Ocean Thermal Energy Conversion (OTEC): Economics Update (2023)

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Executive Summary

This report was prepared to update the economic viability of Ocean Thermal Energy Conversion (OTEC) for the generation of electricity and desalinated water by reassessing specific cases under which both Closed Cycle and Open Cycle plants (CC-OTEC and OC-OTEC) could be competitive considering the following classes[1]: (i) 1 MW land-based plants; (ii) 10 MW and (iii) 50 MW Plantship operating offshore connected via submarine power cable to land.

The main body of this report refrains from technical details beyond what is necessary to define each case. However, for the sake of completeness technical information previously published by the author and his colleagues is reproduced in Appendices 5 and 6. The comprehensive technical aspects documented in these two Appendices continue to be applicable.

The updated assessment provides: (i) **C**apital **C**osts ($/kWnet) estimates from equipment and installation quotes meeting Specifications developed by the author and confirmed with the operation of experimental plants; and (ii) Updating **L**evelized **C**ost **o**f **E**lectricity ($/kWh) as function of loan rates; including desalinated water production credit for specific OC-OTEC cases.

The approach was to:

1st) Extrapolate to the present trusted archival cost estimates using the USA Manufacturing-Price-Index (MPI).

2nd) Document Specifications required to obtain quotes for the major OTEC subsystems. Given that at this developmental stage we must consider generic sites for the floating plants operating throughout the OTEC region, only ship-shaped vessels were considered. For land-based plants bathymetric conditions off Keahole Pt. Hawaii were assumed.

3rd) Solicit quotes from Potential Suppliers of Equipment to estimate Current <u>Costs of complete OTEC systems</u>[2].

4th) Estimate the corresponding LCOE ($/kWh) required to collect enough funds for loan repayment and to cover costs for Operations, Maintenance, Repair & Replacement (OMR&R) without Environmental Credits or profits. That is, the Breakeven cost.

The third step began in October 2022 and was extremely challenging and time consuming due to Vendor's reluctance to collaborate on, yet another OTEC study that might not lead to a Purchase Order. It was necessary to contact potential suppliers' numerous times in the hope of reaching a different employee willing to collaborate. In some cases it took several months to obtain the required information.

[1] The name plate is given for $\Delta T = 21.5$ ºC throughout this report.

[2] It must be noted that some published references of land-based systems do not include all costs under the assumption that the seawater systems will be covered by others such that their cost estimates are not all inclusive.

For example,

- Currently the non-government subsidized commercial shipyards specializing in Tankers and Containers ships adaptable to the implementation of OTEC Plantships are concentrated in Japan and South Korea. Unfortunately, not one agreed to provide cost estimates. Press releases and specialized journals summarizing orders were identified to estimate costs based on vessel Death Weight Tonnage (DWT). In addition and as a magnanimous professional courtesy, *Blue Water Offshore (BWO)* provided guidance and information that allowed for the incorporation of additional and realistic cost estimates based on existing Vessels with the required DWTs.

- Throughout the years and since MiniOTEC in 1979, *Rotoflow* has provided information and quotes for CC-OTEC Turbine (Expander) Generators but this time it was not possible. Fortunately, *Atlas-Copco* was eventually identified, and they provided the information used in this report.

- At first it was notably surprising that Submarine Power Cables manufacturers did not provide information. However, this was because all are extremely busy with an increase in demand from the offshore petroleum industry and for offshore Wind Turbine installations. We were able to obtain an estimate from Prysmian by May 2023.

- In the case of OC-OTEC no new information beyond our archival data was obtained to estimate the costs associated with the Turbine Generators. Fortunately by May 2023 we were able to obtain from *Edwards Vacuum* the required information about the Compressors required for the removal of non-condensable gasses (air) that are released in the vacuum structure.

It was eventually determined that the major updated Capital Cost differences are due to:

- The marked decrease over the last 25 years in fabrication cost ($/tonnage) of ship shaped vessels indicates that it is reasonable to expect that the cost of OTEC ship shaped vessels will be about 35 % lower than the extrapolated estimate.

- High-Density-Polyethylene-Pipes (HDPE) pipes are currently available in larger diameters of appropriate thickness (3 m i.d.) such that they can be used as the cold-water-pipe (CWP) for a 5 MW plant and in bundles for the 10 MW (2 pipes) and the 50 MW (8 pipes) resulting in relatively lower costs.

Levelized-Cost-of-Electricity were estimated using the current Capital Costs and for a reasonable Commercial loan (15 years @ 8%); and for the record: Concessionary loans available from Development Banks for Developing Nations (20 years @ 2.5%). N.B. concessionary loans are not available for first generation technologies but are included for future consideration because the OTEC resource is appropriate in the EEZ of most of these nations.

Experimental plants in Hawaii, Japan and South Korea have confirmed that with proper design no Green House Gasses are emitted during operations, but no credit is taken pending establishment of international/national agreements[3].

As previously documented in the main references: Moored plants would transmit the electricity/desalinated water to shore; and eventually Drifting plants would generate the electricity and desalinated water required to generate and store NH_3 or H_2 as the fuels of the future in the post fossil fuels era. These products could be shipped to land or provide fuel filling stations for commercial shipping lines or Navy vessels away from land.

In addition, there are other potential applications. OTEC, for example, could provide the electricity required for site support of Oil and Gas Platforms off Brasil. Another promising 1st Generation application is for drifting Plantships along Equatorial waters (mild environment with maximum ΔT) supporting energy intensive technologies/applications (e.g., high-density computing) that can operate remotely. These referred to as Demand-Response OTEC (DROTEC) have been proposed by OceanBit (Oceanbitenergy.com).

Figure 1 depicts our long term goal for the World-Wide implementation of OTEC.

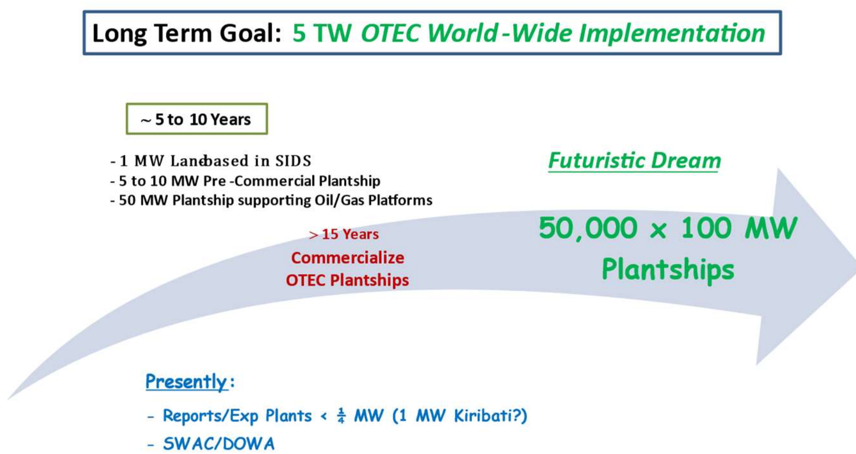

Figure 1 .- Our long term goal for the World-Wide implementation of OTEC.

Furthermore, the major technical, economic, environmental, and political issues related to the implementation of OTEC systems can still be summarized as follows:

Technical

OTEC generates electricity (and desalinated water) all day long with Baseload Generation plus Additional Variable Output depending on the location (highly dependent on surface seawater temperature).

Based on lessons learned with OTEC Preliminary Designs, Model Basin tests, Experimental Plants, and the knowhow available from Offshore-Petroleum Engineering

[3] N.B. Coal fuels emit ≈1 kg CO_2 per kWh electricity; petroleum fuels emit ≈ 0.7 kg CO_2 per kWh; and Natural Gas ≈ 0.5 kg CO_2 per kWh.

firms it can be stated that **no major technical issues** remain for the implementation of OTEC; although, it must be emphasized that site specific Engineering Design processes incorporating Operations, Maintenance, Repair and Replacement (OMR&R) Protocols must be incorporated into the final design process. In addition, the selection of a site must consider the human and equipment infrastructure required for installation and operations. This is extremely important when considering remote locations and Small Island Developing States (SIDS).

However, one of the major engineering challenges associated with the first generation of Plantships (e.g.,10 to 50 MW) relying on adapting equipment designed and implemented for other applications, is that some subsystems will require multiple units linked together[4]. Most noticeable are the cases with seawater pumps ("low-head high flowrate") and CC-OTEC HXs and OC-OTEC TGs.

Per design and as confirmed with our experimental plants, the operational Control Parameters are:

CC-OTEC
The CC-OTEC control parameters are: (i) mass flow rate of warm water; (ii) mass flow rate of cold water; (iii) working fluid (e.g., NH_3) mass flow rate and recirculating-to-feed pumps flow ratios; (iv) warm water temperature; and (v) cold water temperature. The gross power output from a CC-OTEC power plant can be controlled only with the first three parameters while the water temperatures are dictated by natural processes.

OC-OTEC
The OC-OTEC control parameters are: (i) mass flow rate of warm water; (ii) mass flow rate of cold water; (iii) vacuum compressors train inlet pressure; (iv) warm water temperature; and (v) cold water temperature. The gross power output from an OC-OTEC power plant can be controlled only with the first three parameters while the water temperatures are dictated by natural processes. During operations with our 250 kW OC-OTEC Experimental Apparatus gross power output was controlled by varying the water streams flow rates with the water pumps and the inlet pressure with the vacuum pumps train to set the appropriate pressure in the Flash Evaporator.

