corresponding OTEC net power. The steady-state problem where all time derivatives are set to zero already was solved for 'standard conditions' [12].

3.1 Steady-State OTEC Resource Limit

Before presenting an implementation of the time-varying algorithm, the steady-state problem was reconsidered, but some operational flexibility was allowed by varying the seawater flow rate ratio γ in response to reduced OTEC resource ΔT. Results are shown in Figure 3. The abscissa is the deep seawater flow rate per unit area Q_{cw}/A_{OTEC}; it is equal to the inverse of the mixed layer utilization time τ_m defined by Nihous [12] multiplied by h_m/γ (e.g. 3.75 m/yr corresponds to τ_m = 10 years when γ = 2). Also shown as a vertical line is the flow rate equal to w that would correspond to a zero net vertical advection in the layer $z_{cw} > z > z_{mix}$. It is confirmed that maximum steady-state OTEC net power P_{max} would occur at deep seawater flow rates per unit area of the order of w. As anticipated, reducing γ offers the possibility of modest gains, of the order of 10%.

'Standard conditions' ΔT_{design} = 20°C, T_{design} = 25°C and A_{OTEC} = 100 million km^2 seem overly conservative, however, when considering Figure 1. Instead, the region where ΔT_{design} exceeds 18°C was divided in one-degree-by-one-degree 'squares', and the steady-state algorithm was run with T_{design}, ΔT_{design}, K and z_{mix} assigned local values. This procedure raised P_{max} to 4.9 TW, or 80% higher than the former estimate for 'standard conditions'. The revised maximum corresponds to γ = 1.6 rather than 2, and to a deep seawater flow rate per unit area of 5.1 m/yr (τ_m = 9 yr).

Several factors could affect the accuracy of P_{max}, even in the context of a simplified one-dimensional model. The high value ε_{tg} = 0.85 for turbo-generator efficiency could be an overestimate by 0.1. Also, it could be argued that the heat exchanger pinch points δT_{pinch} should be nearly constant rather than proportional to ΔT as shown in Figure 2; this would be equivalent to substituting ($\Delta T/2 - 2\ \delta T_{pinch}$) for 3 $\Delta T/8$ in Eq. (1). Repeating the steady-state calculations with $\varepsilon_{tg} = 0.75$ and δT_{pinch} = 1.25°C, P_{max} drops to 3.9 TW for $\gamma = 1.7$ and a deep seawater flow rate per unit area of 4.5 m/yr (τ_m = 9.9 yr). To balance this possible reduction from an adjustment of OTEC process parameters, external environmental factors could raise the one-dimensional steady-state OTEC resource limit instead. A conservative point in the present approach is the identification of T with the temperature of a 75 m mixed layer. If the temperature data at 20 m depth were considered instead, the unperturbed OTEC thermal resource defined by ΔT_{design} > 18°C would be 16% higher. Also, it had already been shown [12] that in a globally warmer ocean, for example as a result of a prolonged increase in the atmospheric greenhouse forcing, P_{max} could be about 20% higher. It may therefore be concluded that 'standard conditions' (A_{OTEC} = 100 million km^2, ΔT_{design}= 20°C, T_{design}= 25°C) are too conservative, and a one-dimensional estimate of steady-state OTEC resources of the order of 5 TW seems justifiable.

The oceanic thermal structure disturbance corresponding to the OTEC seawater flow rates necessary to generate net power of the order of P_{max} is considerable, however, on the basis of this one-dimensional analysis. Figure 4, (also *Figure 3* in [12]) compares the baseline unperturbed temperature profile $\theta(0, z)$ and the steady-state solution $\theta(\infty, z)$ for Q_{cw}/A_{OTEC} =3.75 m/yr and $\gamma = 2$ (τ_m = 10 years). Since the long-term (steady-state) mixed layer temperature is $T(\infty) = T_0$, and that $\theta(\infty, z) > \theta(0, z)$, the tropical water-column below the mixed layer ($0 > z > L$) has warmed up at all depths as a result of large-scale OTEC operations. Calling F_{in} the overall heat flux into the water column, energy conservation implies that at all times, we have:

$$\int_0^L [\theta(t,z) - \theta(0,z)]dz = \int_0^t F_{in}(t')dt' \tag{10}$$

It can be checked that F_{in} is the sum of the diffusive flux out of the mixed layer $K\,\partial\theta/\partial z(L)$ minus $w(T - T_p)$. Using Eq. (9), it follows that:

$$F_{in} = -(\frac{h_m}{\tau} + w)(T - T_0) - h_m \frac{dT}{dt}$$

Substituting the above result in Eq. (10), we obtain:

$$\int_0^L [\theta(t,z) - \theta(0,z)]dz = -(\frac{h_m}{\tau} + w)\int_0^t [T(t') - T_0]dt' - h_m(T - T_0) \tag{11}$$

When t tends to infinity, the second term in the right-hand-side vanishes. Eq. (11) shows that a warming of the water column (positive left-hand-side) corresponds to a time-integrated cooling of the mixed-layer below the equilibrium value T_0. Zener [3] anticipated that as a result of large-scale OTEC operations, a small transient cooling of the tropical mixed layer would allow heat transfer to the deeper layers. This is investigated further in the next Section. Yet, the changes in the thermal structure of tropical oceans predicted so far point to a serious limitation of a one-dimensional model, since horizontal convective currents cannot be modeled while they undoubtedly would represent a fundamental adjustment mechanism.

