Ocean Thermal Energy Conversion (OTEC): Electricity and Desalinated Water Production

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Puerto Rico Ocean Thermal Resource: Truisms

• OTEC plants **could supply** all the electricity and potable water consumed in Puerto Rico, {but at what cost?}

• Only **indigenous renewable energy resource** that can provide a high degree of energy security to the State and in addition minimize green house gas emissions;
Generalities
Visionary Perspective: Don Quijote de la Mancha

On annual basis:

• Solar energy absorbed by oceans is $\approx 4000 \times$ human consumption;

• < 1 % Extraction would satisfy all.

[OTECC: thermal $\rightarrow$ electric conversion $\approx 3 \%$]
Engineering Perspective: Sancho Panza

- Ocean's vertical temperature distribution?
  heat source and heat sink required to operate heat engine

i.e., two layers with $\Delta T \approx 22 \, ^{\circ}\text{C}$ in equatorial waters...
The Concept
OTEC Concept

Ocean Thermal Resource (fuel) ?

- Cold Water: @1000 m depth
  4 °C to 5 °C

- Warm Water: Tropical seas at “surface”
  24 °C to 30 °C
Open Cycle OTEC

Surface seawater is flash-evaporated in a vacuum chamber. The resulting low-pressure steam is used to drive a turbine-generator. Cold seawater is used to condense the steam after it has passed through the turbine. The open-cycle can, therefore, be configured to also produce fresh water:
Closed Cycle OTEC

Warm surface seawater and cold deep seawater are used to vaporize and condense a working fluid, such as ammonia, which drives a turbine-generator in a closed loop producing electricity.
# Thermal Resource

Temperature Difference between Surface Water and 1,000 m Water (want > 20 °C):

<table>
<thead>
<tr>
<th>Color</th>
<th>Temperature Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yellow</td>
<td>18 to 20 °C</td>
</tr>
<tr>
<td>Orange</td>
<td>20 to 22 °C</td>
</tr>
<tr>
<td>Red</td>
<td>22 to 24 °C</td>
</tr>
</tbody>
</table>
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• Technology & Lessons Learned
• Economics & COE ($/kWh)
• Commercialization
• AC/Energy Carriers/Externalities
• Conclusions
• Annex: Small Plants
What is known about OTEC Technology?

• *Continuous* production of electricity and desalinated water has been demonstrated with experimental plants:
MiniOTEC (1979)
50 kW CC-OTEC
Nauru (1982)

100 kW CC-OTEC
50 kW CC-OTEC (NH$_3$) Test Apparatus
210 kW OC-OTEC Experimental Plant

OTEC-Vega

(Vega: 1993-1998)
Desalinated Water Production (Vega:’94-’98)
OTEC Power Output as Function of Control Parameters

- **Open Cycle Control Parameters:** Seawater Mass Flow Rates; **Seawater Temperatures** & Vacuum Compressor Inlet Pressure
- **Closed Cycle Control Parameters:** Seawater Mass Flow Rates; **Seawater Temperatures**; NH$_3$ Mass Flow Rate & Recirculation/Feed Flow Ratio
Power Output as a Function of Cold Water Temperature

Time (September 8, 1993)

Seawater Temperature (670 m), deg C

OC-OTEC Gross Power Output, kW
OC-OPEC Power Output vs Cold Water Temperature

1-minute Averages of 1-sec samples show:

Cold Seawater Temperature Oscillation as Signature of Internal Waves

(λ ~ 3,500 m; P ~ 60 minutes; H ~ 50 m)
OC-OTEC Power Output as a Function of Warm Water Temperature

![Graph showing OC-OTEC power output as a function of warm water temperature. The x-axis represents time on July 21, 1993, and the y-axis represents sawater temperature (20 m) in degrees Celsius. The graph also shows gross power output in kW, with variations over time.](image-url)
OC-OTEC Power Output vs Warm Water Temperature

1-minute Averages of 1-sec samples show:

Surface Seawater Temperature Variation as Signature of Warmer Water Intrusion driven by Ocean Gyre shed from Alenuihaha Channel between Maui and Hawaii (Big Island)
5 MW Pre-Commercial Plant
OTEC Plant Crew

• 20-people Staff for 24/7 Operations:

  **Minimal:**
  - Technicians: 12 (covers all shifts)
  - Engineering & Admin: 5

  ? Independent of Plant Size
Lessons Learned

- Life-Cycle Design
- Constructability
- System Integration
Lessons Learned

Life-Cycle Design

e.g., locating a component in the water column might yield higher efficiencies but result in elaborate maintenance requirements and higher operational costs
Lessons Learned

Constructability

Can equipment be manufactured using commercially available practices and in existing factories?
Lessons Learned

System Integration

In addition to power block (HXs & T-G), OTEC includes seawater subsystems; dynamic positioning subsystems; and, submarine power cable.
What is known about OTEC Economics?