Economics
Except for relatively small land-based plants (< 5 MW) serving SIDS, commercial size (i.e., potentially cost competitive) Plantships sized at about 50 MW and above are the world-wide future. These might eventually be competitive for: (i) electricity and desalinated water generation onboard Plantships moored offshore transmitting the products to shore; and eventually (ii) NH_3 or H_2 generation away from shore in drifting Plantships.

There might also be 1st Generation applications for drifting Plantships along Equatorial waters (mild environment with maximum ΔT) supporting energy intensive technologies/applications that can operate remotely.

[4] As in the case with other technologies (e.g., Heat Pumps progressing from kW to MW sized) the expectation is that as OTEC is implemented manufacturers will expand and begin to design larger units minimizing linkage requirements.

Considering sites with average seawater temperature differential (ΔT) of 21.5 ºC, the 2023 updated LCOEs ($/kWh) with first generation plants implemented with commercial loans are[5]:

1.36 MW-net Land Based OC-OTEC:	**0.59 $/kWh** with credit for 2,450 m^3/day of Desalinated Water @ 1.5 $/$m^3$;
10 MW OC-OTEC Plantship:	**0.62 $/kWh** with credit for 23,690 m^3/day of Desalinated Water @ 1.5 $/$m^3$;
50 MW OC-OTEC Plantship:	**0.36 $/kWh** with credit for 118,450 m^3/day of Desalinated Water @ 1.5 $/$m^3$;
1.36 MW Land Based CC-OTEC:	**0.64 $/kWh** (no desalinated water credit).
10 MW CC-OTEC Plantship:	**0.55 ± 0.06 $/kWh;**
50 MW CC-OTEC Plantship:	**0.32 ± 0.06 $/kWh;**
100 MW-CC-OTEC Plantship:	**0.25 ± 0.05 $/kWh.**

The 100 MW case is included although currently not feasible for the 1st generation due to the excessive number of units required for the seawater and HXs systems.

These first generation LCOEs are challenging without environmental credits or subsidies.

One might speculate, based on the implementation of similar technologies, that later generation designs will reach cost reductions of about 30%.

It must be noted that for sites with higher ΔT the net output increases such that for a location with ΔT of 24.5 ºC will yield ≈ 40% higher outputs such that the LCOE would be about 30% lower.

To minimize Financial Risks associated with the implementation of commercial size Plantships, a pilot plant sized at about 5 MW, representing a scale version of a commercial size plant, must be implemented, and tested for at least one year. The current cost estimates of the funding required to implement this pre-commercial plant are given in Table 1. This step is dependent on government(s) financing.

CC-OTEC (Demonstration)	**5.26 MW Plantship** (ΔT = 21.5 ºC)	**5.26 MW Drifter** (no mooring/no power cable)
Alfa Laval HXs	$164 M	$112 M
Kelvion HXs	$136 M	$84 M

Table 1 .- Pre-Commercial Demonstration CC-OTEC Options based on our Design.

[5] To extrapolate our values beyond 2023 we recommend assuming an Annual Inflation Rate of 3%. Over the last 20-years, for example, the average USA Manufacturing-Price-Index increase was 2.65 %.

Perhaps a lesson can be learned from the successful commercialization of Wind Energy that has been achieved due to consistent government funding of pre-commercial projects (with first generation LCOEs much higher than the rates estimated herein for OTEC) 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.

Environment
Dr. Gerard Nihous, at the University of Hawai'i, led the implementation of a numerical model with state-of-the-art (SOA) atmosphere-ocean coupling including ocean currents and thermohaline circulation to assess the environmental impact of thousands of plants. He, essentially, divided the OTEC resource region into 25 km x 25 km squares with a "100 MW/ΔT: 20 ºC" plantship station in the middle of each square. His theoretical conclusions can be conservatively interpreted by stating, for example, that 50,000 plants (5 TW) could be installed with "acceptable" world-wide environmental impact. Annual energy generation from these plants: *5TW x* 8760 hrs. of electrical energy represent a substantial contribution to the current worldwide primary energy consumption: 18 TW x 8760 hrs*.* (Note that it takes 3 units of primary energy to generate one unit of electrical energy). Nihous also modeled installation exclusively within national EEZs and obtained similar results.

Dr. Nihous also made available two links maintained by the University of Hawaii that allow the user to obtain monthly average values of ΔT as a function of Latitude/Longitude; and monthly electricity production (GWh/month) with his baseline 100 MW (sized for ΔT 20 ºC) OTEC power plant:

https://www.hnei.hawaii.edu/hinmrec-reports/AnnualTempDiff.html

https://www.hnei.hawaii.edu/hinmrec-reports/powermaps.html

Figure 2 illustrates Nihous' work.

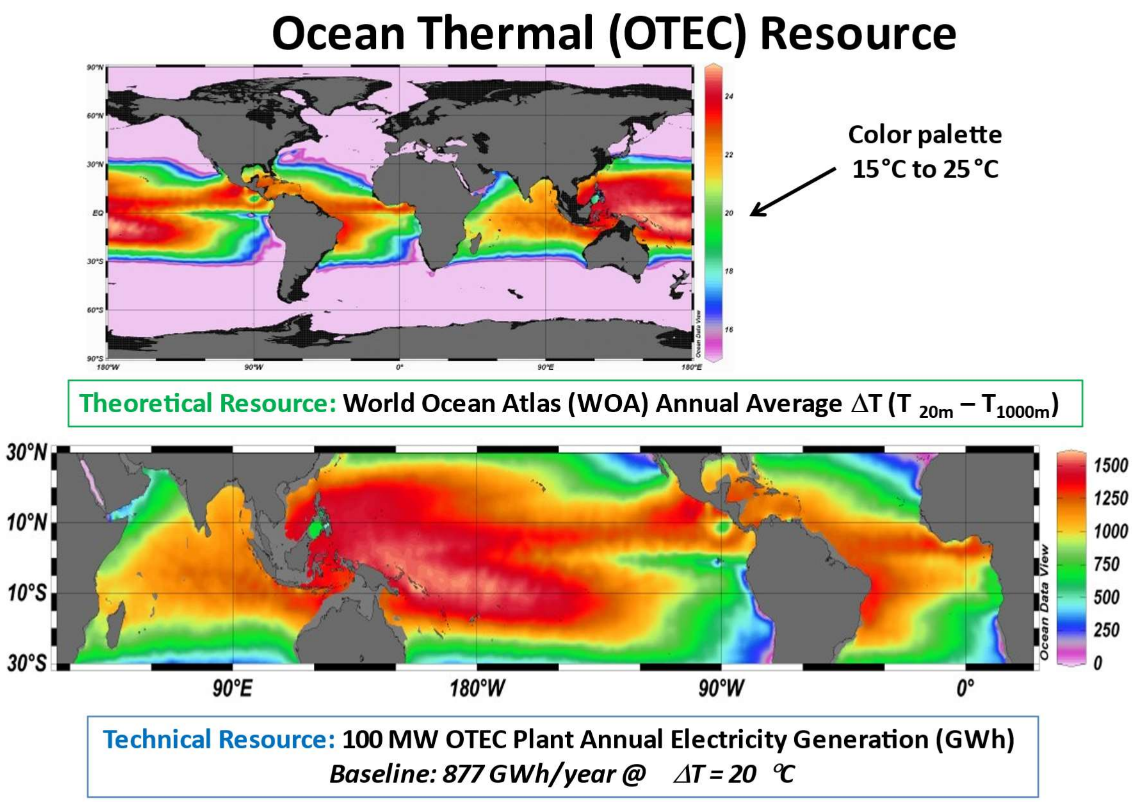

Figure 2.- OTEC Worldwide Region: Ocean Thermal Resource and Annual Electricity Generation (GWh) with a 100 MW OTEC Plant (name plate @ ΔT = 20 ºC).

We have also established what parameters must be measured to assess environmental impact from the operation of OTEC plants such that a protocol will be implemented beginning with the first installation. The environmental impact parameters will be continuously measured, and restrictions implemented as necessary.

<u>Political</u>

The implementation of the required pre-commercial OTEC plantship depends on Government or “Angel” Patient Financing because the electricity generated will not be cost competitive at the 5 MW size. This step from final engineering design to electricity generation will take 4 to 5 years and is required before proceeding with the implementation of commercial sized Plantships.

The first Commercial Plantship (≥ 50 MW) will be operational 5 years after the pre-commercial plant before income generation.

<u>New Developments</u>

As stated above, drifting Plantships could also house data centers or other applications that would use the OTEC electricity on-board and transmit data to land stations via satellite connections. We are aware of a project designed to house Application Specific Integrated Circuits (ASIC) in a drifting Plantship along equatorial waters (no hurricanes and the highest feasible surface water temperatures within the OTEC region). Figure 3 illustrates the area under consideration.