3.2 Time-varying Scenarios

With little loss of generality and given the range of uncertainty associated with the proposed approach, 'standard conditions' were used in time-varying calculations; as a result, excessive computing requirements were avoided, with single input values of A_{OTEC} , ΔT_{design}, T_{design} etc. The OTEC flow rate ratio was held constant (γ= 2). Two types of OTEC scenarios were considered: 'instantaneous' in a stepwise fashion (at t = 0), and gradual (e.g. with a progressive buildup of OTEC capacity from t = 0). The former are not realistic, but may provide insight into the system's basic time constants; the latter do correspond to possible pathways to develop OTEC as a power resource. Gradual implementation consisted of an aggressive scenario, where 100 'design' GW per year are added, and a moderate one, with only 10 additional 'design' GW per year; the corresponding flow rates are determined via Eq. (2) where $\Delta T = \Delta T_{design}$ and $T = T_{design}$.

Figure 5 shows the predicted time history of the mixed layer temperature for the 'instantaneous' scenario corresponding to the steady-state water-column temperature profile in Figure 4. As anticipated from Eq. (11), the mixed layer would experience a transient cooling of the order of 1°C. The small residual value between T and T_0 for asymptotically large times is a measure of the accuracy of the numerical scheme. Here, a time step just over half a day was selected to ensure numerical convergence for a vertical grid with a mesh of less than 3 m. Figure 6 illustrates the OTEC net power production time histories for various ‘instantaneous’ scenarios.

More realistic ‘gradual’ scenarios were considered next. Results are displayed in Figure 7. With an aggressive implementation of 100 ‘design’ GW/yr, it would take about a century to reach a power maximum, before rapidly deteriorating the OTEC resource. With a moderate implementation of 10 ‘design’ GW/yr, maximum net power production would not be reached for about six centuries, and the ensuing decline would be quite slow. In both cases, a theoretical capacity of 5.7 ‘design’ TW (at standard conditions) corresponding to a steady-state actual maximum of 2.7 TW should not be exceeded to avoid long-term power production losses from a lack of sustainability of OTEC resources at large enough scale. Even in the case of an aggressive implementation of the OTEC technology, however, a potential capacity limit may not easily be exceeded; if OTEC systems, for example, only had a design life of the order of 60 years, it would take a continuous installation of about 100 ‘design’ GW/yr to maintain maximum OTEC net power production, as obsolete plants would have to be replaced.

4.0 CONCLUSIONS

A straightforward one-dimensional analysis has showed that theoretically, worldwide power resources that could be extracted from the operation of Ocean Thermal Energy Conversion (OTEC) plants may be limited. This would stem from the disruption of the vertical thermal structure of the oceanic water column by the massive seawater flow rates needed to sustain large-scale OTEC operations. Calculations indicate a long-term heating of the tropical water column if deep cold seawater were used at flow rates per unit area of the order of the average abyssal upwelling. This phenomenon would correspond to a transient cooling of the tropical mixed layer. Such predictions, however, should be further evaluated with a three-dimensional model of the oceanic circulation since a one-dimensional representation does not allow any potential adjustment from convective horizontal currents.

According to the present study, about 5 TW of steady-state OTEC power may be available at most. This is slightly more than a recent estimate based on conservative 'standardized OTEC conditions', but it remains much smaller than values generally available in the technical literature. The present OTEC resource estimates still largely exceed today's worldwide electricity consumption, however. It is unlikely that a possible lack of sustainability of OTEC resources at very large scales will ever be tested in practice.

Nomenclature

A	overall oceanic surface area (m^2)
A_{OTEC}	oceanic surface area for practical OTEC power production (m^2)
c_p	specific heat of seawater (J/kg-K)
h_m	mixed layer thickness (m)
K	vertical eddy diffusion coefficient (m^2/s)
L	water-column thickness below mixed layer (m)
P_g	OTEC gross power (W)
P_{max}	estimated maximum steady-state OTEC net power (W)
P_{net}	OTEC net power (W)
Q_{cw}	OTEC cold deep seawater volume flow rate (m^3/s)
Q_{ww}	OTEC warm surface seawater volume flow rate (m^3/s)

T surface (mixed-layer) seawater temperature (°C)

T_{design} design surface (mixed-layer) seawater temperature (°C)

T_0 initial surface (mixed-layer) seawater temperature (°C)

