A Preliminary Assessment of Ocean Thermal Energy Conversion Resources

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1 Introduction

The concept of 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 1990s 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 2002.1 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 [13], as shown in Fig. 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 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, $\Delta T$, 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 Fig. 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 $\eta = \Delta T/(2T)$, where $T$ is the surface water temperature and $\eta$ is the turbogenerator efficiency possibly as high as

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1 http://www.eia.doe.gov/aer/txt/ptb1117.html

Contributed by the Advanced Energy System Division of ASME for publication in the JOURNAL OF ENERGY RESOURCES TECHNOLOGY. Manuscript received November 23, 2005; final manuscript received July 7, 2006. Review conducted by Salvador M. Acesa.
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 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 \( T_{cw}/T_{ww} \) representing \( Q_{ww}/Q_{cw} \). Also, \( T_{cw}/T_{ww} \) 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

\[
P_g = \frac{Q_{cw} \rho c_p 3 \gamma_{cw} \Delta T^2}{16(1 + \gamma)T}
\]

where \( \rho \) is an average seawater density, say 1025 kg/m³, 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 \( \gamma=2 \), and a fairly constant absolute surface seawater temperature \( T_{cw} \) in K, the effect of this parasitic power was represented as a decrease of \( 0.30 \Delta T_{design}^2 \) imposed on \( T_{design}^2 \) 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 \( T_{cw}/T_{ww} \) were 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 \( \gamma=2 \).

\[
P_{net} = \frac{Q_{cw} \rho c_p 3 \gamma_{cw} \Delta T^2}{8T} \left[ \frac{3 \gamma}{2(1 + \gamma)} \Delta T^2 - 0.18 \Delta T_{design}^2 \right] - 0.12 \left( \frac{3}{2} \right)^{2.75} \Delta T_{design}^2
\]

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 m³/s per MW (net) at design conditions with \( \gamma=2 \).

2.2 One-Dimensional Model of Ocean Temperature. A fundamental assumption is that OTEC operations take place over an area \( A_{OTE C} \) 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 Fig. 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 km² 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 \( dz \):

\[
\frac{\partial \theta}{\partial t} = K \frac{\partial^2 \theta}{\partial z^2} - w \frac{\partial \theta}{\partial z} 
\]  

(3)

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

\[-K \frac{\partial \theta}{\partial z}(t,0) + w \theta(t,0) = w T_p \]

(4)

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

\[ \theta(t,L) = T(t) \]  

(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):

\[ \theta(0,z) = T_p + \left[ T_0 - T_p \right] \exp\left\{ \frac{z-L}{K} \right\} \]

(6)

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

The choice \( w = 4 \text{ m/yr} \) 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 \( T_p = 25°C \) and a value \( K = 2300 \text{ m2/yr} \) selected to yield a temperature of 5°C at a targeted OTEC deep water withdrawal depth of 1000 m (\( z_{cw} = 3075 \text{ m} \) with \( L = 4000 \text{ m} \) and a mixed layer 75 m thick). In other words, he considered an initial OTEC resource \( \Delta T_{\text{design}} = 20 \text{ K} \); accordingly, \( \lambda_{\text{OTEC}} \) was taken equal to 100 million km². Finally, he opted for a neutrally buoyant OTEC mixed effluent discharge; on the basis of temperature, this yielded a depth of 253 m (\( z_{\text{mix}} = 3822 \text{ m} \)) with \( \gamma = 2 \). 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 \( \Delta T \) between a 75 m thick mixed layer and a water depth of 1000 m according to Eq. (6); in turn, the value of \( z_{\text{mix}} \) 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 \( \gamma Q_{cw} \) 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 \( z_{\text{mix}} \). 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 \( z_{\text{mix}} \), there is an additional velocity \(-Q_{cw}/A_{\text{OTEC}} \) (downward); and between \( z_{\text{mix}} \) and the mixed layer, there is an additional velocity \( \gamma Q_{cw}/A_{\text{OTEC}} \) (upward). Accordingly, three coupled initial boundary value problems (IBVPs) must be solved.