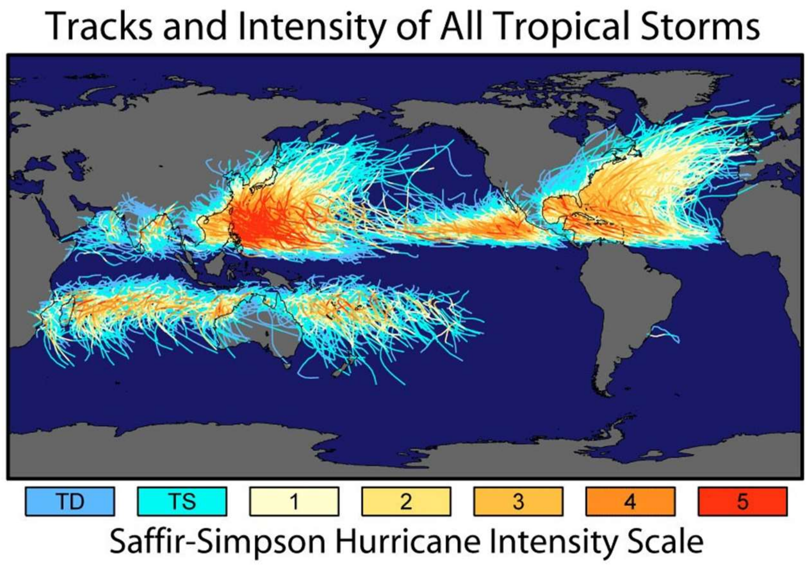

Figure 3.- Hurricane Tracks as indicator, correlating with Figure 2, of minimal environmental loading locations along the Equator, Off Brasil and Off West Africa.

The plantship based on our design for a plant sized at ≈ 10 MW for the average thermal resource off Hawaii (21.5 ºC average temperature differential) operating along this equatorial region would generate at least 40% more electricity in an annual basis because of the higher temperature differences therein. Moreover, because a drifting plantship does not require a submarine power cable or a mooring system the electricity generated would be cost competitive compared with an ASIC operation on land.

1.0 Introduction

Significant research and efforts have been applied to the implementation of OTEC around the world, leading to an existing body of technical and economic data at the Preliminary Design level[6]. Given the limited scope of this report, we refrain from technical details on OTEC beyond what is necessary to define each case. We provide an updated summary of the economics of OTEC considering three classes: 1 MW land-based; 10 MW and 50 MW floating Plantships. Current costs of the major components are presented along with archival cost estimates extrapolated to current conditions using USA Manufacturing Price Indexes.

Our biases can be summarized as follows:

- Due to the size of the Cold Water Pipes (CWPs) land-based plants will be sized at less than about 5 MW;

- The first few generations OTEC Plantships will be positioned relatively close to shore transmitting electricity via submarine power cables (and desalinated water via hose-pipes) to shore stations;

- First generation Plantships will be ship/barge shaped and positioned, for example, using spread mooring or single-point mooring assisted with thrusters;

- All major components (e.g., HXs and seawater pumps) can be manufactured by existing companies, however, for the larger size plants (≥ 10 MW) they must be involved in the final design processes to optimize components integration;

- Historically, for Plantships, we considered FRP-sandwich CWPs based on designs and at-sea tests. However, current developments in the manufacturing of HDPE pipes lead to the selection of pipe bundles. The full-length CWPs bundles should be towed horizontally and upended at the site where the plantship is already positioned.

- The CWPs might need to be attached using a gimbal to decouple pitch and roll vessel motions;

- Later generation plants will be grazing in the tropical oceans generating energy carriers (e.g., H_2 or NH_3) to be shipped to shore or used as filling stations for long range ships needing refueling.

OTEC power block heat & mass balances confirmed through the years with experimental plants in Japan, South Korea, and the USA/Hawaii were used to document technical specifications for the OTEC plants components to solicit vendor quotes. We knew that this step would pose a significant challenge because 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 participation did not yield a single large order (excluding the experimental plants), mainly because there were no real customers for the technology. Efforts were made to adapt pertinent data to the scenarios selected in this project.

[6] Previously published and still up-to-date information is reproduced in the Appendices 5 and 6 as an aid to the reader.

The analytical model previously implemented (Ref. 4) was used to assess scenarios under which OTEC might be cost competitive with conventional technologies. First, the capital cost for OTEC plants, expressed in $/kW, was estimated from current costs for the major components of OTEC systems including installation costs. Subsequently, the relative cost of producing electricity ($/kWh) with OTEC, offset when considering OC-OTEC by the desalinated water production revenue, was estimated. No attempt is made at speculating about future costs. It is simply stated that OTEC could be competitive if a location is represented by one of the scenarios.

The following provides a summary of relevant previous work (Appendices 5 and 6):

Independently of economics and only considering technical aspects, two distinct markets were identified: (i) industrialized nations; and (ii) small island developing states (SIDS) with modest needs for power and fresh water. For example, 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.

It was also determined that floating plants (e.g., Plantships) 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.

The previous work includes, for example, estimates for land-based ≈1.3 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 hotel). These plants would use the state-of-the-art, bottom-mounted cold water pipe technology used in Hawaii and Kumejima (Okinawa.)

It was also concluded that OTEC-based, mariculture operations and air-conditioning systems can only make use of the seawater available from relatively small land based~ 1 to 2 MW plants. The use of energy carriers (e.g.: Hydrogen, Ammonia) to transport OTEC energy generated in floating plants, drifting in tropical waters at distances beyond the length of state-of-the art submarine power cables, was also determined to be technically feasible.

Regarding the economic aspects, credit for the avoidance of the External Costs of energy production and consumption with conventional technologies are not included in the determination of the OTEC LCOE because there is no widely acceptable technique to determine such credits. Considering all stages of generation, from initial fuel extraction to plant decommissioning, it has been determined that no conventional 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 costs of all externalities are *reported to be equivalent to, for example, adding from at least $80 (basically doubling the current cost in large markets) to $400 for each petroleum barrel[7]. Accounting for these externalities might eventually help the development and expand the applicability of OTEC.*

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 plantship without operational records. As previously concluded, it must be emphasized that before OTEC Plantships can be commercialized, a prototypical (pre-commercial) plant must be built and operated to obtain the information required to design optimized commercial systems and to gain the confidence of the financial community and industry. Experimental work with relatively small plants had unambiguously demonstrated continuous production of electricity and desalinated water however it would be necessary to build a pre-commercial plant sized around 5 MW to establish the operational records 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 is required from national governments. It must be noted that Development Banks like the Asian Development Bank and the World Bank do not provide concessionary loans for precommercial (pilot) plants.

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 freshwater plant outputs should match local consumption in orders of magnitude.

Another critical point to consider is the preservation of the environment around the selected site since preservation of the environment anywhere is bound to have positive effects elsewhere. OTEC offers one of the most benign power production technologies, since the handling of hazardous substances is limited to the working fluid (e.g.: ammonia for CC-OTEC), and no noxious by-products are generated. 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 and 500 for natural gas fired plants, while for both OC-OTEC and CC-OTEC plants it has been confirmed with experimental plants that no CO_2 is released to the atmosphere.

Ninety-eight nations and territories with access to the OTEC thermal resource within their 200 nautical miles exclusive economic zone (EEZ) were identified in the 1980's. In most of these locations, the OTEC resource is applicable only to floating plants.

[7] It must be noted that the cost of a barrel (42 US Gallons) is typically reported delivered to a large location like New York, but the cost delivered to small markets like SIDS and islands hosting military installations is currently doubled.

2.0 Archival OTEC Capital Costs Estimates

Our archival Capital Costs gathered over the last 30 years for different OTEC systems, categorized by net power output for the indicated average temperature difference, are summarized in Table 2. The Table includes source and year of publication with values extrapolated to the present using the USA Manufacturing-Price-Index (MPI) from the date of the original estimate to December 2021. This date was chosen on the advice of most manufacturing companies contacted. The consensus was that during 2022 a marked raw materials price increase due to the Covid Pandemic was temporary and the expectation was a return to December 2021 costs.

The last three entries are for plants whose costs are based on our current upper limit estimates obtained between January and June 2023. These estimates are at the Preliminary Design level that is also referred to as Front-End-Engineering-Design (FEED). The FEED estimates will need to be followed with the Final or site specific Detailed-Design documented as required to guide construction and operation. This final step is beyond the purpose of this report. It is interesting to note that it is common practice for most Offshore Engineering firms operating in the Gulf of Mexico and the North Sea to add between 30% to 50% to their cost estimates at the FEED stage as indicative of what might be expected after site specific Detailed-Design-Engineering is completed.

As done before over the years (Ref. 3 and 4), the capital costs extrapolated to the present are plotted in Figure 4 wherein for convenience a curve has been fitted to the archival values identified by the power rating (MW) assigned in the different references (i.e., without correcting for ΔT because not all designs parameters are reported):

$$\textbf{Capital Cost (\$/kW) = 61980 x [Plant Size (MW)]}^{-0.348}$$

For the purpose of this report we also documented our specifications (Appendices 2 and 3) as input to the FEED stage and obtained current estimates for three CC-OTEC Plantships sized at 5.3, 10.6 and 53.5 MW-net for ΔT 21.5 ºC. Our estimates are also plotted as indicated by the red circles. At this design level, the general agreement indicates that it is appropriate to use these values as the input to the estimation of LCOE ($/kWh).

