OTC 21016

Economics of Ocean Thermal Energy Conversion (OTEC): An Update

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Abstract

Worldwide information indicates that although there are sufficient petroleum resources to meet demand for about 50 years, production is peaking and we will face a steadily diminishing petroleum supply. This situation justifies re-evaluating OTEC for the production of electricity, desalinated water and energy intensive products. It is postulated that the US should begin to implement the first generation of OTEC plantships providing electricity, via submarine power cables, to shore stations, followed, in about 20 years, with OTEC factories deployed along equatorial waters producing, for example, ammonia and hydrogen as the fuels that would support the post-petroleum era.

Historical estimates of investment and operational costs associated with preliminary designs of OTEC plants are summarized along with current information. These are used to estimate the cost of electricity production and assess site specific cost effectiveness. It is determined that, for example, 50 to 100 MW OTEC plants could produce cost effective electricity in Hawai'i. In the absence of operational records, however, financing for such plants remains a daunting challenge. A pre-commercial plant, representing a scaled version of the 50 to 100 MW plants, must be deployed and operated to obtain the necessary records. This pre-commercial plant would not produce cost competitive electricity and, therefore, should be government funded.

Introduction: Previous Work

An analytical model is available to assess scenarios under which OTEC might be competitive with conventional technologies (Vega, 1992). First, the capital cost for OTEC plants, expressed in $/kW, is estimated. Subsequently, the relative cost of producing electricity ($/kWh) with OTEC, offset by the desalinated water production revenue, is equated to the fuel cost of electricity produced with conventional techniques[1] to determine the scenarios (*i.e., fuel cost and cost of fresh water production*) under which OTEC could be competitive. For each scenario, the cost of desalinated water produced from seawater via reverse osmosis (RO) is estimated to set the upper limit of the OTEC water production credit. No attempt is made at speculating about the future cost of fossil fuels. It is simply stated that if a location is represented by one of the scenarios, OTEC could be competitive.

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

Floating plants of at least 50 MW capacity would be required for the industrialized nations. These would be moored or dynamically positioned a few kilometers from land, transmitting the electricity to shore via submarine power cables. The moored vessel could also house an OC- OTEC plant and transport the desalinated water produced via flexible pipes. It was noted that the State of Hawai'i could be independent; of conventional fuels for the production of electricity, using 50 MW to

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[1] The methodologies used to estimate the fossil-fuel costs component of both electricity and RO-desalinated-water production are summarized in the Appendix.

100 MW floating plants for the larger communities in Oahu, Kauai, Maui and the Island of Hawaii.

The 1992 report also provided estimates for land-based 1 MW open cycle plants with and without second-stage desalinated water production as well as a plant with a system including the use of 90 kg/s of 6°C cold seawater as the chiller fluid for a standard air-conditioning unit supporting a 300 ton load (~300 rooms). These plants would be designed utilizing the state-of-the-art, bottom-mounted cold water pipe technology (Nihous et al, 1989). The report also included cost estimates for other plants ranging from 10 to 100 MW. These have been extrapolated to present day costs and included in Table 2 below.

It was also established that OTEC–based, mariculture operations and air-conditioning systems could only make use of a small amount of the seawater available; and therefore, could only impact small plants. The use of energy carriers (e.g.: Hydrogen, Ammonia) to transport OTEC energy generated in floating plants, drifting in tropical waters away from land, was determined to be technically feasible but requiring increases in the cost of fossil fuels of at least an order of magnitude (to about $400/barrel) to be cost effective.

Presently, the external costs of energy production and consumption are not included in the determination of the charges to the consumer. Considering all stages of generation, from initial fuel extraction to plant decommissioning, it has been determined that no energy technology is completely environmentally benign. The net social costs of the different methods of energy production continue to be a topic under study. Estimates of costs due to: corrosion, health impacts, crop losses, radioactive waste, military expenditures, employment loss, subsidies (tax credits and research funding for present technologies) are found in the literature. The range of all estimates is equivalent to adding from $80/barrel to over $400/barrel. Accounting for these externalities might eventually help the development and expand the applicability of OTEC, but in the interim the scenarios that were identified in the original 1992 report should be considered again.

Industry did not take advantage of the information because in the 1990's the prices of oil fuels and coal were such that conventional power plants produced cost-effective electricity (excluding externalities). Moreover, the power industry could only invest in power plants whose designs were based on similar plants with an operational record. It was concluded that before OTEC could be commercialized, a prototypical plant must be built and operated to obtain the information required to design commercial systems and to gain the confidence of the financial community and industry. Conventional power plants pollute the environment more than an OTEC plant would and the fuel for OTEC is vast and free, as long as the sun heats the oceans; however, it is futile to use these arguments to convince the financial community to invest in an OTEC plant without operational records.

Site Selection Criteria for OTEC Plants

The search for marine renewable energy resources has resulted in OTEC's second revival. As it is well know the concept utilizes the differences in temperature, ΔT, between the warm ($T_W \sim 22$ °C to 29 °C) tropical surface waters, and the cold ($T_C \sim 4$ °C to 5 °C) deep ocean waters available at depths of about 1,000 m, as the source of the thermal energy required. There are two approaches one referred to as "closed cycle" and the other as "open cycle." In the closed cycle, seawater is used to vaporize and condense a working fluid, such as ammonia, which drives a turbine-generator in a closed loop, producing electricity. In the open cycle, surface water 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 produce fresh water as well as electricity (Vega, 2003).

The historical monthly averages of ΔT for February and August are depicted in Figures 1 and 2 respectively. Values are color coded as indicated in the right-hand-side of the Figures. The values were obtained by Prof. Gerard Nihous of the University of Hawai'i from the National Ocean Data Center's World Ocean Atlas (Nihous, 2010). Deep seawater flows from the Polar Regions. These polar water, which represents up to 60% of all seawater, originates mainly from the Arctic for the Atlantic and North Pacific Oceans, and from the Antarctic (Weddell Sea) for all other major oceans. Therefore, T_C at a given depth, approximately below 500 m, does not vary much throughout all regions of interest for OTEC. It is also a weak function of depth, with a typical gradient of 1°C per 150 m between 500 m and 1000 m. These considerations may lead to regard T_C as nearly constant, with a value of 4°C to 5°C at 1000 m.

A desirable OTEC thermal resource of at least 20°C requires typical values of T_W of the order of 25°C. Globally speaking, regions between latitudes 20°N and 20°S are adequate. Some definite exceptions exist due to strong cold currents: along the West Coast of South America, tropical coastal water temperatures remain below 20°C, and are often of the order of 15°C; a similar situation prevails to a lesser extent for the West Coast of Southern Africa. Moreover, T_W varies throughout the year, and sometimes exhibits a significant seasonal drop due to the upwelling of deeper water induced by the action of the wind: such are the cases of the West Coast of Northern Africa in the winter (Figure 2). A careful OTEC site selection requires a comprehensive knowledge of local climate features inasmuch as they may affect T_W seasonally.

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

- Equatorial waters, defined as lying between 10°N and 10°S are adequate except for the West Coasts of South America and Southern Africa;

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

The accessibility of deep cold seawater represents the most important physical criterion for OTEC site selection, once the existence of an adequate thermal resource has been established. In the case of a floating plant, the issue of cold seawater accessibility is only relevant inasmuch as submarine power cables, and, maybe, a desalinated water hose, are needed to transfer the OTEC products to shore. For the grazing plantship, with energy intensive products like hydrogen or ammonia as the product, the distance is important from the perspective of the transit time for the vessels that would transport the product to shore.