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

\[
\frac{\partial \theta}{\partial t} = K \frac{\partial^2 \theta}{\partial z^2} - \left( w - \frac{Q_{cw}}{A_{\text{OTEC}}} \right) \frac{\partial \theta}{\partial z} 
\]  

(7)

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

\[
\frac{\partial \theta}{\partial t} = K \frac{\partial^2 \theta}{\partial z^2} - \left( w + \frac{Q_{cw}}{A_{\text{OTEC}}} \right) \frac{\partial \theta}{\partial z} 
\]  

(8)

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

The three IBVPs are well defined, but there remain three unknowns: \( \theta(z_{cw}) \) and \( \theta(z_{\text{mix}}) \), 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 \( z_{\text{mix}} \) provides an additional condition; if the small amount of energy extracted by OTEC plants is neglected, this flux jump is \( Q_{cw}/[\gamma T + \theta(z_{cw})]/A_{\text{OTEC}} \). Finally, a differential equation is needed for the heat balance of the mixed layer:

\[
\frac{dT}{dt} = \frac{(T - T_0)}{\tau} + \frac{1}{h_m} \left( -K \frac{\partial \theta}{\partial z}(L) + w(T_0 - T_p) \right) 
\]  

(9)

where \( \tau \) 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 Results and Discussion

The one-dimensional model of the oceanic thermal structure developed in Sec. 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 \( \gamma \) in response to reduced OTEC resource \( \Delta T \). Results are shown in Fig. 3. The abscissa is the deep seawater flow rate per unit area \( Q_{cw}/A_{\text{OTEC}} \); it is equal to the inverse of the mixed layer utilization time \( \tau_{\text{mix}} \) defined by Nihous [12] multiplied by \( h_m/\gamma \) (e.g., 3.75 m²/yr corresponds to \( \tau_{\text{mix}} = 10 \text{ years} \) when \( \gamma = 2 \)). 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 \( z_{cw} > z > z_{\text{mix}} \). By virtue of Eq. (2), the slope at the origin for each curve, corresponding to a given value of \( \gamma \), would define net power production as a function of flow rate if the oceanic thermal structure were unaffected by OTEC operations. It is confirmed that maximum steady-state
OTEC net power $P_{\text{max}}$ would occur at deep seawater flow rates per unit area of the order of $w$. As anticipated, reducing $\gamma$ offers the possibility of modest gains, of the order of 10%.

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

Several factors could affect the accuracy of $P_{\text{max}}$, even in the context of a simplified one-dimensional model. The high value $\varepsilon_{\text{tg}}=0.85$ for turbogenerator efficiency could be an overestimate by 0.1. Also, it could be argued that the heat exchanger pinch points $T_{\text{pinch}}$ should be nearly constant rather than proportional to $\Delta T$ as shown in Fig. 2; this would be equivalent to substituting $(\Delta T/2-2T_{\text{pinch}})$ for $3\Delta T/8$ in Eq. (1). Repeating the steady-state calculations with $\varepsilon_{\text{tg}}=0.75$ and $T_{\text{pinch}}=1.25^\circ \text{C}$, $P_{\text{max}}$ drops to 3.9 TW for $\gamma=1.7$ and a deep seawater flow rate per unit area of 4.5 m/yr ($\tau_{\text{m}}=9.9$ 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 $\Delta T_{\text{design}}>18^\circ \text{C}$ 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, $P_{\text{max}}$ could be about 20% higher. It may therefore be concluded that standard conditions ($A_{\text{OTEC}}=100$ million km$^2$, $\Delta T_{\text{design}}=20^\circ \text{C}$, $T_{\text{design}}=25^\circ \text{C}$) 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 $P_{\text{max}}$ is considerable, however, on the basis of this one-dimensional analysis. Figure 4, (also Fig. 3 in Ref. [12]) compares the base line unperturbed temperature profile $\theta(0,z)$ and the steady-state solution $\theta(\infty,z)$ for $Q_{\text{cw}}/A_{\text{OTEC}}=3.75$ m/yr and $\gamma=2$ ($\tau_{\text{m}}=10$ 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 $F_{\text{in}}$ the overall heat flux into the water column, energy conservation implies that at all times, we have

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

It can be checked that $F_{\text{in}}$ 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

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

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

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

$$-h_m(T-T_0) \tag{11}$$

When $t$ tends to infinity, the second term in the right-hand side vanishes. Equation (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 $A_{\text{OTEC}}$, $\Delta T_{\text{design}}$, $T_{\text{design}}$, etc. The OTEC flow rate ratio was held constant ($\gamma=2$). 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 \( \Delta T = \Delta T_{\text{design}} \) and \( T = T_{\text{design}} \).