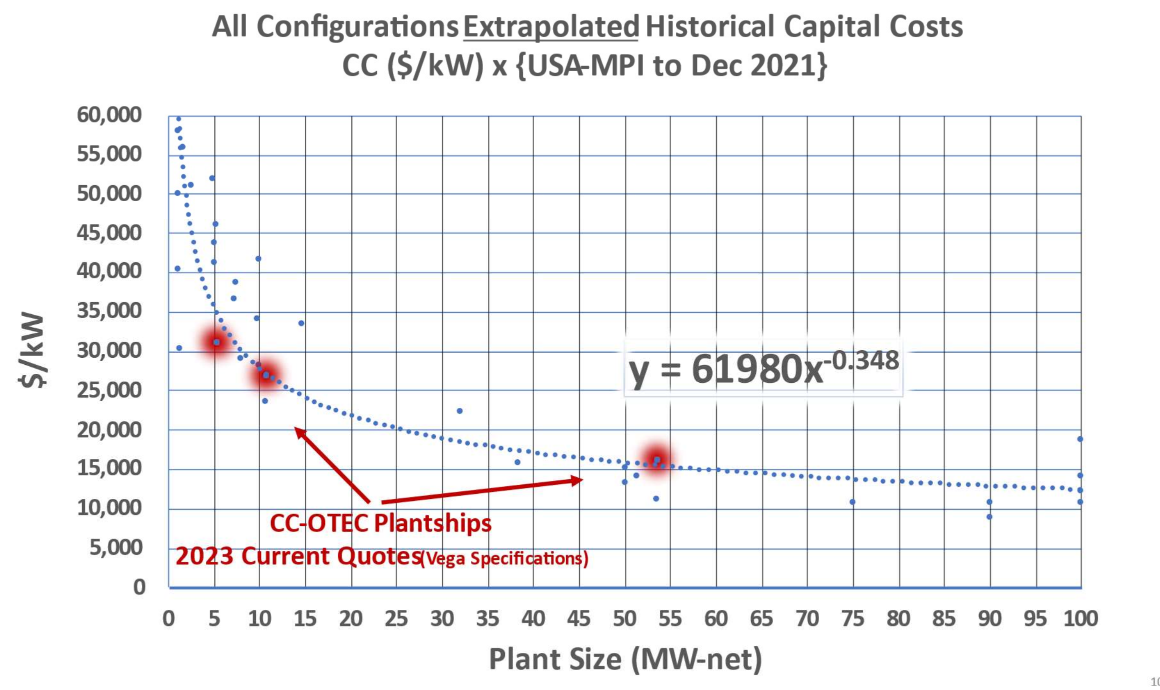

Fig 4.- Historical Capital Costs of all Credible published estimates for both CC-OTEC and OC-OTEC extrapolated to 2023 using Manufacturing Price Index. Three current estimates (5, 10 and 50 MW-class) from this report are shown (ΔT = 21.5 ºC).

Land/ Floater	CC OC Hybrid	MW-net	Desalinated Water m^3/day	ΔT (ºC) Design	Installed CC ($/kW)	Year	Offshore Distance km	Quote (1) Old (2) New	Source	CC ($/kW) x MPI Dec 2021
L	**OC+2nd**	1.0	4,000	20.0	30,000	1990	0	SOA	Vega	57,960
L	**OC**	1.08	1,700	20.0	25,900	1990	0	SOA	Vega	50,039
L	**OC+2nd**	1.126	5,153	22.0	24,000	2000	0	(1)&(2)	Vega	40,464
L	**OC**	1.234	2,232	22.0	18,000	2000	0	(1)&(2)	Vega	30,348
L	**H**	1.67	3,800	21.5	40,598	2008	0	(1)	E3Tec	56,025
F	**CC**	2.5	0	21.6	42,800	2011	20	(1)&(2)	LM	51,103
L	**CC**	4.93	0	22.7	41,457	2015	0	(1)	E3Tec	51,946
L	**CC**	5.0	0	22.0	22,812	1995	0	(1)&(2)	Wenzel	41,221
F	**CC**	5.0	0	24.3	35,000	2015	10	(1)&(2)	Technip	43,860
F	**CC**	5.26	0	21.5	24,715	1994	10	(2)	Vega	45,995
L	**OC+2nd**	7.2	35,000	20.0	19,000	1990	0	SOA	Vega	36,708
L	**CC**	7.43	0	22.7	30,865	2015	0	(1)	E3Tec	38,674
L	**OC**	8.0	15,000	20.0	15,000	1990	0	SOA	Vega	28,980
F	**H**	9.7	23,680	21.5	25,080	2007	10	(1)	Vega	34,034
F	**CC**	9.97	0	22.7	33,325	2015	22	(1)	E3Tec	41,756
F	**CC**	10.0	0	24.3	22,500	2015	10	(1)&(2)	Technip	28,200
F	**CC**	10.6	0	21.5	18,680	2007	10	(1)	Vega	25,349
F	**CC**	10.66	0	21.5	17,452	2007	10	(1)&(2)	Vega	23,682
F	**CC**	14.71	0	22.7	26,767	2015	22	(1)	E3Tec	33,539
L	**H**	31.96	62,000	20.0	11,600	1990	0	SOA	Vega	22,411
L	**CC**	38.3	0	20.0	8,200	1990	0	SOA	Vega	15,842
F	**CC**	50	0	20.0	6,900	1990	10	SOA	Vega	13,331
F	**CC**	50	0	20.0	7,900	1990	50	SOA	Vega	15,263
F	**OC**	51.25	118,434	21.5	10,751	2009	10	(1)&(2)	Vega	14,256
F	**CC**	53.5	0	21.5	8,430	2009	10	(1)&(2)	Vega	11,178
F	**CC**	75.0	0	21.5	7,893	2007	10	(1)	E3Tec	10,710
F	**CC**	90	0	21.5	7,517	2011	10	(1)&(2)	Nihous	8,975
F	**CC**	90	0	21.5	9,038	2011	100	(1)&(2)	Nihous	10,791
F	**CC**	100	0	21.5	7,900	2007	10	(1)	Vega	10,720
F	**CC**	100	0	20.0	6,300	1990	10	SOA	Vega	12,172
F	**CC**	100	0	20.0	7,300	1990	50	SOA	Vega	14,104
F	**CC**	100	0	24.3	15,000	2015	10	(1)&(2)	Technip	18,800
F	***CC***	*5.26*	0	*21.5*	*31,250*	*2023*	*10*	*(2)*	*Vega*	*NA*
F	***CC***	*10.6*	0	*21.5*	*27,012*	*2023*	*10*	*(2)*	*Vega*	*NA*
F	***CC***	*53.5*	0	*21.5*	*16,578*	*2023*	*10*	*(2)*	*Vega*	*NA*

Table 2.- Historical Cost Estimates Extrapolated to 2023. Data labelled E3Tec was supplied by Dr. C.B. Panchal. Technip is from the 3rd OTEC Symposium (2015) presentation by Jim O'Sullivan. All others from work performed with our participation.

Table 3, for example, provides the variations in output for our 53.5 MW CC-OTEC plantship (for average ΔT of 21.5 ºC) for sites with different average ΔT. This is indicative of the corrections that would be required in the Capital Cost Table to compare the different values obtained by different organizations at the FEED stage.

50 MW Class Power Output as a function of ΔT

ΔT	P (MW-net)	Pnet/Pdesign
19.5	39.7	0.74
20.5	46.5	0.87
21.5	**53.5**	**Design Tww:26 ºC/Tcw:4.5 ºC**
22.5	60.8	1.14
23.5	68.4	1.28
24.5	76.3	1.43

14

Table 3.- 50 MW-Class Power Output as a function of ΔT indicating the 43% increase in electricity generation for DROTEC Applications. Note that this is with a plant designed for ΔT average conditions @ 21.5 ºC and keeping the same mass flow rate of working fluid (e.g., the same HXs).

3.0 Updated Cost Estimates

As stated above we documented Equipment Specifications for plants utilizing either closed cycle (CC) or open cycle (OC) technology. A 50 MW-class CC-OTEC plant, for example, requires a 198 m long ship-shaped platform with 39 m beam and an operating draft of 16 m resulting in 120,600 tonnes (metric ton) displacement. The OC-OTEC plant would be shorter at 176 m but beamier 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.

For our 50 MW class design, the combined needs for substantial amounts of cold seawater (≈140 m^3/s), and minimal pumping power losses result in a relatively large diameter CWP. Originally, a 1,000 m long 8.7 m i.d. fiber-reinforced-plastic (FRP) sandwich construction CWP was selected. However, we found out that HDPE pipes are currently available in larger diameters that can be used as the CWP in bundles for the 10 MW (2 pipes) and the 50 MW (8 pipes) resulting in relatively lower costs. The CWP bundle would be attached to a gimbal at midship. Applicable single point mooring systems, including electrical and fluid swivels, are available from the offshore industry. For this case, the heat exchangers considered for the ammonia cycle can be manufactured primarily in the EU with some alternatives also available 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).

For the 50 MW class plant considered, for example, electricity and desalinated water production rates are: 432,609 MWh/year for the CC-OTEC; and, 414,415 MWh/year and 118,434 m^3/day for the OC-OTEC.

Our updated survey confirms that the equipment for all subsystems (except for TGs for OC-OTEC) is available based on off-the-shelve designs that are currently manufactured. However, because they were not designed specifically for OTEC's high seawater flow rates numerous units are required to be installed in parallel to meet our specifications. For example, the CC-OTEC 10 MW class (5x for the 50 MW class) using Plate-Frame Ti HXs would require at least 48 evaporator units and 36 condenser units; and 28 warm seawater pumps and 6 cold seawater pumps. The hope is that as plants are implemented markets develop for OTEC-specific components resulting in a considerable decrease in subsystems' costs.