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

Another important point to consider is the preservation of the environment in the area of the selected site, inasmuch as preservation of the environment anywhere is bound to have positive effects elsewhere. OTEC definitely offers one of the most benign power production technology, since the handling of hazardous substances is limited to the working fluid (e.g.: ammonia), and no noxious by-products are generated; OTEC merely requires the pumping and return of various seawater masses, which, according to preliminary studies, can be accomplished with virtually no adverse impact. This argument should be very attractive, for pristine island ecosystems, as well as for already polluted and overburdened environments. For example, the amount of CO_2 released from electricity-producing plants (expressed in gr of CO_2 per kWh) ranges from 1000, for coal fired plants, to 700, for fuel-oil plants, while for OC-OTEC plants it is at most $\sim 1\ \%$ of the amount released by fuel oil plants. The value is much lower in the case of a CC-OTEC plant.

Ninety-eight nations and territories with access to the OTEC thermal resource within their 200 nautical mile exclusive economic zone (EEZ) were identified in the 1980's. A partial list is provided in Table 1. For the majority of these locations, the OTEC resource is applicable only to floating plants. Unfortunately, now as then, there is no OTEC plant with an operational record available. This still remains the impediment to OTEC commercialization.

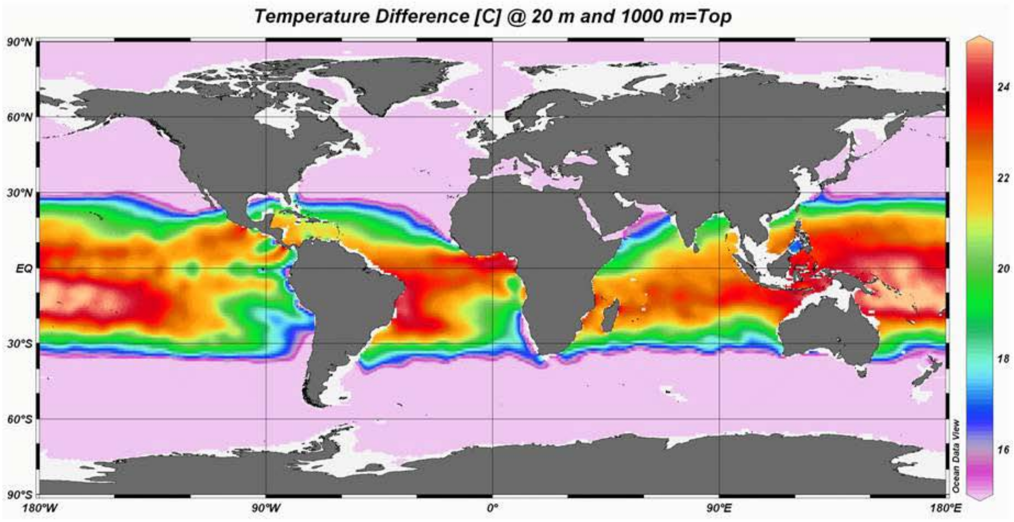

Figure 1.- Historical Monthly average of ΔT during February (Nihous, 2010)

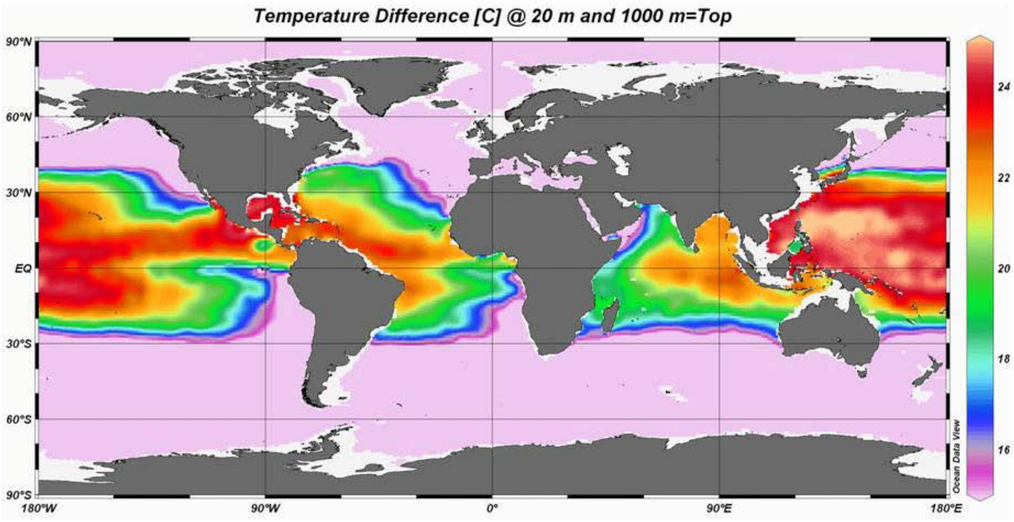

Figure 2.- Historical Monthly average of ΔT during August (Nihous, 2010).

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

Table 1.- List of Nations with Appropriate Ocean Thermal Resource within their 200 nautical miles Exclusive Economic Zone (Vega, 1992).

OTEC Capital Costs

Capital cost archival information, documented in *Economics of Ocean Thermal Energy Conversion* in 1992, was converted to present day costs using the USA 20-year average for equipment price-index inflation. In addition, current technical specifications for 10, 50 and 100 MW OTEC plants were used by the author to solicit budgetary quotes. All estimates are summarized in Table 2 and in Figure 3.

Nominal Plant Size, MW-net	Installed Capital Cost, $/kW	Land/Floater	Source(Extrapolated)
1.4	41562	L	*Vega 1992*
5	22812	L	*Jim Wenzel, 1995*
5.3	35237	F	*Vega et al 1994*
10	24071	L	*Vega 1992*
10	18600	F	This report
35	12000	F	"
50	11072	F	*Vega 1992*
53.5	8430	F	This report
100	7900	F	"

Table 2.- First Generation OTEC Plant Capital Cost Estimates: (i) Extrapolated Archival Estimates (1 – 50 MW) and Current Estimates (10- 100 MW) in $/kW-net.

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

With more detailed equipment information, the first generation design can be optimized and likely lead to lower capital costs. However, some potential suppliers of key components have been reluctant to provide the detailed information needed to optimize the design. This is because, in the past, their OTEC work did not yield a single order (excluding the experimental plants), mainly because there were no real customers for the technology. This situation will change if, for example, the USA Federal Government gets involved as outlined in the Conclusions Section (e.g., see Table 7).