T_p polar seawater temperature (°C)

w upward advection (upwelling) rate (m/s)

z vertical water-column coordinate (m)

z_{cw} vertical coordinate of OTEC deep seawater withdrawal (m)

z_{mix} vertical coordinate of OTEC mixed effluent discharge (m)

Greek letters

γ ratio of OTEC seawater flow rates Q_{ww}/Q_{cw}

ΔT temperature difference available for OTEC process (°C)

ΔT_{design} design temperature difference available for OTEC process (°C)

δT_{pinch} OTEC heat exchanger pinch points (°C)

ε_{tg} turbogenerator efficiency

ρ seawater density (kg/m^3)

θ water-column temperature (°C)

τ characteristic mixed-layer radiative cooling time (s)

τ_m OTEC mixed layer utilization time (s)

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LIST OF FIGURE CAPTIONS

Figure 1 – A map of the OTEC resource: temperature difference ΔT_{design} between a 75 m surface mixed layer and 1000 m deep water; 1°C contours are plotted for $\Delta T_{design} > 18$°C.

Figure 2 – Illustration of the OTEC temperature ladder.

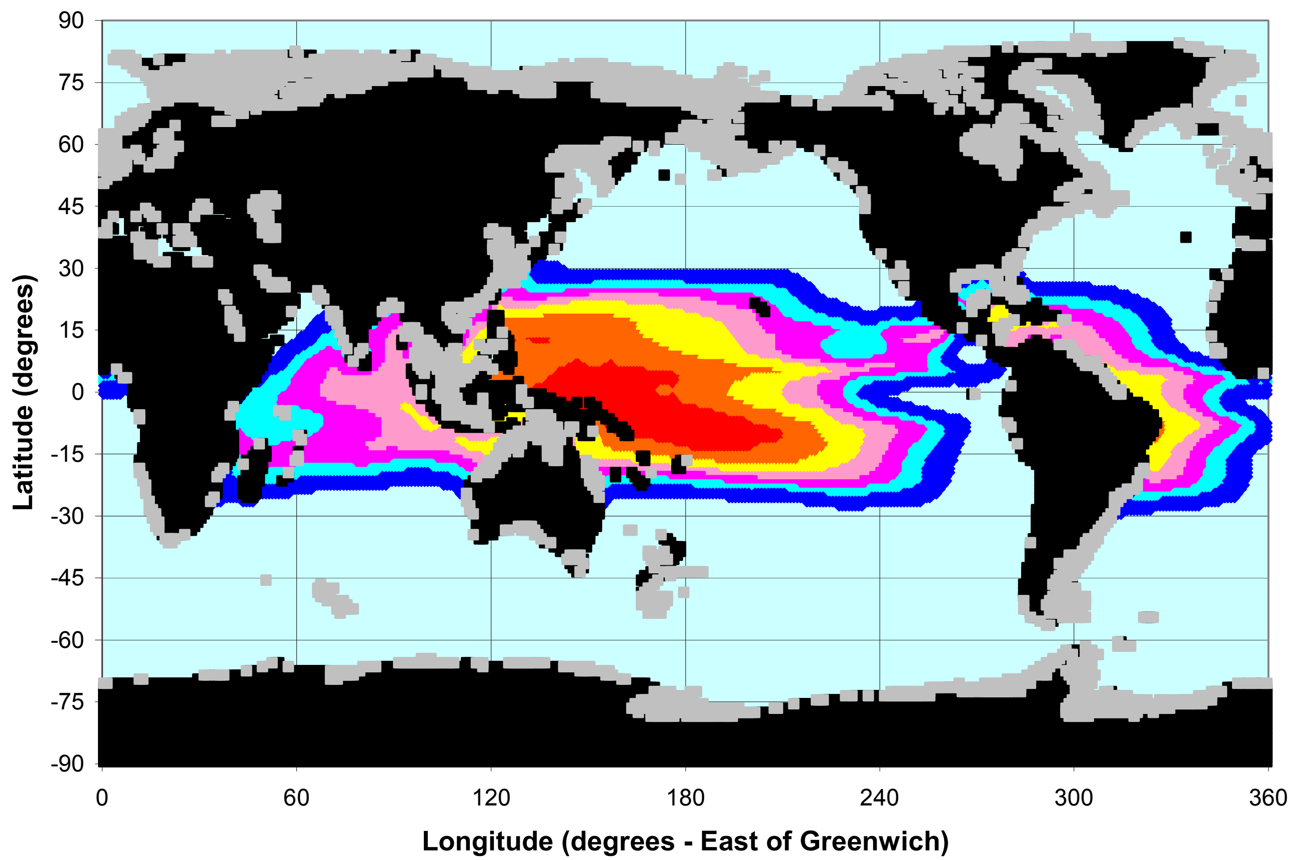
Figure 3 – Steady-state OTEC net power (at standard conditions) as a function of deep seawater flow rate per unit area.

Figure 4 – Steady-state oceanic temperature profiles: baseline, or with large-scale OTEC operations (standard conditions and deep seawater flow rate per unit area of 3.75 m/yr).