The deep ocean was partitioned into three regions where a given partial differential equation applies, i.e., Eqs. (3) and (7) or (8). Each region was spatially discretized so that the determination of \( \theta(t, z) \) was reduced to the solution of a set of first-order ordinary differential equations (ODEs) for the time-dependent temperatures at all spatial nodes excluding boundaries. Boundary values were obtained from the continuity and flux conditions discussed in Sec. 2.2, except for the mixed-layer temperature \( T \) which satisfies an additional ODE, Eq. (9). Upwind differencing for the first-order space derivatives (advective terms) and center differencing for the second-order space derivatives (diffusive terms) were selected. The complete set of ODEs was solved with a fourth order Runge–Kutta scheme from the initial conditions Eq. (6) and \( T=T_0 \). To test convergence and accuracy, the instantaneous OTEC scenario corresponding to the steady-state water-column temperature profile in Fig. 4 \( (t_n=10 \text{ years}) \) was adopted as a benchmark. Convergence is controlled by diffusion in the deep-ocean equations, with the approximate condition \( 2Kd^2/(dz)^2 < 1 \). With 1164 variables in the deepest ocean layer of thickness 3075 m, 272 variables in the intermediate layer of thickness 747 m, and 60 variables in the upper deep-ocean region of thickness 178 m, a vertical deep-ocean grid mesh \( dz \) of less than 3 m was obtained. Accurate convergent results were secured with a time step \( dt \) of just over half a day (640 steps per year). The complete numerical solution for a simulated time of 1000 years took about 2.5 minutes on a desktop computer (1.7 GHz processor).

Figure 5 shows the predicted time history of the mixed layer temperature for the benchmark “\( t_n=10 \text{ years} \)” scenario. As anticipated from Eq. (11), the mixed layer would experience 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 (0.15%). Figure 6 displays the corresponding evolution of the deep-seawater withdrawal temperature \( \theta_{cw} = \theta(t, z_{cw}) \). \( \theta_{cw} \) increases steadily before leveling off. The combined initial drop in \( T \) and rise in \( \theta_{cw} \) would sharply reduce the available OTEC temperature difference and, therefore, net power production.

While net radiative processes ultimately bring the mixed-layer temperature back to \( T_0 \), the warming of the deep ocean and a corresponding decline in OTEC resources are permanent.

Before examining the more realistic “gradual” OTEC scenarios, attempts were made to derive simple relationships for the initial rates of change \( dT/dt \) and \( d\theta_{cw}/dt \) when OTEC operations start abruptly. Just before OTEC flows are stepped up at \( t=0 \), the ocean water column is in equilibrium with \( \theta(0, z) \) given by Eq. (6). For small enough positive times, it seems intuitive that \( \theta \) should remain close to \( \theta(0, z) \). Using this heuristic argument, Eqs. (3), (7), and (8), would be approximated as follow in their respective domains.

\[
\frac{\partial \theta}{\partial t} \approx 0 \tag{12}
\]

\[
\frac{\partial \theta}{\partial t} \approx \frac{Q_{cw}}{A_{OTEC}} \frac{\partial \theta}{\partial z} = \frac{Q_{cw w}}{A_{OTEC} K} (\theta(0, z) - T_p) \tag{13}
\]

\[
\frac{\partial \theta}{\partial t} \approx - \frac{Q_{cw}}{A_{OTEC}} \frac{\partial \theta}{\partial z} \approx - \frac{Q_{cw w}}{A_{OTEC} K} (\theta(0, z) - T_p) \tag{14}
\]