Figure 3 illustrates that OTEC capital cost ($/kW) is a strong function of plant size (MW). For convenience and future reference a least-squares curve fit is provided:

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

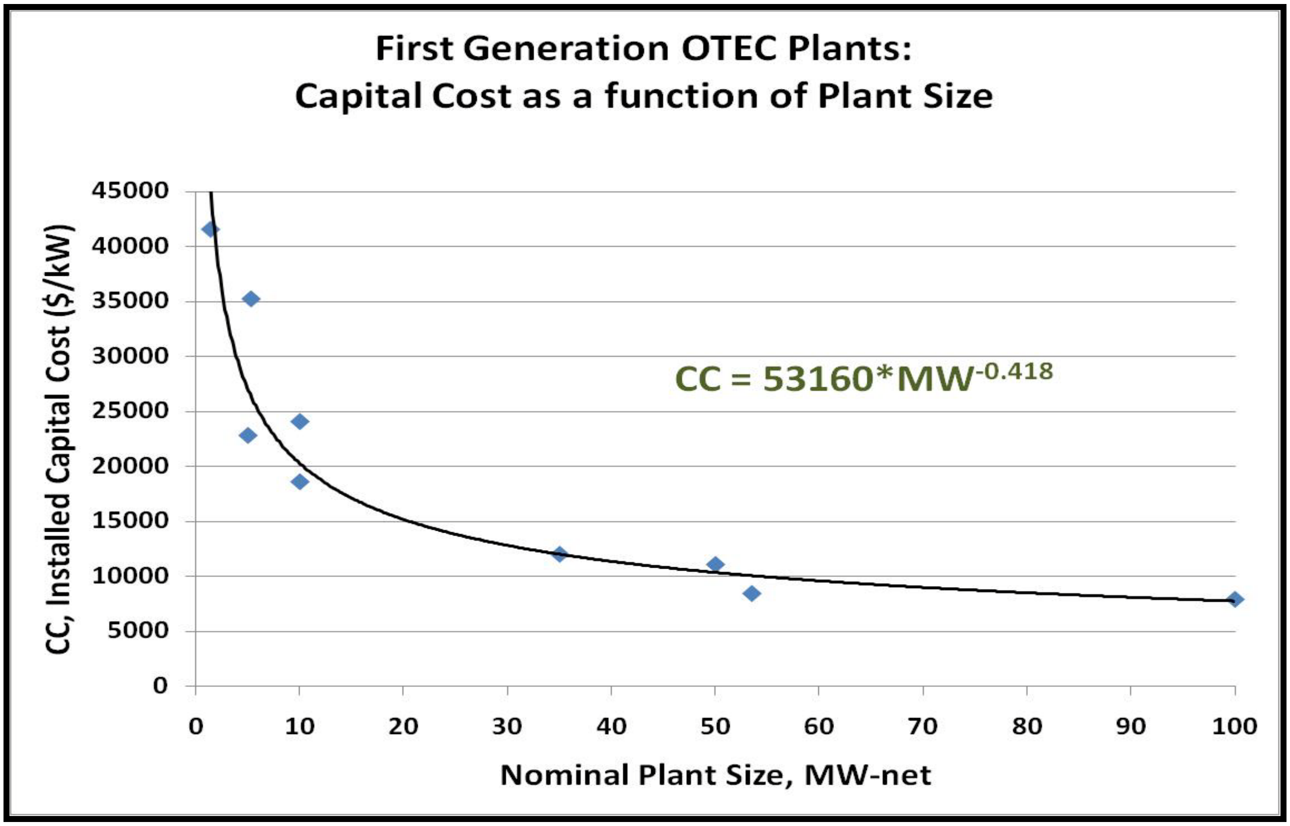

Figure 3.- Capital Cost Estimated for First Generation OTEC Plants.

Capital Cost: 50 MW OTEC Plantship

Designs for 50 MW OTEC first generation plants utilizing either closed cycle (CC) or open cycle (OC) technology are presented in a separate paper at this conference (OTC # 20957). The capital costs estimated for these plants are summarized in Table 3. The estimate for the CC-OTEC plant is $451M and for the OC-OTEC plant $551M. The CC-OTEC plant would require a 198 m long ship-shaped platform with 39 m beam and an operating draft of 16 m resulting in 120,600 tonne (metric ton) displacement. The OC-OTEC plant would be shorter at 176 m but beamer at 90 m resulting in a displacement of 247,400 tonnes.

The plantship required for the CC-OTEC system is comparable to typical double-hulled vessels and could be constructed in numerous shipyards throughout the world. The OC-OTEC system, incorporating desalinated water production, requires a vessel that is about three times wider (beam direction) than the standard tanker and container ships and might limit the number of shipyards with appropriate fabrication capabilities.

The combined needs for large amounts of cold seawater (138.6 m^3/s), and minimal pumping power losses result in a relatively large diameter CWP. A 1,000 m long 8.7 m i.d. fiber-reinforced-plastic (FRP) sandwich construction CWP is selected. This will be attached to a gimbal at midship. Applicable single point mooring systems, including electrical and fluid swivels, are available from the offshore industry. The Aluminum plate-fin heat exchangers considered for the ammonia cycle can be manufactured in the USA. The electricity is transmitted to shore via a submarine power cable and the desalinated water via a flexible pipe (e.g., hose). Several firms manufacture the submarine power cable required for the OTEC plant.

	Closed Cycle				
Size:	53.5 MW-net				
Date:	Feb 2009				
Component	**$M**	**$/kW**	**Percentage**	**Ops 1st Year ($M)**	**Replacement 1st Year ($M)**
Floating Vessel	100	1869	22%		3.3
Mooring	24	449	5%		0.8
Submarine Power Cable (10 km)	41	766	9%		1.4
Seawater Pipes Installed	60	1121	13%		2.0
Seawater Pumps Installed	24	449	5%		1.6
Power Block (15 MW-gross Modules)					
Heat Exchangers	95	1776	21%		6.3
Turbine-Generator	33	617	7%		2.2
Electrical/NH3/Cl2/Controls	31	579	7%		1.0
Installation Mechanical & Electrical	43	804	10%		1.4
All Components Total:	**451**	**8430**	100%	**3.4**	**20.1**
					15-year 30-year

Notes:

Capital Cost

* Vega's archival information for USA/Japan/EU Manufacturers.

* At Conceptual Level the CC for Open Cycle will double cost of Floating Vessel.

* Assume the sum of all other cost are equivalent to Closed Cycle. Therefore,
the CC for the Open Cycle Plant is $ 551M

Operations, Maintenance, Repair and Replacement (OMR&R)

* A total staff of 17 is required to manage and operate floating plant in shifts 24/7

Using USA Labor Rates the O&M portion for the first year is $ 3.4M (for both OC-OTEC and CC-OTEC)

* To estimate the R&R portion for the first year: Pumps, HXs and T-G replaced in 15-years
all other components in 30-years.

First year estimate for R&R portion is (as given in Table) $ 20.1M for CC-OTEC and 23.4 for OC-OTEC

If vessel and HXs manufactured in China the R&R portion would be 17.7 instead of 20.1

Table 3.- 50 MW CC-OTEC and OC-OTEC Capital Cost Estimates.

Given that the cost of a ship-shaped vessel is proportional to displacement it is safe to assume that the OC-OTEC platform subsystem (excluding other subsystems) would cost twice as much as the CC-OTEC platform. Costs associated with all other subsystems (e.g., power block, seawater pipes, pumps, submarine power cable, mooring and positioning) are approximately the same for the CC-OTEC and the OC-OTEC designs. Therefore, the capital cost estimate of the OC-OTEC design is higher by an amount given by the platform cost differential. It follows that concept selection is site specific depending on the value of the desalinated water product.