Some long-lead items would require from 18-months to 24-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.

We were able to obtain current cost estimates for all major components of the power block with the noticeable exception of TGs for OC-OTEC. Our archival estimates included information from *Mitsubishi Heavy Industries* (MHI) for 2.5 MW units based on the low pressure end of turbines designed for nuclear plants (e.g., Appendix 6).

Unfortunately, *Mitsubishi Heavy Industries* is no longer manufacturing such units and we were not able to identify a new supplier. *Siemens* was extremely helpful in our search, but they don't have a current design adaptable to our conditions.

Our current capital cost estimates for the CC-OTEC class are summarized in Table 4 and Figure 5 and for the OC-OTEC class in Table 5A and Figure 6. For the baseline conditions, the OC-OTEC estimate is higher than the CC-OTEC estimate by 32% for the 10 MW-class and 47% for the 50 MW-class. Therefore, presently we should concentrate on the implementation of CC-OTEC Plantships unless sites with relatively high costs of desalinated water are identified[8].

In addition Table 5B provides our current cost estimate for the Land- Based 1.36 MW OC-OTEC Plant including the generation of 2,450 m^3/day desalinated water.

These current estimates are applicable for equipment purchased from firms with headquarters in the EU and USA, and with installation by firms with expertise in offshore petroleum deepwater installations.

One might speculate, based on the implementation of similar technologies, that later generation designs will reach cost reductions of about 30%.

CC-OTEC	10.6 MW		53.5 MW	
Component	**$M**	**10 MW %**	**$M**	**50 MW %**
New Plantship	28.3	10%	84.5	10%
Mooring (*BWO*)	22.0	8%	29.0	3%
Pwr Cable (*PRYSMIAN*)	3.7	1%	4.2	0%
Pipes (*AGRU*)	10.9	4%	43.5	5%
Water Pumps (*FLYGT*)	11.5	4%	57.5	6%
NH3 Pumps (DICKOW)	0.65	0.2%	3.4	0.4%
HXs Ti (*Alfa Laval*)	84.0	29%	420.0	47%
TG (*Atlas Copco*)	13.5	5%	67.5	8%
*Generic Install & Assem	111.8	39%	177.3	20%
TOTAL ($M)	**286.3**		**886.9**	
$/kW (w/ Alfa Laval)	***27,012***		***16,578***	
$/kW (w/ Kelvion)	***21,606***		***11,223***	
Install & Assembly	***$M***		***$M***	
Mooring & Power Cable	*43.5*		*58.4*	
Pipes & Pumps	*8.0*		*34.8*	
Power Block	*33.2*		*57.0*	
Electrical & Controls	*27.1*		*27.1*	

Table 4.- CC-OTEC Current Cost Estimates for major Subsystems. The category "Installation and Assembly" is the same amount independently of HXs supplier and includes educated estimates associated with transportation to a generic site and equipment mobilization and demobilization. Category % are with Alfa Laval HXs.

[8] The levelized cost of electricity with credit for desalinated water production is discussed in Chapter 4,

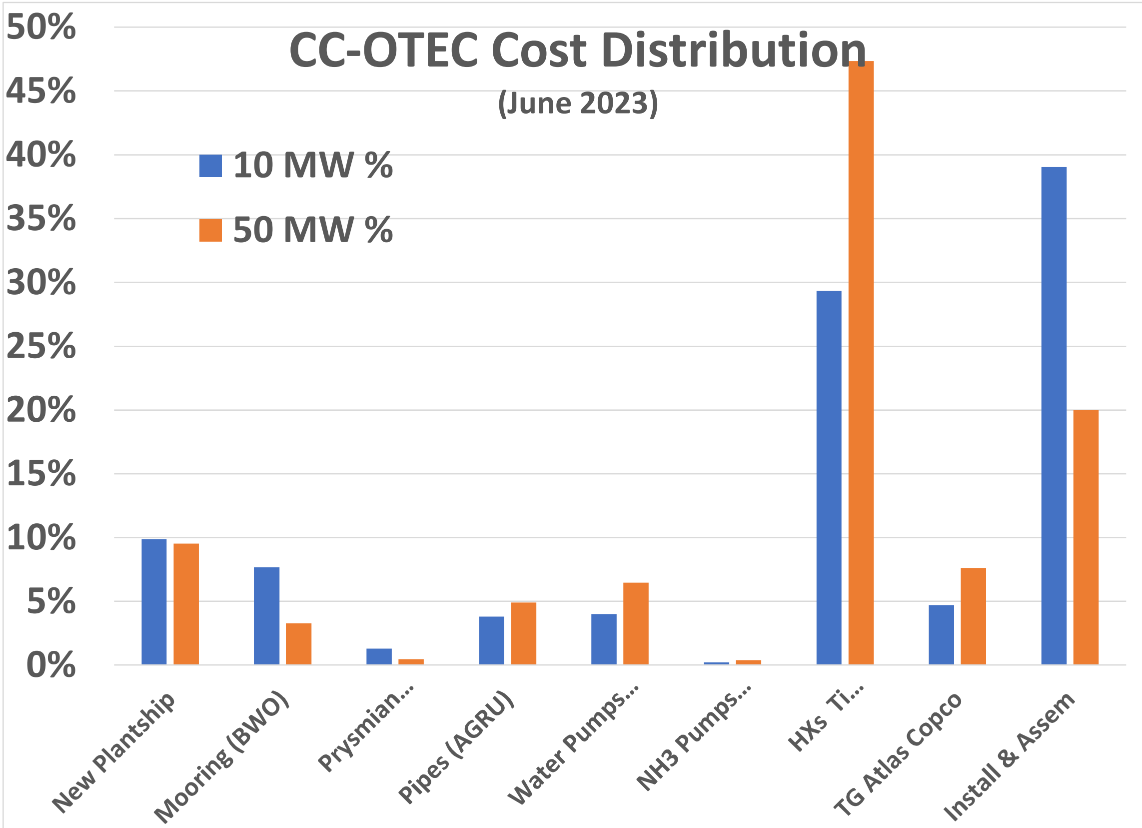

Figure 5.- CC-OTEC Cost Distribution with Alfa Laval Heat Exchangers. The HXs cost distribution with Kelvion is 12% instead of 29% (10 MW); and 22% instead of 47% (50 MW).

OC-OTEC	10.2 MW	6.3 MGD	51.25 MW	31.3 MGD
Component	**$M**	**10 MW %**	**$M**	**50 MW %**
New Plantship	47.3	13%	141.0	11%
Mooring (BWO)	22.0	6%	29.0	2%
Prysmian Power Cable	3.7	1%	4.2	0%
Pipes (AGRU)	10.9	3%	43.5	3%
Water Pumps (FLYGT)	11.5	3%	57.5	4%
Compressors (Edwards)	61.40	16.2%	307.0	23.5%
Flash Evp/SurfCndsr	56.7	15%	283.5	22%
TG (TBD)	53.1	14%	265.5	20%
Install & Assem	111.8	30%	177.3	14%
TOTAL ($M)	**378.4**		**1308.6**	
$/kW	**35,697**		**24,459**	
$/kW (with DCC)	**33,962**		**22,722**	

Table 5A.- OC-OTEC Plantship Current Cost Estimates. The category "Installation and Assembly" distribution is the same amount as in the case of CC-OTEC (Table 2) and independent of Condenser type and includes educated estimates associated with transportation to a generic site and equipment mobilization and demobilization.

Component	Cost: $ 42.8 M 31,470 $/kW	Percentage
CWP/WWP/RP	**$4 M**	**9.3 %**
SW Pumps	**$1.3 M**	**3 %**
Installation SW Pipes/Pumps	**$11 M**	**25.7 %**
Land Structure w/ *Power Block Install*	**$8.4 M**	**19.6 %**
Flash Evaporator	**$1.7 M**	**4 %**
Surface Condenser	**$4.6 M**	**10.7 %**
Turbine-Generator	**$5.9 M**	**13.8%**
NC Removal Compressor	**$3.4 M**	**8 %**
Auxiliary Genset	**$0.8 M**	**1.9 %**
Balance (Utility Connect)	**$1.7 M**	**4 %**

Table 5 B.- Land-Based 1.36 MW-net OC-OTEC with Desalinated H_2O generation at 2,450 m^3/day (Ref. Appendix 6)