- Economically competitive under certain “scenarios” (defined by fuel-and-water-costs) 

OTEC-Vega 34
Cost of Electricity Production

\[ \text{COE ($/kWh)} = \text{CC} + \text{OMR&R} + \text{Profit} \]
\[ + \text{Fuel (for OTEC zero)} \]
\[ - \text{Environmental Credit} \]

\[ \text{CC} = \text{Capital Cost Amortization} \]
\[ \text{(N.B. much higher for OTEC)} \]

\[ \text{OMR&R} = \text{Operations} + \text{Maintenance} \]
\[ + \text{Repair} + \text{Replacement} \]

\[ \text{Tariff} = \text{COE} - \text{Subsidy} \]
OTEC Capital Cost Estimates

- Land-Based Upper Limit
- Land-Based Lower Limit
- Plantship

MW-net

$/kW

1990 $
Please Beware!!

Economy of Scale 10 vs. 100 MW?

- Power Block Cost of 100 MW plant is \( \sim 10 \times 10 \) MW
- Seawater Subsystems & At-Sea Deployment of 100 MW is \(< 10 \times 10\) MW
- Staffing requirements constant
  \[ 100 \text{ MW} = 10 \text{ MW} \]
OTEC Capital Cost: Plant Size Dependency

Structure  Seawater  HXs  T-G  Other

10 MW  100 MW
<table>
<thead>
<tr>
<th>Nominal Size, MW</th>
<th>TYPE (After Eng. Dev.)</th>
<th>Scenario (by ~ 10th Plant)</th>
<th>Potential Sites</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Land-Based OC-OTEC with 2nd Stage for Additional Water Production.</td>
<td>Diesel: $45/barrel, Water: $1.6/m³</td>
<td>Present Situation in Some Small Island States.</td>
</tr>
<tr>
<td>10</td>
<td>Same as Above.</td>
<td>Fuel Oil: $30/barrel, Water: $0.9/m³</td>
<td>U.S. Pacific Insular Areas and other Island Nations.</td>
</tr>
<tr>
<td>50</td>
<td>Land-Based Hybrid CC-OTEC with 2nd Stage.</td>
<td>$50/barrel, $0.4/m³ or $30/barrel, $0.8/m³</td>
<td>Hawaii, Puerto Rico If fuel or water cost doubles.</td>
</tr>
<tr>
<td>50</td>
<td>Land-Based CC-OTEC</td>
<td>$40/barrel</td>
<td>Same as Above.</td>
</tr>
<tr>
<td>100</td>
<td>CC-OTEC Plantship</td>
<td>$20/barrel</td>
<td>Numerous sites</td>
</tr>
</tbody>
</table>

Fuel and Water Costs Required for Competitiveness (1990)
## Cost of Electricity Production

<table>
<thead>
<tr>
<th>Offshore Distance, km</th>
<th>Capital Cost, $/kW 10th Plant</th>
<th>COE, $/kWh 10%/20-years</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>4,200</td>
<td>0.07</td>
</tr>
<tr>
<td>50</td>
<td>5,000</td>
<td>0.08</td>
</tr>
<tr>
<td>100</td>
<td>6,000</td>
<td>0.10</td>
</tr>
<tr>
<td>200</td>
<td>8,100</td>
<td>0.13</td>
</tr>
<tr>
<td>300</td>
<td>10,200</td>
<td>0.17</td>
</tr>
<tr>
<td>400</td>
<td>12,300</td>
<td>0.22</td>
</tr>
</tbody>
</table>

**2nd Generation 100 MW CC-OTEC**

*(1992 Analysis/Projection)*
Updated Assessment (’07)

- For example, Avoided Energy Cost in Hawaii ~ 0.20 $/kWh \([\text{was } < 0.06 \text{ $/kWh in 90’s}]\)

- Petroleum resources (IEA, API, USGS) available to meet world demand for the next 30-50 years; however, diminishing resources? price increases

- This situation justifies re-evaluating OTEC for the production of electricity
Global Oil Resources

• Consumption (IEA, API): \( \sim 80 \text{ MBPD} \) (million barrels per day)
  By 2030 \( \sim 1.5 \times \);

• Resource (IEA, USGS, API):
  \( \sim 1.4 \text{ Trillion BBLs} \) (others say 1 to 3)
  e.g., Saudi Arabia “claimed and claims”
  265 Billion BBLs (presently produces 11 MBPD)

• 70% of Barrel used transporting people and goods
Global Oil Resources

• Consensus:
  - 30 to 50 years until oil gone
  - Diminishing resources? Price Increases

• Presently, $H_2$ produced with OTEC electricity is equivalent to $\sim 8 \times$ price of oil

? Would it be wise to begin to consider $H_2$ production onboard OTEC plantships deployed along Equator?
OTEC Commercialization?