The CC-OTEC plant could support a population of 500,000 with a per capita daily consumption of 2.3 kWh. This value is representative of the all encompassing per capita consumption in developing countries like the Philippines. In addition, the OC-OTEC system could also supply 240 l/day per capita. The per capita water consumption in the Philippines, for example, is estimated at 160 l/day in the domestic sector and 940 l/day for all sectors (i.e., domestic, industrial and agricultural).

Electricity and desalinated water production rates are given in the following Table. The products are 432,609 MWh/year for the CC-OTEC; and, 414,415 MWh/year and 118,434 m^3/day for the OC-OTEC.

System	Electricity MWh/year	Water m^3 / day	Capital Cost $/kWnet
Closed Cycle (53.5 MW)	432,609	0	8,430
Open Cycle (51.25 MW) (1485 kg/s)	414,415	118,434	10,751

OTEC Operational Costs and Cost of Production

The methodology used to estimate the cost of electricity production (COE) is documented in the Appendix. The COE is defined by adding the amortized annual capital-loan repayment divided by the annual production ($/kWh) to the annual levelized cost incurred due to operations, maintenance, repair and equipment replacement (OMR&R) divided by the annual electricity production ($/kWh). Figure 4 and Table 4 summarize the COE in US cents (c) per kilowatt-hour (kWh) for first generation plants.

These levelized costs were estimated for an 8%, 15-year commercial loan. Figure 4 also includes the COE for a capital improvement loan based on government bonds (e.g., in Hawai'i a 4.2%, 20 year rate is realistic). Al cases consider a fixed inflation rate of 3%[2]. Figure 4, for example, can be used to determine the CC-OTEC plant size that would be cost competitive in an specific location. Presently, in Hawai'i, for example, COEs less than about 20 c/kWh must be achieved and, therefore, plants larger that about 50 MW are required. In the case of American Samoa, a 35 MW plant (not included in Figure 4) would be cost competitive producing about 282,000 MWh to meet current and forecast demand under a power-purchase-agreement at 25 c/kWh for 15-years.

OTEC in Hawai'i and US Insular Territories

The assessment of the ocean thermal resource off Hawai'i clearly shows that OTEC plants could supply all the electricity and potable water consumed in the State (http://hinmrec.hnei.hawaii.edu/). This is the 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. This statement is also applicable to all US Insular Territories (e.g., American Samoa, Guam, Northern Mariana Islands, Virgin Islands and Puerto Rico).

Over a decade ago, the detailed evaluation of economic feasibility and financial viability of OTEC revealed that, for example, in Hawai'i plants would have to be sized at about 50 to 100 MW to produce electricity at a price corresponding to the Utility's avoided cost . Smaller plants were not cost effective in Hawai'i. It was also concluded that, although experimental work with relatively small plants had unambiguously demonstrated continuous production of electricity (Steinbach, 1982; Vega, 1995) and desalinated water (Vega, 1995), it would be necessary to build a pre-commercial plant sized around 5 MW to establish the operational record required to secure financing for the commercial size plants. The pre-commercial plant would produce relatively high cost electricity and desalinated water such that support funding was required from the federal and state governments. Unfortunately, development did not proceed beyond experimental plant sized at less than 0.25 MW (Vega, 2003).

In the mid 90s a group led by the author designed a 5 MW pre-commercial plant and made the information available in the public domain (Vega et al, 1994). However, because the price of petroleum fuels was relatively low and fossil fuels were considered to be abundantly available, government funding for the pre-commercial plant could not be obtained. Direct extrapolation from the experimental plants to commercial sizes, bypassing the pre-commercial stage, would have required a leap of faith with high technical and economic risks that no financial institution was willing to take.

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[2] this corresponds to the 20-year USA average: 1988-2007.

In Hawai'i a 100 MW OTEC plant, for example, could be housed in a floating platform stationed less than 10 km offshore, and would have the capability of delivering 800 million kWh to the electrical grid every year. Budgetary quotes from potential equipment suppliers indicate that the installed cost would be $790 million using state-of-the-art components (Table 2). The annual costs for operations and maintenance are estimated at $40 million (Table 4) such that under realistic financing terms (15 year loan at 8% annual interest and 3% average annual inflation) electricity could be produced at a levelized cost of less than 0.18 $/kWh such that a realistic power-purchase-agreement from the utility[3] at around 0.20 $/kWh would include ample return on investment. It is interesting to note that if the plant could be funded via government bonds at a realistic rate of 4.2% over 20 years the COE would be 0.14 $/kWh (Figure 4).