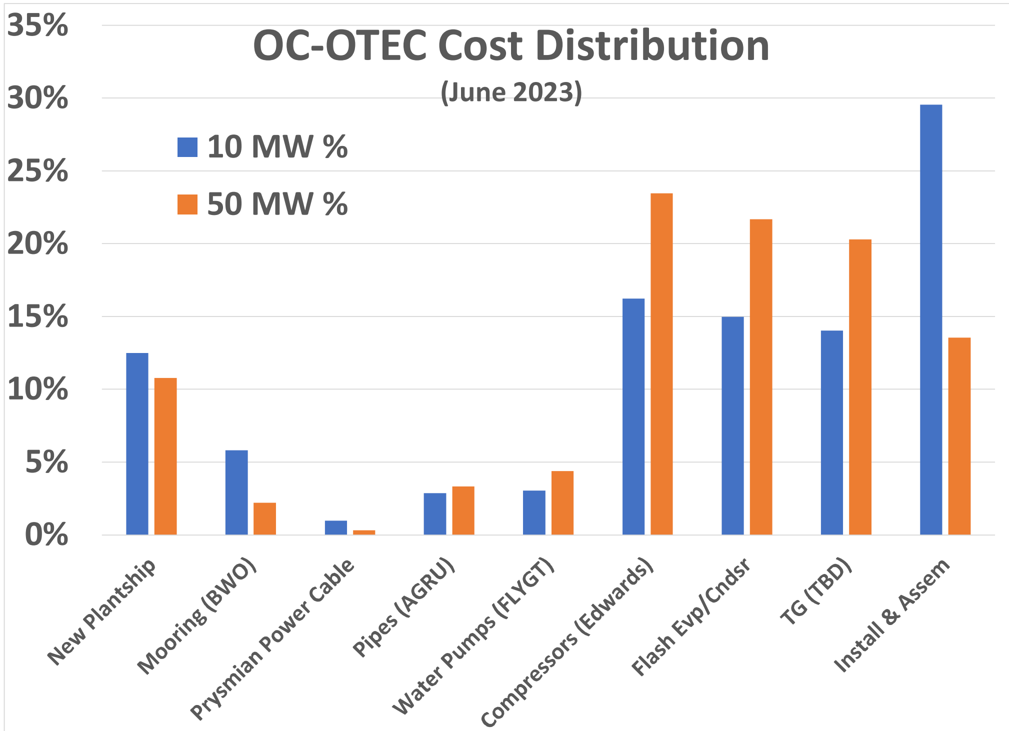

Figure 6.- OC-OTEC Cost Distribution with the Surface Condensers required for Desalinated Water Generation. The Direct-Contact-Condensers are less expensive but Desalinated Water is required to compete with CC-OTEC in Specific Locations.

	15 MW	
Component	**$M**	**15 MW %**
Refurbished Vessel	25.4	12%
Mooring (NA)	0.0	0%
Power Cable (NA)	0.0	0%
Pipes (AGRU)	10.9	5%
Water Pumps (FLYGT)	11.5	5%
NH3 Pumps (DICKOW)	0.65	0.3%
HXs Ti (Alfa Laval)	84.0	39%
TG Atlas Copco	13.5	6%
Install & Assem	68.3	32%
TOTAL ($M)	**214.2**	**w/Alfa Laval**
$/kW	**14,283**	**"**
LCOE @ 8%/15 yrs	***0.325 $/kWh***	**"**
TOTAL ($M)	**156.9**	**w/Kelvion**
$/kW	**10,463**	**"**
LCOE @ 8%/15 yrs	***0.238 $/kWh***	**"**

Table 6.- 15 MW Demand Response OTEC (DROTEC) to Drift along the Equator with ΔT = 24.5 ºC instead of design value of 21. 5 ºC generating electricity to be used onboard to support energy intensive technologies/applications (e.g., high-density computing) that can operate remotely communicating via Satellite.

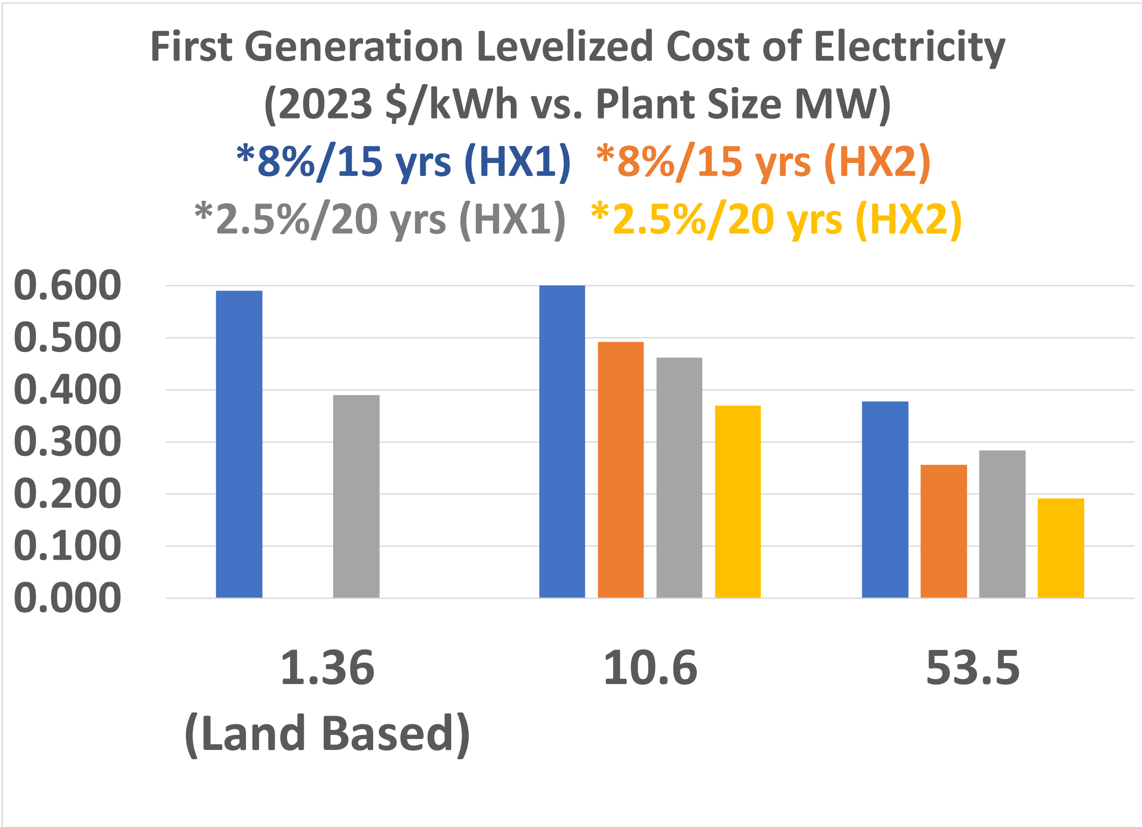

Figure 7.- LCOE ($/kWh) as a function of Plant Size. The 1.36 MW Land Based is OC-OTEC with credit for 2,450 m^3/day Desalinated Water @ 1.5 $/$m^3$. The 10.6 and 53.5 MW are for CC-OTEC Plantships per our Specifications (ΔT = 21.5 ºC). Although Concessionary Loans (e.g., 2.5 % /20 years) are not feasible for first generation plants, estimates are included as reference. Comparing HX1 (Alfa Laval) with HX2 (Kelvion) illustrates the importance of resolving the cost differential for the most expensive components of CC-OTEC. Clearly the next step towards worldwide development is the implementation of a government funded demonstration plant sized at ≈ 5 MW.

3.1 Vessel (Ship-Shaped)

At this developmental stage we must consider generic sites for the floating plants operating throughout the OTEC region, therefore, only ship-shaped vessels were considered. It must be noted that, for example, Semisubmersible or Spar vessels will at least double the costs estimated herein for the ship shaped vessels.

Given that most government-unsubsidized Container Ships and Tankers are currently manufactured in Japan and South Korea the following shipyards were contacted multiple times without success. We also asked colleagues in South Korea and Japan to contact the shipyards, but they were also not able to obtain quotes.

Container Ships & Tankers Manufacturers	Location
HYUNDAI Heavy Industries Korea Shipbuilding & Offshore Engineering Company (**KSOE**)	South Korea
DAEWOO Shipbuilding & Marine Eng. Company (DSME)	″ N.B. Hyundai/Daewoo Merger blocked by EU
SAMSUNG Heavy Industries	″
K Shipbuilding	″
IMABARI Shipbuilding	Japan
MITSUBISHI Heavy Industries	″
MITSUI	″
SUMITOMO	″

As an alternative we searched press releases and trade magazines for information about current orders and costs for vessels of Dimensions and Dead-Weight-Tonnage (DWT) matching our specifications (Appendices 2 and 3). Relevant information is given in Table 7 and incorporated into Figure 8.

In addition and as a professional courtesy, *Blue Water Offshore (BWO)* provided guidance and information that allowed for additional and realistic cost estimates to be incorporated. Figure 8 provides the relationship between the cost of a Vessel ($/tonne) and DWT from all sources. Our colleague Dr. Kim (former Head of the South Korea OTEC team) was also able to share the current cost of their 10,000 DWT barge that matches within 10% the relationship that we derived.

Note that the cost for a vessel labelled as “New Tankers” in Figure 8 refers to vessels that are brand new and currently available at much lower cost because the purchasers were unable to meet financial obligations. In addition we include the cost of vessels that are 10-years old and available for purchase “second-hand”. As suggested by *BWO* we could consider existing classes, for example, a 40,000 DWT *“MR CLEAN”* product tanker seems suitable for the 10 MW case with plenty additional space (only 18,980 DWT required for the CC-OTEC components). For the 50 MW case consider a 95,000 DWT *“AFRAMAX”* (vs 88,038 DWT required). Considering 10 years old units, the following prices are realistic in 2023:

MR CLEAN 10 years: $20 M
AFRAMAX 10 years: $30 M

During conversion the hull would be significantly reinforced. <u>The cost of conversion of the hull, integration of the plant and commissioning will at least double those values.</u>

Although these vessels could be used in our cost estimating, we decide to <u>use the algorithm derived from the curve labelled “Container Ships 2015-2021”</u> (Figure 8 and Table 8) because we are not prepared to place an order.