Pro:
• Less environmental impact than conventional power plants;
• As long as the sun heats the oceans, the fuel for OTEC is unlimited and free.

Con:
• No operational record with large size plant
What Next for OTEC?

Realistic Financing

Based on detailed cost estimates not wishful dreaming
Punta Tunas

• 1,000 m Depth 3,000 m Offshore
• Surface Water Temperature: 27.7 ± 1.7 °C
• Deep Ocean (1,000 m) Water: 5.4 ± 0.3 °C
• Design for ΔT : 22 °C (27.5/5.5)
m: mass flowrate of NH₃, kg/s
( ): state points

OTEC Process Flow Diagram
### OTEC Capital Cost: 75 to 100 MW

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floating Vessel</td>
<td>25%</td>
</tr>
<tr>
<td>Mooring</td>
<td>4%</td>
</tr>
<tr>
<td>Submarine Power Cable</td>
<td>7% (10 km)</td>
</tr>
<tr>
<td>Seawater Pipes &amp; Pumps</td>
<td>17%</td>
</tr>
<tr>
<td>Turbine-Generator</td>
<td>8%</td>
</tr>
<tr>
<td>Heat Exchangers</td>
<td>24%</td>
</tr>
<tr>
<td>All Controls (electrical/NH₃/Cl₂)</td>
<td>8%</td>
</tr>
<tr>
<td>Install Mech/Electr</td>
<td>7%</td>
</tr>
</tbody>
</table>
75 MW OTEC
(10 km offshore)
### Electricity Cost ($/kWh): 75 MW

<table>
<thead>
<tr>
<th></th>
<th>1st Generation</th>
<th>1st Generation</th>
<th>Later Generations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Financing:</strong></td>
<td>7.75%/10-years</td>
<td>idem/15-years</td>
<td>idem/10-years</td>
</tr>
<tr>
<td><strong>CC:</strong></td>
<td>0.144</td>
<td>0.112</td>
<td>0.101</td>
</tr>
<tr>
<td><strong>OMR&amp;R:</strong></td>
<td>0.023</td>
<td>0.024</td>
<td>0.023</td>
</tr>
<tr>
<td></td>
<td>(3% Annual Inflation)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total:</strong></td>
<td>0.166</td>
<td>0.136</td>
<td>0.123</td>
</tr>
<tr>
<td><strong>“Avoided” Cost Equivalent:</strong></td>
<td>70 $/bbl [accounting for capital cost but no tax credit]</td>
<td>55 $/bbl</td>
<td>42 $/bbl</td>
</tr>
</tbody>
</table>
Commercialization (Puerto Rico)

- Puerto Rico could use OTEC to Generate 100% of Electricity Presently Consumed;

- Commercial-size ≈ 75-100 MW floater - C.O.E competitive with ~ $60 per barrel Oil fired Generators. Later units competitive with ~$40 barrel
Development Barriers
(Puerto Rico)

Cost Issues: Cost Effective for Size
≈ 75 - 100 MW

Tech. Issues: Would be 1st Generation
Commercial Size Plant

Enviro. Issues: Relatively Minimal

Political Issues: Need broad based
bi-partisan support
Other Applications: AC

Cold deep water as the chiller fluid in air conditioning (AC) systems: load can be met using 1/10 of the energy required for conventional systems and with an investment payback period estimated at 3 to 4 years.
Energy Carriers

OTEC energy could be transported via electrical, chemical, thermal and electrochemical carriers:

Presently, all yield costs higher than those estimated for the submarine power cable (< 400 km offshore).
EXTERNALITIES

• What are external costs of energy production and consumption?

• In USA equivalent to adding $85 to $327 to oil barrel

• USA to safeguard overseas oil supplies → add ~ $23 to barrel (before Iraq)
Final Thoughts:

Accounting for externalities will facilitate development and expand applicability of OTEC;

Presently, can use OTEC plantships to transmit the electricity (and water) to land via submarine power cables (and flexible pipelines).
Annex
US Navy Small Island Installations

- Kwajalein Atoll (Marshall Islands) Current (May’05-June’06)
  - ~ 10 MW Capacity (diesel gensets)
  - COE ($/kWh) : \([0.16 + 0.05] = 0.21\) [fuel + OMR&R]

10 MW OTEC
- Levelized COE ~ 0.30 $/kWh
US Navy Small Island Installations

- Situation similar in Diego Garcia (Indian Ocean Island)

- USN willing to issue Power-Purchase-Agreement if COE reduced by at least 10% (~ 0.9 x 0.21 = 0.19 $/kWh)

- **Can not do** with ~ 10 MW OTEC