Figure 5 – Time history of mixed layer temperature with large-scale OTEC operations initiated at $t = 0$ (standard conditions and deep seawater flow rate per unit area of 3.75 m/yr).

Figure 6 – Time histories of OTEC net power (at standard conditions) for selected cases of large-scale OTEC operations initiated at $t = 0$.

Figure 7 – Time histories of OTEC net power (at standard conditions) for selected cases of gradually implemented large-scale OTEC operations.



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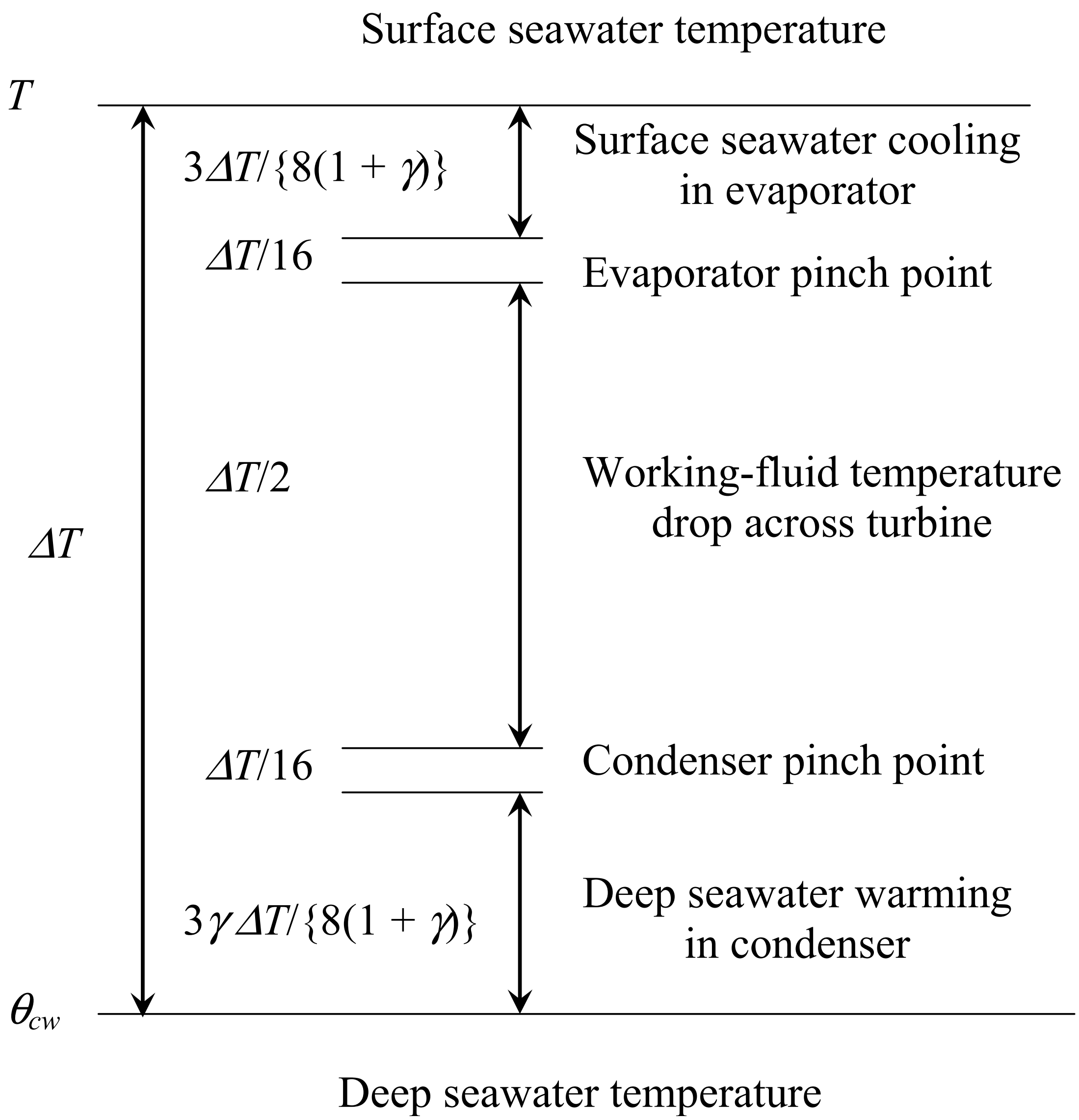