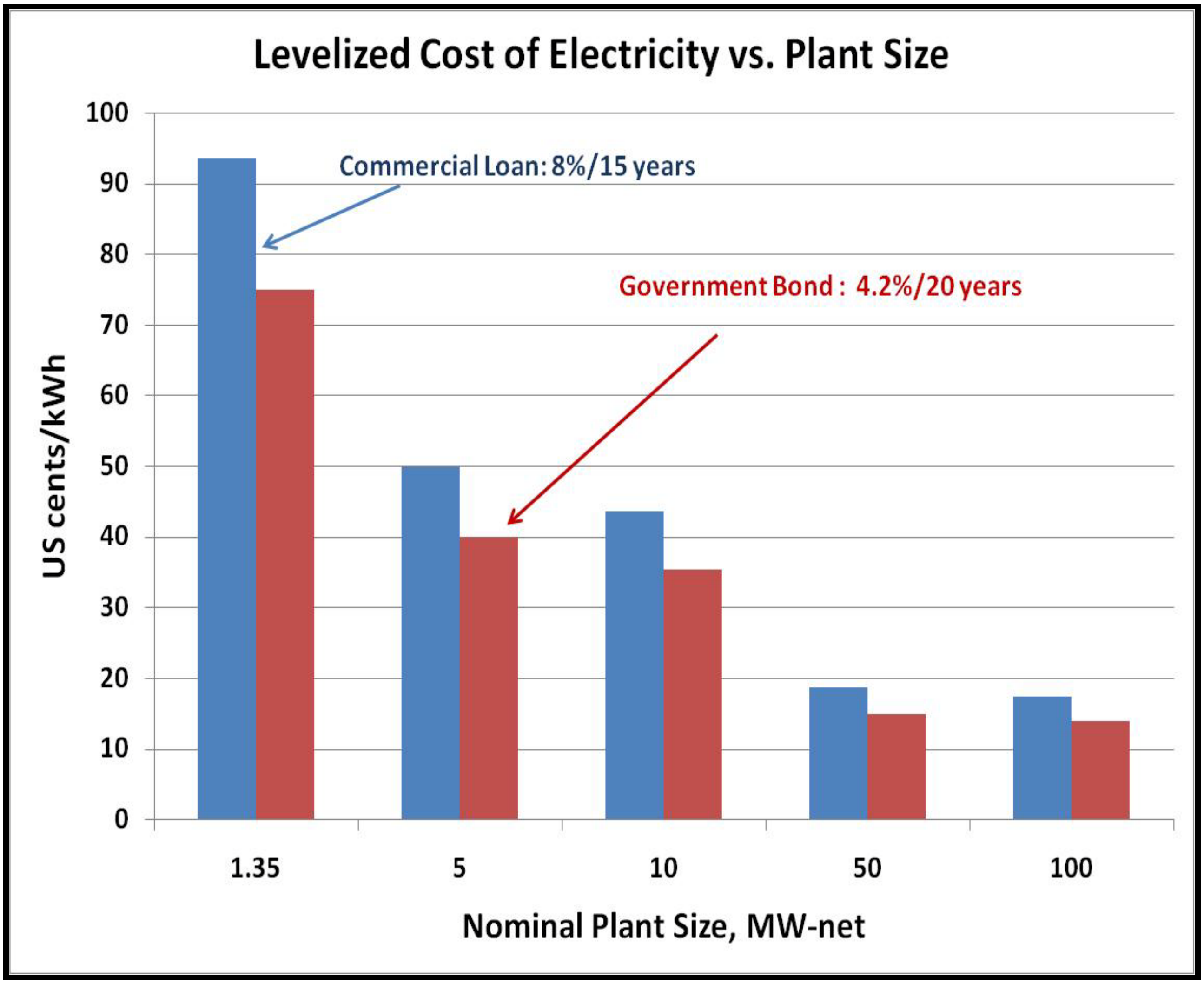

Figure 4.- Cost of Electricity (*Capital Cost Amortization* + *OMR&R Levelized Cost*) Production for First Generation OTEC Plants as a function of Plant Size with Loan Terms (*interest and term*) as Parameter. Annual Inflation assumed constant at 3%.

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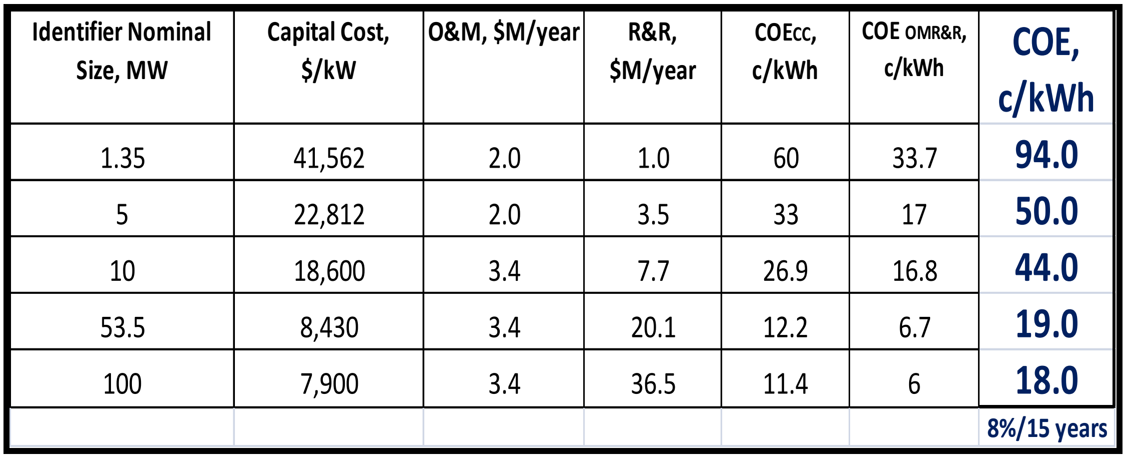
[3] Presently, the electrical utilities in the state of Hawai'i can purchase baseload (dispatchable) capacity for as much as 0.20 $/kWh.



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

Table 4.- Levelized COE (US-cents/kWh) for CC-OTEC Plants (no desalinated water production) with Capital Costs (CC) Amortized through an 8%/15 Year Loan and Annual Inflation at 3%, considering USA Labor Rates (O&M) and First Year Repair and Replacement Cost (R&R) as Indicated. First two entries are Land Based as indicated by lower O&M (see Table 2).

Economics of 50 MW OTEC Plants

Using as input the updated capital costs given in Table 3 for 50 MW plants, the levelized costs of production were determined for the CC-OTEC plant (Table 5). In the case of the OC-OTEC plant the combination of electricity rate ($/kWh) and desalinated water rate ($/m^3) required to breakeven were estimated (Table 6).

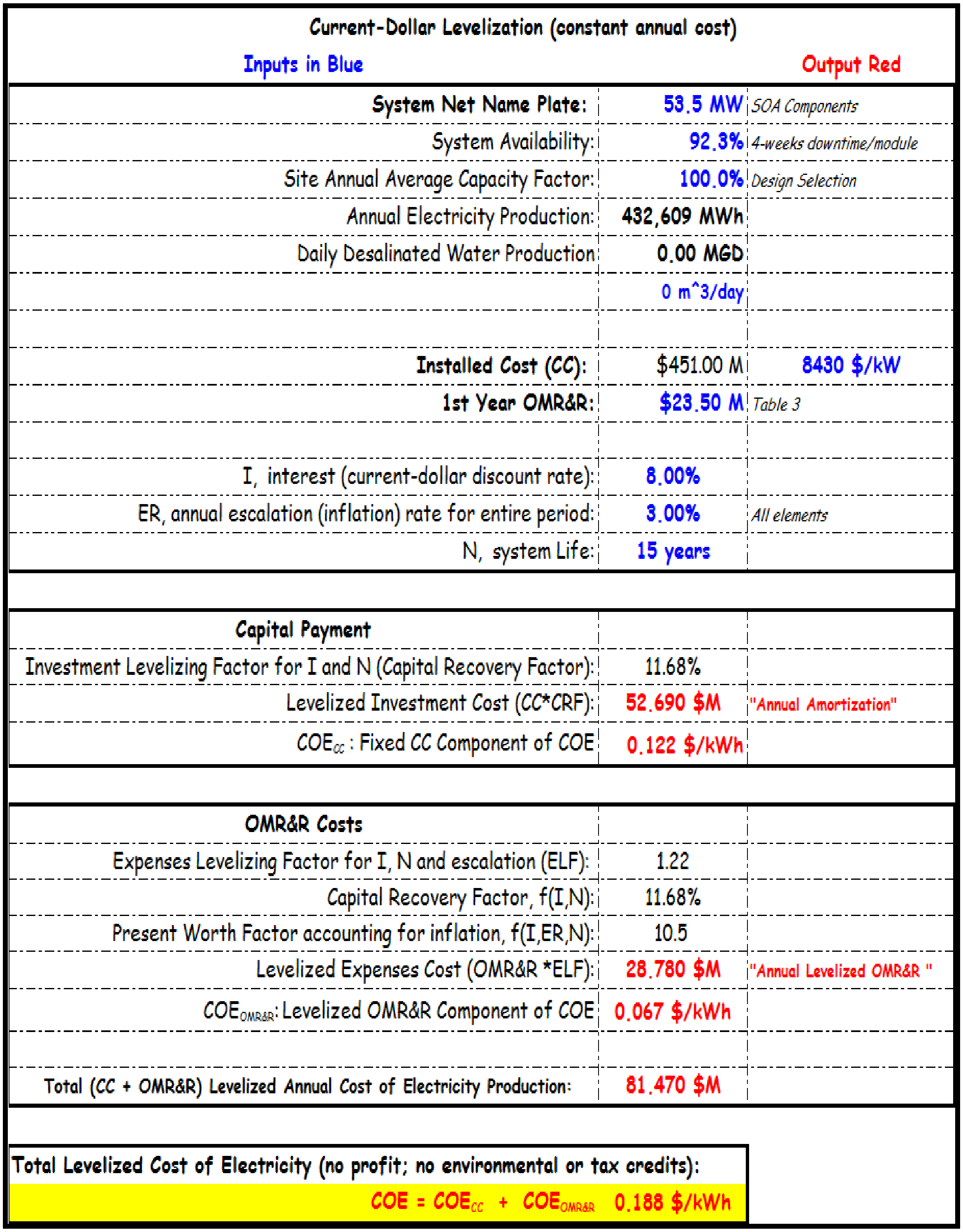
An 8% loan over 15 years was considered for the capital investment and for the OMR&R costs current-dollar levelization was evaluated at a fixed annual inflation rate of 3%. For continuous operation of OTEC plantships, a crew of seventeen full-time employees would be required. This includes one administrator and sixteen operators for the power plant and the ship systems. Eight operators would be on duty at one time while the other eight rest. The administrator works a regular schedule. Using USA labor rates the fully loaded annual salary costs would be ≈ $3.4 M. This figure is taken as the first year operation & maintenance portion (OM) of recurring costs; and, based on replacement costs for the capital investment (Table 3), the first year annual costs associated with repair and replacement (R&R) are taken as: $20.1 M for the CC-OTEC plant (Table 5); and, $23.4M for the OC-OTEC plant (Table 6).