If somehow funding could be obtained to implement the much desired pilot plant a “10-Years Old” vessel should be considered. This would represent a substantially lower cost.

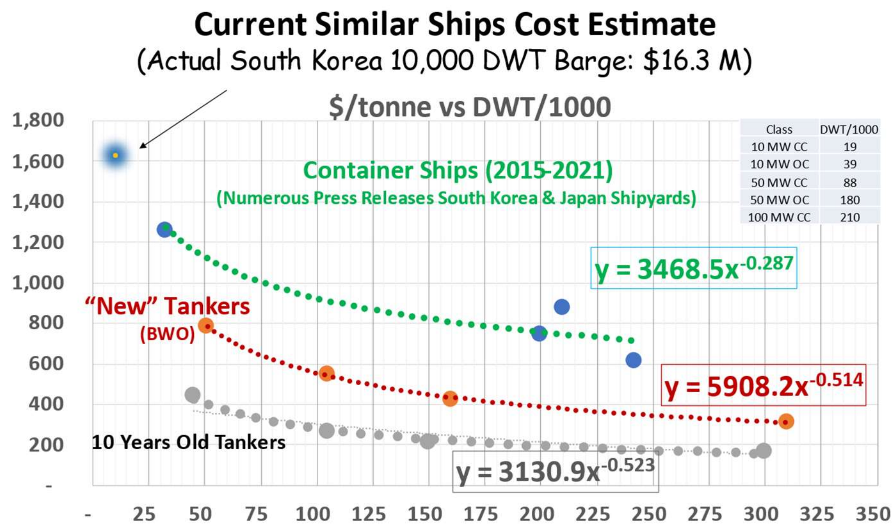

Figure 8.- Plantship Capital Cost including Propulsion System, Excluding Mooring, OTEC Power Block and Seawater Piping System.

Existing Container Ships	LBP x Beam x Draught meters	"Displacement" tonnes	Date & Shipyard	All included Cost US $M
Ever Orient (Evergreen O-Class)	195 x 32 x 11.4	Deadwght: 32,500 Displacement: 43,749 (Cb:0.6) **2634 TEU** **12.3 t/TEU**	**2021** Cost taken from similar order by Namsung Shipping to Hyundai for 2500 TEU ships	**41 (2021)** **43 (2022)** **CC ($M)/(LBPxBxD)= 576 $/m³** **CC ($M)/DWT= 1262 $/t** **CC ($M)/TEU= 15566 $/TEU**
Ever Given *(Evergreen G-Class)* Container Ship 1 of 13 ships **"Imabari 20000 Design"**	399.94 x 58.8 x 14.5 (Height: 32.9 m) Single Engine: 59 MW **Two Bow Thrusters: 2.5 MW each**	**265,876** (Cb : 0.76) Deadwgth: 199,629 Lightwgth: 66,247 (25%) **20,124 TEU** 9.9 t/TEU	**Sep 2018** **Imabari** Shipbldg Japan	**150** **CC ($M)/(LBPxBxD)= 440 $/m³** **CC ($M)/DWT= 751 $/t** **CC ($M)/TEU= 7454 $/TEU**
Maersk Triple E 2 11 Container Ships 2nd Generation	400 x 59 x 17 (Height: 73 m)	DWT: **210,019** **20,568 TEU** each 10.9 t/TEU	Other placed in 2015 delivered 2017-2019 **Daewoo** **(South Korea)**	**185 each** **CC ($M)/(LBPxBxD)= 461 $/m³** **CC ($M)/DWT= 881$/t** **CC ($M)/TEU= 8995 $/TEU**
Evergreen A-Class 13 Ships	400 x 61.5 x 16.5	Ever Ace (July 2021) Deadwgth: 241,960 **23,992 TEU** 10.1 t/TEU	**2021 to 2022** **6** (Samsung) **7** (China State Shipbuilding Co.)	**150 ± 10** **CC ($M)/(LBPxBxD)= 370 ± 25 $/m³** **CC ($M)/DWT= 619 ± 41 $/t** **CC ($M)/TEU= 6252 ± 417 $/TEU**

Table 7.- Container Ships with Displacement matching 10 to 100 MW OTEC Plantships.

OTEC Plantship	DWT	Container Ship Algorithm	"New" Tanker Algorithm	10-Year Old Tanker Algorithm
10 MW CC-OTEC	18,980	$28.3 M	*$24.7 M*	*$12.7 M*
10 MW OC-OTEC	38,982	$47.3 M	*$35.0 M*	*$18.0 M*
50 MW CC-OTEC	88,038	$84.5 M	*$52.1 M*	*$26.5 M*
50 MW OC-OTEC	180,602	$141.0 M	*$73.8 M*	*$37.3 M*

Table 8.- Empty OTEC Plantship Cost Estimates per Figure 8.

Table 8 provides the costs estimated for the Plantships. Note that Semisubmersible or Spars with similar DWT will at least double the costs tabulated for the ship shaped vessels.

Note that to these acquisition estimates we must add conversion and installation costs for all major components. These would at least add $20 M to $30 M to the costs tabulated for the "Empty Plantship".

3.2 Cold Water Pipe

Historically, for Plantships, we considered FRP-sandwich CWPs based on designs that led to the proof of concept NOAA 1982 at-sea test. However, current developments in the manufacturing of High-Density-Polyethylene-Pipes (HDPE) lead us to the selection of pipe bundles. HDPE pipes are currently available in larger diameters of appropriate thickness (3 m i.d.) such that they can be used as the cold-water-pipe (CWP) for a 5 MW plant (*the dream baseline for a demonstration plant*) and in bundles for the 10 MW (2 pipes) and the 50 MW (8 pipes) resulting in relatively lower costs. Depending on design specific environmental (waves and currents) conditions the CWPs might need to be attached using a gimbal to decouple pitch and roll vessel motions. The full-length CWPs bundles should be towed horizontally and upended at the site where the plantship is already positioned. Further information is found in Appendix 5.

Due to CWPs installation considerations the size of OTEC land-based plants should be sized at less than about 5 MW. Further information is found in Appendix 6.

Table 9 provides the costs estimated for the CWPs. To these estimates we must add transportation costs from the factory to a "generic" site, assembly, and installation costs incorporating the warm water pipe (WWP) and mixed return pipe (MRP). Similar costs also must be added for the components listed in all sections of Chapter 3.

Class	Length(m)/OD(m)/DR	AGRU Factory Cost	PIPELIFE* Factory Cost
Land Based 1.3 MW-net	1200/1.6/32.5	$ 1,057,900	$ 927,048
	600/1.6/26	$ 651,050	$ 570,096
	600/1.6/21	$ 801,860	$ 668,964
5 MW-net Plantship	1000/3.26/26	$ 4,733,060	NA
10 MW-net Plantship	2 x 1000/3.26/26	$ 9,466,120	NA
50 MW-net Plantship	8 x 1000/3.26/26	$ 37,864,480	NA

DR = OD/t; t = thickness
*PIPELIFE (Norway) January 2023 quote in Euros @1.07 $/EUR

Table 9.- HDPE Cold-Water-Pipe Cost Estimates.

The cost of the nominally 100 m long pipe system combining the cold and warm seawater return ("discharge") to depths below the photic layer is estimated at 15% of the cost of the CWPs.

3.3 Mooring System

We contacted *SBM*, *SOFEC* and *BWO* for price estimates based on the mooring design information that we have collected over the years considering different sites (e.g., Appendix 5). *SBM* required a subcontract to provide design concepts. *SOFEC* provided some guidance via teleconferences and *BWO* documented their suggestions as summarized below.

As suggested and kindly shared by BWO considering a MR CLEAN tanker for the 10 MW case and an AFRAMAX for the 50 MW case, Spread Mooring should be optimal for the proposed combination of water depth (≈ 1,000 m) and Hs (6 to 7 m) in non-cyclonic areas such as Brasil. Each mooring leg is preliminary devised as 90mm bottom chain R4 100m from suction anchor (100MT) + 1800m Ø 150-160mm Polyester Rope + 200m upper wire Ø77 + Fairleads + Chain Stopper. Estimated to $1.8 M each.

A MR CLEAN should require a 4 x 3 legs arrangement for an estimated total of $21.6 M;
An AFRAMAX should require a 4 x 4 legs arrangement for an estimated total of $28.8 M.

In addition, BWO indicated that Turret Mooring should be required under cyclonic conditions such as off Hawaii. Such a solution avoids any interference with the CWPs. However, it requires stern thrust to always pull the vessel away. This represents additional capital and operational costs. Moreover, it implies an electrical swivel sitting subsea on the yoke table. A subsea electrical swivel, mounted as a detachable cartridge so that you could pull it up for IMR is perfectly feasible but certainly not straight forward and IMR would be quite costly. For OTEC parameters the cost estimate is $40 M - $45 M.

BWO also evaluated Internal Turrets with the CWPs suspended in the center of the large moon pool under the internal turret. Given that the CWP bottom end is free and open it might not be necessary to incorporate a swivel joint as shown in most design reports we provided. We are not to swivel the Cold Water Intake GRP pipe as its bottom end is free and open. In such a central position, it should not slash with the mooring legs.