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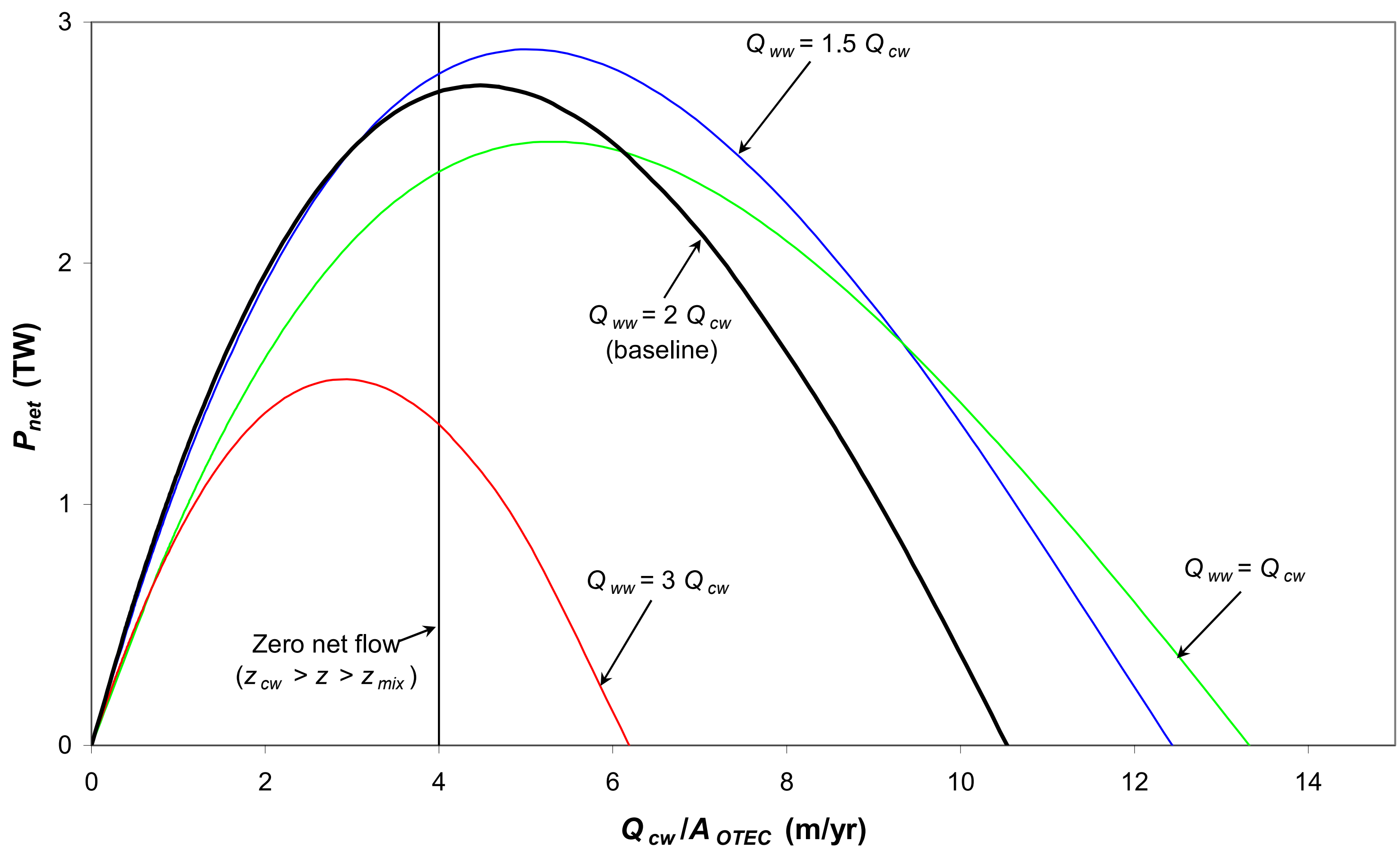

Figure 3 – Steady-state OTEC net power (at standard conditions) as a function of deep seawater flow rate per unit area.