As shown in Table 5, excluding profits and credits, the breakeven point (defined as: levelized annual costs = annual revenue) for the 50 MW CC-OTEC plant is given by a 15-year power-purchase-agreement for at least 0.19 $/kWh.

In the case of the OC-OTEC plant, there are two (of many) scenarios that illustrate the breakeven point:

(i) sell electricity for at least 0.15 $/kWh; and water for 0.8 $/m^3 (3 $/kgallon) {see Table 6}
(ii) sell electricity for at least 0.07 $/kWh; and water for 1.6 $/m^3 (6 $/kgallon)

It must be emphasized that the economic analysis summarized here is based in capital and operational cost applicable in the USA.

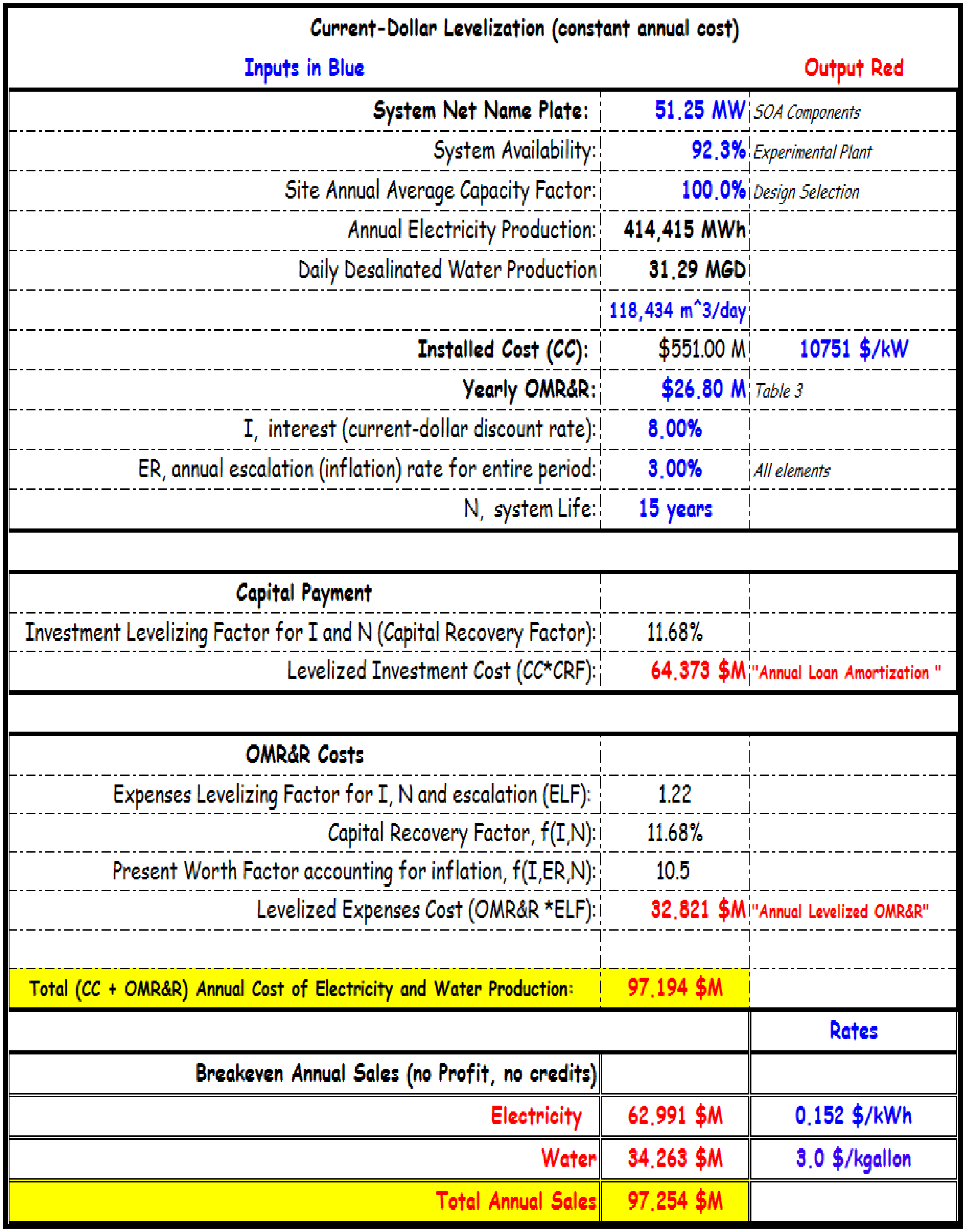


Current-Dollar Levelization (constant annual cost)

Inputs in Blue | Output Red

System Net Name Plate:	**53.5 MW**	*SOA Components*
System Availability:	**92.3%**	*4-weeks downtime/module*
Site Annual Average Capacity Factor:	**100.0%**	*Design Selection*
Annual Electricity Production:	**432,609 MWh**	
Daily Desalinated Water Production	**0.00 MGD**	
	0 m^3/day	
Installed Cost (CC):	$451.00 M	**8430 $/kW**
1st Year OMR&R:	**$23.50 M**	*Table 3*
I, interest (current-dollar discount rate):	**8.00%**	
ER, annual escalation (inflation) rate for entire period:	**3.00%**	*All elements*
N, system Life:	**15 years**	
Capital Payment		
Investment Levelizing Factor for I and N (Capital Recovery Factor):	11.68%	
Levelized Investment Cost (CC*CRF):	**52.690 $M**	"Annual Amortization"
COE_{cc} : Fixed CC Component of COE	**0.122 $/kWh**	
OMR&R Costs		
Expenses Levelizing Factor for I, N and escalation (ELF):	1.22	
Capital Recovery Factor, f(I,N):	11.68%	
Present Worth Factor accounting for inflation, f(I,ER,N):	10.5	
Levelized Expenses Cost (OMR&R *ELF):	**28.780 $M**	"Annual Levelized OMR&R "
$COE_{OMR\&R}$: Levelized OMR&R Component of COE	**0.067 $/kWh**	
Total (CC + OMR&R) Levelized Annual Cost of Electricity Production:	**81.470 $M**	
Total Levelized Cost of Electricity (no profit; no environmental or tax credits):		
$COE = COE_{CC} + COE_{OMR\&R}$	**0.188 $/kWh**	

Table 5.- CC-OTEC: Levelized Cost of Electricity Production.