Equation (13) indicates that warming would take place in the region \( z_{cw} > z > z_{mix} \) while Eq. (14) suggests a cooling trend from \( z_{mix} \) to the mixed layer. These effects are produced by the modification of advective heat fluxes from OTEC-induced vertical operations (standard conditions and deep seawater flow rate per unit area of 3.75 m/yr)
flows. Eqs. (12) and (13) apply to either side of the deep seawater withdrawal depth \( z = z_{cw} \). Averaging both rates of change yields

\[
\frac{d\theta_{cw}}{dt} = \frac{Q_{cw}}{2A_{OTEK}}(\theta_{cw}(0) - T_p)
\]

(15)

With this approximation, an initial rate of change of 0.016°C per year is obtained for the conditions corresponding to Fig. 6. This is slightly less than the calculated value (0.018°C). Because of the shape of the curve \( \theta_{cw}(t) \), however, the mean rate of change \( \{\theta_{cw}(t) - \theta_{cw}(0)\}/t \) over a hundred years of OTEC operations turns out to be 0.016°C per year.

The simple approach outlined to derive Eq. (15) fails in the case of \( dT/dt \). If accurate all the way to \( z = L \), Eq. (14) would correspond to a decrease in the heat flux \( K\partial\theta/\partial z \) out of the mixed layer and, therefore, to a warming of the mixed layer. Temperature continuity at \( z = L \), then, would break down. A close examination of numerical results reveals that just below the mixed layer, the diffusive term \( K\partial\theta/\partial z \) cannot be neglected from Eq. (8) so that Eq. (14) is incorrect. While cooling takes place in the upper ocean, the temperature profile “bends” in the vicinity of the mixed layer and with this higher curvature, the diffusive flux \( K\partial\theta/\partial z(L) \) actually increases.

More realistic gradual OTEC scenarios were considered last. Results are displayed in Fig. 8. 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 re-
source. 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 Conclusions

A straightforward one-dimensional analysis has showed that theoretically, worldwide power resources that could be extracted from the operation of 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

![Graph showing time histories of OTEC net power](image1)

Fig. 7 Time histories of OTEC net power (at standard conditions) for selected cases of large-scale OTEC operations initiated at t=0

![Graph showing time histories of OTEC net power](image2)

Fig. 8 Time histories of OTEC net power (at standard conditions) for selected cases of gradually implemented large-scale OTEC operations
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

\[
\begin{align*}
A_{\text{OTE}} & = \text{overall oceanic surface area (m}^2) \\
A_{\text{OTEC}} & = \text{oceanic surface area for practical OTEC power production (m}^2) \\
\epsilon_p & = \text{specific heat of seawater (J/kg K)} \\
K & = \text{vertical eddy diffusion coefficient (m}^2/\text{s}) \\
L & = \text{water-column thickness below mixed layer (m)} \\
P_{\text{g}} & = \text{OTE} \text{C gross power (W)} \\
P_{\text{max}} & = \text{estimated maximum steady-state OTEC net power (W)} \\
P_{\text{net}} & = \text{OTE} \text{C net power (W)} \\
Q_{\text{cw}} & = \text{OTE} \text{C cold deep seawater volume flow rate (m}^3/\text{s}) \\
Q_{\text{ww}} & = \text{OTE} \text{C warm surface seawater volume flow rate (m}^3/\text{s}) \\
T & = \text{surface (mixed-layer) seawater temperature (°C)} \\
T_{\text{design}} & = \text{design surface (mixed-layer) seawater temperature (°C)} \\
T_0 & = \text{initial surface (mixed-layer) seawater temperature (°C)} \\
T_p & = \text{polar seawater temperature (°C)} \\
w & = \text{upward advection (upwelling) rate (m/s)} \\
z & = \text{vertical water-column coordinate (m)} \\
z_{\text{cw}} & = \text{vertical coordinate of OTEC deep seawater withdrawal (m)} \\
z_{\text{mix}} & = \text{vertical coordinate of OTEC mixed effluent discharge (m)} \\
\theta_{\text{m}} & = \text{turbogenerator efficiency} \\
\rho & = \text{seawater density (kg/m}^3) \\
\theta & = \text{water-column temperature (°C)} \\
\theta_{\text{cw}} & = \text{temperature of OTEC deep seawater withdrawal (°C)} \\
\tau & = \text{characteristic mixed-layer radiative cooling time (s)} \\
\tau_{\text{mix}} & = \text{OTE} \text{C mixed layer utilization time (s)}
\end{align*}
\]

References


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