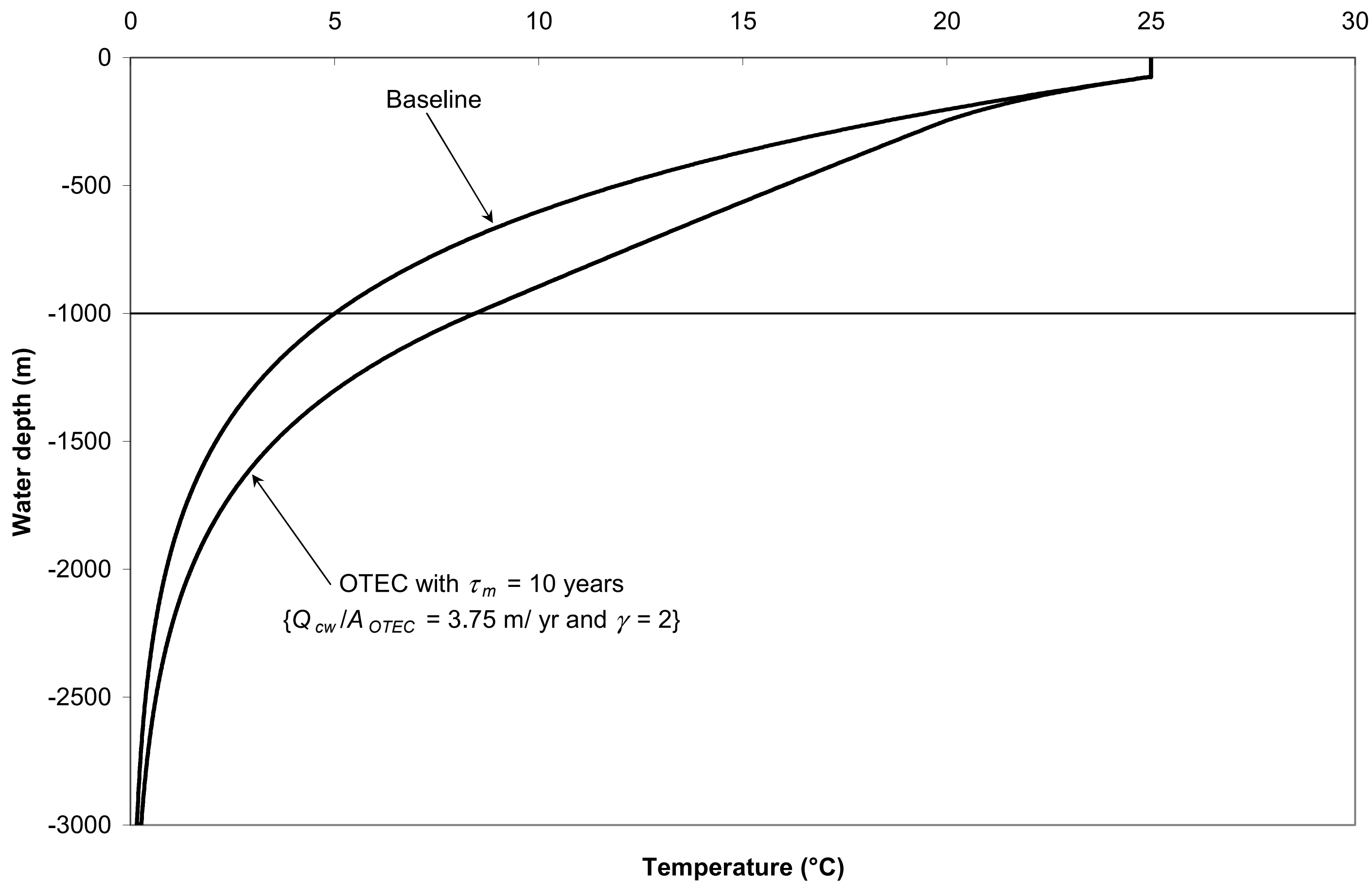

Figure 4 – Steady-state oceanic temperature profiles: baseline, or with large-scale OTEC operations (standard conditions and deep seawater flow rate per unit area of 3.75 m/yr).