Current-Dollar Levelization (constant annual cost)		
Inputs in Blue		**Output Red**
System Net Name Plate:	**51.25 MW**	*SOA Components*
System Availability:	**92.3%**	*Experimental Plant*
Site Annual Average Capacity Factor:	**100.0%**	*Design Selection*
Annual Electricity Production:	**414,415 MWh**	
Daily Desalinated Water Production	**31.29 MGD**	
	118,434 m^3/day	
Installed Cost (CC):	$551.00 M	**10751 $/kW**
Yearly OMR&R:	**$26.80 M**	*Table 3*
I, interest (current-dollar discount rate):	**8.00%**	
ER, annual escalation (inflation) rate for entire period:	**3.00%**	*All elements*
N, system Life:	**15 years**	
Capital Payment		
Investment Levelizing Factor for I and N (Capital Recovery Factor):	11.68%	
Levelized Investment Cost (CC*CRF):	**64.373 $M**	"Annual Loan Amortization "
OMR&R Costs		
Expenses Levelizing Factor for I, N and escalation (ELF):	1.22	
Capital Recovery Factor, f(I,N):	11.68%	
Present Worth Factor accounting for inflation, f(I,ER,N):	10.5	
Levelized Expenses Cost (OMR&R *ELF):	**32.821 $M**	"Annual Levelized OMR&R"
Total (CC + OMR&R) Annual Cost of Electricity and Water Production:	**97.194 $M**	
		Rates
Breakeven Annual Sales (no Profit, no credits)		
Electricity	62.991 $M	0.152 $/kWh
Water	34.263 $M	3.0 $/kgallon
Total Annual Sales	97.254 $M	

Table 6.- OC-OTEC: Breakeven Electricity and Water Rates Required {one of many scenarios given here with 0.152 $/kWh and 0.8 $/m^3 (3 $/kilogallon)}.

Conclusions and Recommendations

The major conclusion reached in the earlier report continues to be applicable: *there is a market for OTEC plants that produce electricity and desalinated water*, however, operational data must be obtained by building and operating demonstration plants scaled down from sizes identified as cost effective. OTEC systems are in the pre-commercial phase with several experimental projects having already demonstrated that the technology works but lacking the operational records required to proceeding into commercialization. Adequately sized pilot projects must be operated in situ and for at least one continuous year to obtain these records. Our analysis indicates that a pre-commercial or demonstration plants sized at about 5 MW must be operated prior implementation of 50 to 100 MW commercial plants.

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

The major challenge continues to be the requirement to finance relatively high capital investments that must be balanced by the expected but yet to be demonstrated low operational costs. Perhaps a lesson can be learned from the successful commercialization of wind energy due to consistent government funding of pilot or pre-commercial projects that led to appropriate and realistic determination of technical requirements and operational costs in Germany, Denmark and Spain. In this context, by commercialization we mean that equipment can be financed under terms that yield cost competitive electricity. This of course depends on specific conditions at each site. Presently, for example, in Hawai'i cost competitiveness requires electricity produced at less than about 0.20 $/kWh. Our analysis indicates that, without subsidies or environmental credits, plants would have to be 50 MW or bigger to be cost competitive in Hawai'i.

In discussing OTEC's potential it is important to remember that implementation of the first plant would take about 5-years after order is placed. This is illustrated with the baseline schedule shown in Table 7. The time required for each major activity also applies to the pre-commercial or demonstration plant. Completion of the engineering design with specifications and shop drawings would take one-year. Presently it is estimated that the licensing and permitting process through NOAA (in accordance with the OTEC Act) would take longer than 2-years for commercial plants with the provision of exemptions from the licensing process for plants considered to be *demonstration plants* because of the limited duration of the operational phase.

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

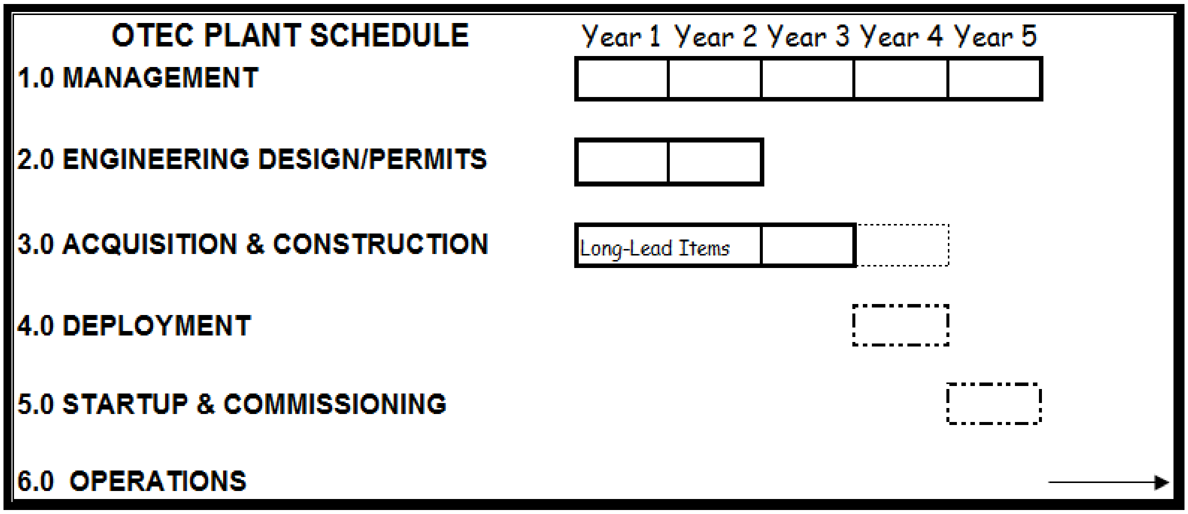
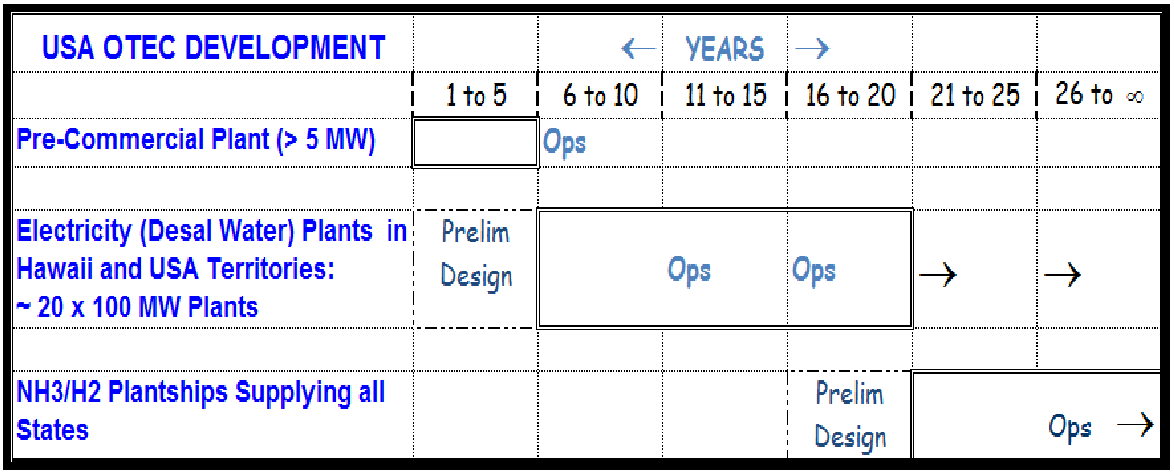


Table 7.- First Generation OTEC Plantship Implementation Schedule.