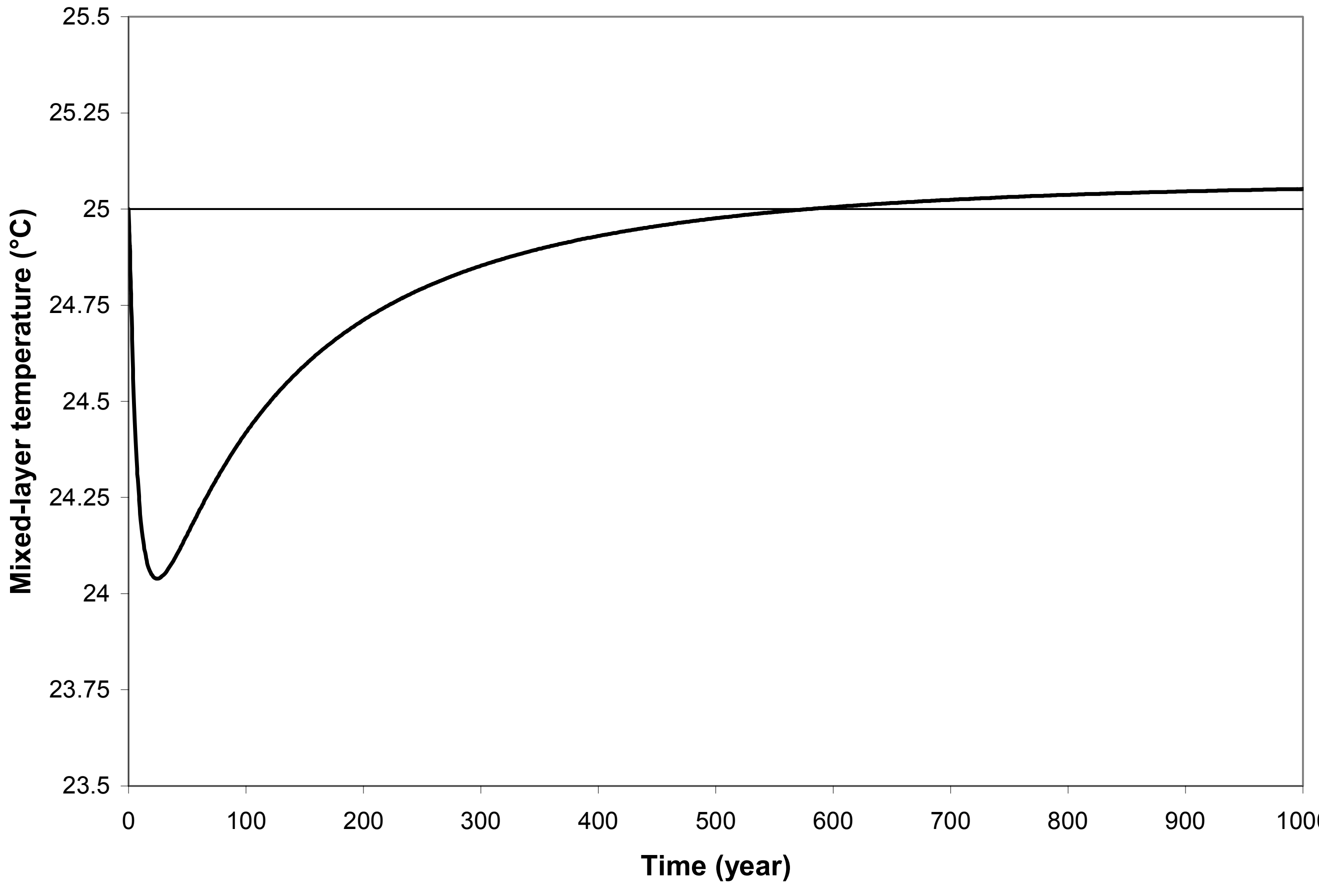

Figure 5 – Time history of mixed layer temperature with large-scale OTEC operations initiated at *t* = 0 (standard conditions and deep seawater flow rate per unit area of 3.75 m/yr).

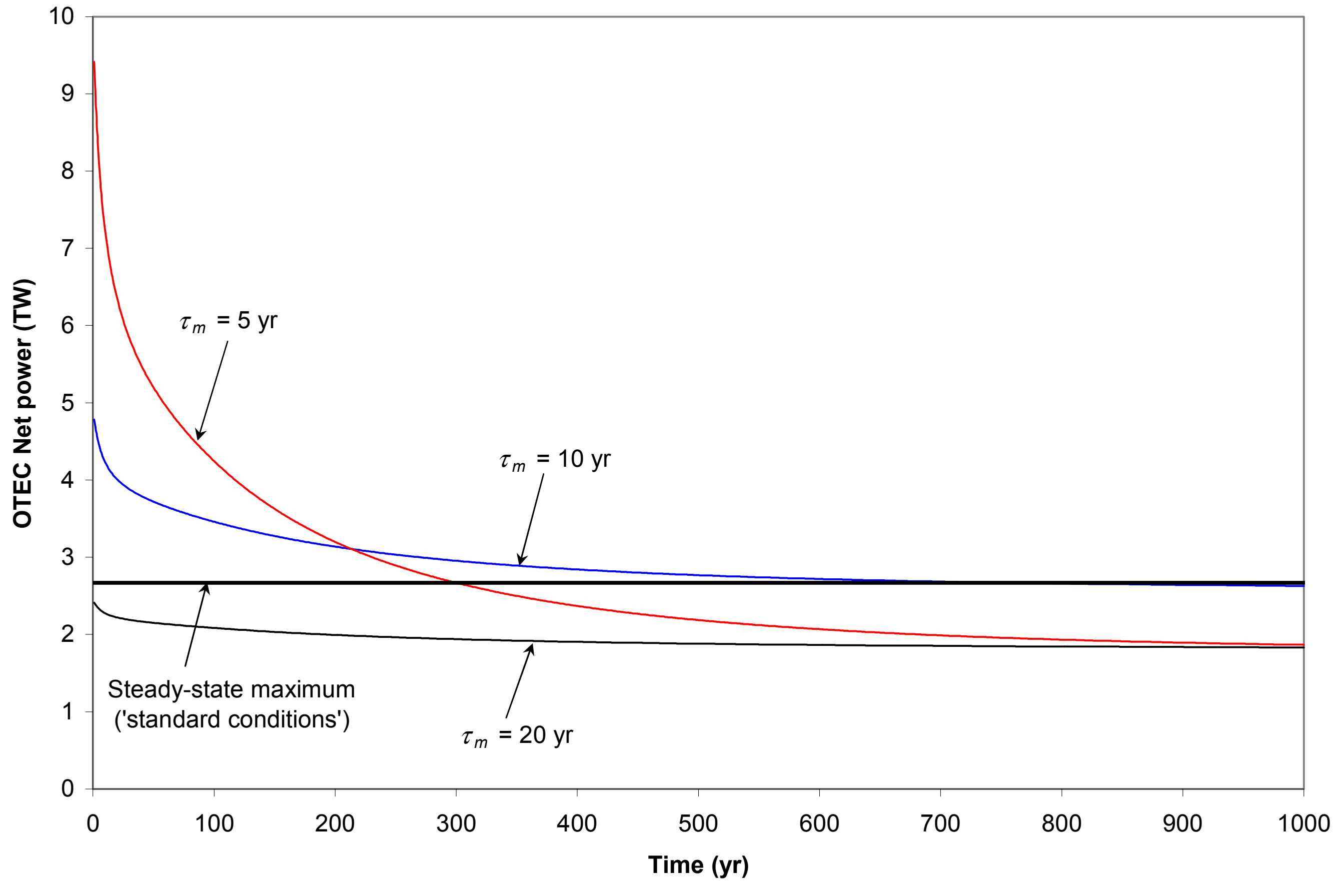

Figure 6 – Time histories of OTEC net power (at standard conditions) for selected cases of large-scale OTEC operations initiated at $t = 0$.

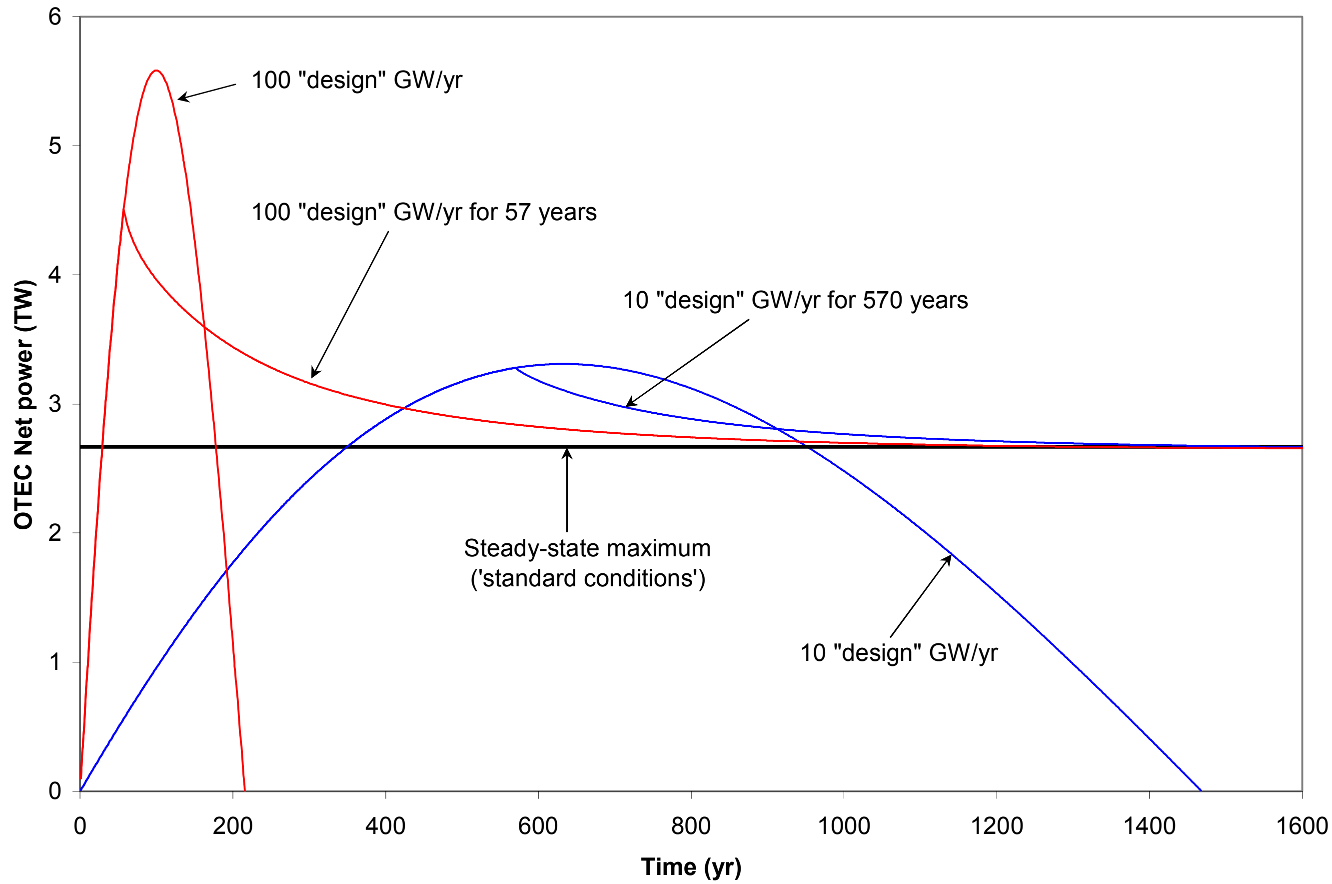

Figure 7 – Time histories of OTEC net power (at standard conditions) for selected cases of gradually implemented large-scale OTEC operations.