As stated above, there are sufficient petroleum resources to meet demand for at most 50 years and with production peaking we will face a steadily diminishing petroleum supply. This situation justifies re-evaluating OTEC for the production of electricity as well as energy intensive products. The US should begin to implement the first generation of OTEC plantships providing electricity, via submarine power cables, to shore stations. This would be followed, in about 20 years, with OTEC factories deployed along equatorial waters producing, for example, ammonia and hydrogen as the fuels that would support the post-petroleum era.

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

The design of the first commercial plant sized at 50 to 100 MW would be completed and optimized after the first year of operations with the pre-commercial plant. This would be followed with the installation of numerous plants in Hawai’i and US Insular Territories for a cumulative total of about 2,000 MW over 15-years. As indicated in Table 8, the design of the grazing factory plantships that will produce the fuels of the future (e.g., hydrogen and ammonia) could be initiated as early as 15-years after the development program is implemented.



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

Table 8.- OTEC Implementation Program Required in Preparation for the Post-Petroleum Age.

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Appendix

Conventional Production of Electricity

The thermal efficiency (η) of a well maintained conventional steam power plants, fired with oil or coal can be as high as 36%. This implies that 36% of the heat added is converted to net work. Net work is defined as the difference between the output from the turbine-generator and the work required to run the plant.

The convention followed in power plant technology, to express plant performance, is to consider the heat added to produce a unit amount of net work. This parameter is called the heat rate (HR) of the plant and is usually given in Btu/kWh. Therefore, the heat rate is inversely proportional to the thermal efficiency, $\eta = 3413/HR$ (i.e., 1 kWh = 3413 Btu at 60°F), such that a thermal efficiency of 36% corresponds to a HR of 9500 Btu/kWh. [Herein common usage dictates the use of mixed units.]

The heating values of standard coal and fuel oil are 12,000 x (1 ± 0.17) Btu/lbm and 144,000 x (1 ± 0.04) Btu/U.S. gallon, respectively. Therefore, within 6%, the fuel cost incurred in producing electricity, expressed in $/kWh, with an oil-fired plant is:

$COE_{fuel} = 1.6 \times 10^{-3} \times CB$,
CB is the <u>C</u>ost of a (42 U.S. gallons) <u>B</u>arrel of fuel.

Therefore, for example, at $62.5 per barrel the COE_{fuel} is 0.10 $/kWh.

The same expression can be used for diesel generators without a loss of generality.

In the case of coal, the standard heating value is 12,500 Btu/lbm with a current price of about $62 per metric ton such that the fuel cost incurred in producing electricity with a thermal efficiency of 36% would be 0.021 $/kWh. This is equivalent to oil fuel cost of $13/barrel.

To estimate the total cost of electricity production the COE_{fuel} must be added to the capital cost as well as costs associated with OMR&R .

Conventional Production of Desalinated Water

For convenience and because the first generation OTEC plants are expected to be deployed around islands it is assumed that the cost of seawater desalination with OTEC must be compared with that of reverse osmosis (RO) desalination of seawater.

RO plants require energy solely as shaft power from, for example, an electric motor. It can be shown that, expressed in $/$m^3$, fresh water production by RO costs 0.049 x CB, where CB is the cost of a barrel of fuel. This expression was used in the previous report to establish the desalinated water cost corresponding to a given fuel cost scenario (Vega, 1992).

Levelized Cost of Electricity: Methodology

The levelized cost of electricity (COE) expressed in constant annual cost is given by the sum of the levelized investment cost (i.e., the loan amortization payment expressed in $/kWh) and the levelized operations, maintenance, repair and replacement (OMR&R) expense cost.

Referring to Table 5, the following terms are defined:

<u>System Net Name Plate (MW)</u>: OTEC system net power is inputted based on design specific conditions (53.5 MW-net);

<u>System (equipment) Availability</u>: The percentage of time that system is available. Based on experimental data it is assumed that this system consists of five modules with annual maintenance downtime of 4-week per module such that annual availability is 0.923 (92.3%);

<u>Site Annual (resource) Capacity Factor</u>: To account for resource variability. In this case 100% because design already accounted for resource variability (accounted for by the selection of name plate, in this case for a site, with constant Tc and Tw ranging from 24 °C to 28 °C throughout year). This parameter is used for evaluation of intermittent resources like wind and waves;

<u>Annual Electricity Production (MWh)</u>: Name Plate x Availability x Capacity Factor x 8760;

Daily Desalinated Water Production (MGD; m^3/day): Used for OC-OTEC systems (e.g., see Table 6);

Installed Cost (Capital Cost, CC): This is the amount (given in million dollars) of the loan: inputted cost estimate {given in \$/kW from Table 2 (or Table 3 as appropriate)} times the Name Plate;

First Year OMR&R: Estimated as illustrated in Table 3 (in million dollars) to account for the funds that must be collected to cover all operational costs;

Interest (I): From the loan term (herein 8% is assumed for a commercial loan and 4.2% for government bonds);

Escalation (Inflation) Rate: taken at a constant 3% in this report;

System Life (N): As a conservative assumption, this is defined as the loan term (15 years for the commercial loan; and 20-years for the bonds) although the OTEC system is designed for a 30-year useful life. As illustrated in Table 3, for example, some components are replaced in 15-year intervals others require 30-year intervals;

Under Capital Payment (loan amortization):

Capital Recovery Factor (CRF):

$$\mathrm{CRF} = [I \times (1 + I)^N]/[(1+I)^N - 1]$$

such that for parameters in Table 5 the CRF is 0.1168;

Levelized Investment Cost: Amount (\$) required yearly to pay capital loan: CC x CRF;

Fixed Capital Cost Component of Cost of Electricity (\$/kWh): Levelized Investment Cost/Annual Electricity Production. This is the amount that must be collected per kWh produced to pay the loan;

Under OMR&R Costs (levelized costs):

Present Worth Factor (PWF):

$$\mathrm{WF} = [(1 + ER)/(I - ER)]/[1 - \{(1 + ER)/(1 + I)\}^N]$$

such that for parameters given in Table 5 the PWF is 10.48 years;

Expenses Levelizing Factor (ELF):

$$\mathrm{ELF} = \mathrm{PWF} \times \mathrm{CRF}$$

such that for the parameters given in Table 5 the levelizing factor is 1.22;

Levelized Expenses Cost: The fixed amount that must be collected yearly to cover all OMR&R costs accounting for inflation. This is equal to the amount estimated for the first year (as given above) times the ELF. For the parameters and estimates given in Table 5 the value is 22% higher of what would be required the first year;

Levelized OMR&R Component of COE (\$/kWh): The levelized expenses cost (\$) divided the annual production of electricity (kWh);

Total Levelized Cost of Electricity (\$/kWh): This is the sum of COE_{CC} and $\mathrm{COE}_{OMR\&R}$; The value given here excludes environmental credits, tax credits and profit.