Mooring: 3x3 arrangement. 90mm bottom chain R4 100m from suction anchor (100MT) + 1800m Ø 150-160mm Polyester Rope + 200m upper wire Ø77 Estimated at $15 M. The Internal Turret also $15 M. The Electrical Swivel: $8 M for the 10 MW Case and $15 M$ for the 50 MW. The total capital cost estimates are $ 38 M for the 10 MW case and $45 M for the 50 MW case. Ship modification and integration is not included.

At this stage, BWO recommended for hurricane prone sites like Hawaii to stay focused on an Internal Turret solution.

For this report considering generic OTEC sites we opted to utilize the costs estimated provided by *BWO* for spread moorings. That is, **$22 M for a 10 MW** (note from Table 8 that a Mr. Clean can be used to estimate both the CC-OTEC and OC-OTEC cases) **and $29 M for a 50 MW CC-OTEC.**

These estimates exclude Deck modification and integration.

3.4 Submarine Power Cables

Given the numerous press releases and project descriptions over the last 5 to 15 years from several manufacturers of submarine power cables that would qualify for OTEC applications we were surprised by our inability to obtain current quotes. Fortunately, at the Offshore Technology Conference (OTC May 2023) some colleagues were able to contact *PRYSMIAN* in person and we got the required information by June 2, 2023.

The following companies were also contacted but unfortunately did not provide information for what was considered an academic study: *JDR, NEXANS, XLCC*.

The letter soliciting information included the following statement extracted from a study conducted for my team by *Pirelli* twenty years ago:

> *A submarine power cable is required to transmit the electricity produced by an OTEC power plant from the moored floating platform (Plantship) to shore. We envision two potential nominal cases: (i) Plantship moored 10 km offshore; and (ii) Plantship moored 100 km offshore. We envision, for example, submarine power cables in 3-core AC configurations with ethylene- propylene-rubber (EPR) insulation operating at a voltage of 34.5 kV for the 10 MWe case and 69 kV for the 50 MWe case.* *Each copper wire conductor would be approximately 15 mm diameter.* *We expect that the submarine power cables would have an outside diameter of about 10 cm for the 10 MWe plant and about 13 cm for the 50 MWe plant. The power cables would be attached to the Plantship via a single point mooring/power-swivel system.*

Table 10 provides a summary of the information provided by *PRYSMIAN* for their factory located at Vila Velha – Brasil. For the 10km case they could ship in one or two 8.6m reels while for 100km they would need a carousel.

Plantship Class	Cable Length	Power Cable Voltage	Cost FOB Brasil Factory
10 MWe	10 km	34.5 kV/ 1.5 % voltage drop	3.68 $M *(FDT-1736)*
10 MWe	100 km	34.5 kV/ 8.1 % voltage drop	34.8 $M *(FDT-1736)*
50 MWe	10 km	69 kV/ 1.6 % voltage drop	4.16 $M *(FDT-1737)*
50 MWe	100 km	69 kV/ 10.3 % voltage drop	39.3 $M *(FDT-1737)*

Table 10.- Submarine Power Cables by PRYSMIAN.

As emphasized by Prysmian, cost of cable installation cannot be accurately estimated without specifying location. For example, a deep water installation off Hawaii will require to mobilize a Jones Act compliant DP cable installation vessel or specialized vessel coming from Europe. Such vessels are available on the east coast of the USA or from Europe which would take several weeks for mob/demob.

Moreover there is no supply chain on the Pacific Coast for highly specialized services such as ROV survey and route preparation. Currently, such expertise would have to be mobilized from the East Coast passing through Panama Canal.

Herein, we will assume a simple case under optimum circumstances. Installation from the shoreline to 10 km offshore with a specialized cable laying vessel requiring as much as 6 $M for mobilization/demobilization alone plus on site charges requiring a budget of as much as 15 $M. In addition to about 1 $M for the survey and, in some cases, horizontal-directional-drilling for shore landing adds to the cost such that an Installation Budget of 20 $M (2023 estimate) is used herein for a generic site[9] in addition to the actual cable cost from Table 10.

3.5 Seawater Pumps

Using the Specifications from Appendices 2 and 3, we were able to obtain current quotes from Flygt (Xylem) for the submersible seawater pumps required for the OTEC plants (same flow rates for both Open and Closed Cycle) under consideration. We have positive field experience operating their pumps.

Flygt pumps are also currently in use at NELHA (Natural Energy Laboratory of Hawaii Authority), but it must be noticed that their total flowrate is at most 10% of the rate required for our 10 MW case. The numerous pumps required will be installed submerged in a sump (moon pool) in parallel requiring substantial piping and appendages. The total cost given in the Table below excludes Freight and Installation costs.

Class	Warm Water Pumps PL 7101/765	Cold Water Pumps PL 7121/936	Total Cost
10 MW net	28 @ $8M total	6 @ $3.5M total	$11.5M
50 MW net	140 @ $40M total	30 @ $17.5M total	$57.5M

- KSB, Torishima, Goulds, Johnson, Clyde Union could not meet our Specifications.

Table 11.- Seawater Pumps by Flygt. Note that due to the required “Low Head-High Flow Rate” the number of “off-the-shelve” Warm Water Pumps is challenging. Manufacturers will consider implementing bigger pumps once a real market is available. This requires as a next step the implementation of the “5 MW” demonstration plant (Table 1) or alternatively DROTEC (Table 5).

Table 11 provides the costs estimated for the seawater pumps. To these estimates we must add transportation costs from the factory to a “generic” site, assembly, and installation costs. Similar costs also must be added for all the components listed in all the sections of Chapter 3.

It must be noticed that the seawater pumps required for OTEC are what is categorized by pump manufacturers as *“high flow rate low head”* and, therefore, are not widely available. The number of “off-the-shelve” pumps that would be required are summarized in Table 11. For a 50 MW warm water stream 140 pumps represent an installation challenge.

[9] Per *Prysmian,* appropriate cable laying vessels are booked through 2028-2029 and Installation Costs for some OTEC locations would be twice the amount of $20 M used herein.

3.6 Closed Cycle Heat Exchangers (Evaporator and Condenser)

Using the Specifications from Appendices 2 and 3, we were able to obtain current quotes from the companies listed in Table 12. The process took several months and ultimately all companies were extremely cooperative. Their cost estimates for equipment delivered at their factories are included in Table 12,

It must be emphasized that a strict requirement imposed for CC-OTEC HXs is the goal of achieving low values for what is called the "Pinch Point". That is, the temperature difference between the working fluid (NH_3) and the seawater temperature:

Condenser Pinch Point = Liquid NH3 Temp out of Cndsr - Cold Seawater Temp out

Evaporator (Boiler) Pinch Point = Warm Seawater Temp out – Liquid NH3 Temp into Boiler

As indicated in Appendices 2 and 3 our goals are 1.1 ºC and 1.2 ºC respectively such that Plate Frame or Plate Fin heat exchangers are preferred because typical Tube & Shell cannot meet such stringent requirements.

Extensive testing of Aluminum coupons exposed to surface and deep ocean water at NELHA were conducted by Makai Ocean Engineering. Their major conclusions were:

> *An evaporator constructed from Al 3003 or Al 5052 can be expected to last up to 15 years with little risk of failure. Extending their lifetime beyond 15 years increases the risk of failure. A condenser constructed from Al 3003 or Al 5052 can be expected to last 10 years with little risk of failure. Brazed joints are only acceptable in the NH_3 side of the condenser and not the side exposed to deep ocean water. Crevice corrosion is severe in stagnant cold seawater, especially for Alloy 3003.*

In addition, it is general knowledge that Titanium HXs exposed to ocean water will last at least 30 years. Depending on costs, an option would be Titanium in the Condenser and Aluminum in the Evaporator. However, for a relatively short test with demonstration plants (say less than 5 years) Aluminum can be used for both HXs.

In addition, it was demonstrated with experimental plants that biofouling in the CC-OTEC evaporator warm water loop can be controlled with, for example, chlorination at 100 ppb applied for one hour per day. Above ground cold water supply lines must be darkened to avoid light penetration eliminating biofouling and the need for chlorination. Biofouling is not an issue with OC-OTEC HXs[10].

Table 12 provides the costs estimated for the "10 MW-class" HXs delivered at the factory. To these estimates we must add transportation costs from the factory to a "generic" site, assembly, and installation costs. Similar cost also must be added for all the components listed in all the sections of Chapter 3.

[10] One of the positive characteristics of OC-OTEC is that biofouling is not an issue, and the working fluid is the surface seawater.

Supplier	10 MW Evp.	10 MW Cnd.	10 MW Total	Note
Plate Frame Ti.				
Kelvion	15.2 $M	11.5 $M	**26.7 $M**	*Off-the-Shelve LWC250S BA-300*
Alfa Laval	48.0 $M AlfaVap 700-FM	36.0 $M AlfaCond 800-FM	**84.0 $M**	*Off-the-Shelve*
Xenesys	24.0 $M	36.0 $M	60.0 $M	*Conceptual Design*
Plate Fin Al.				
Fives Cryo	20.8 $M	31.2 $M	52.0 $M	*Conceptual Design*
CHART	48.0 $M	40.0 $M	88.0 $M	*Off-the-Shelve Units*

**Enerquip, Siemens and Exergy currently don't manufacture components that could meet our Specifications; * Toshiba: no reply.*

Table 12.- Potential Suppliers of CC-OTEC Heat Exchangers. The differential between Alfa Laval and Kelvion quotes, well established manufacturers of Plate Frame Ti HXs, using "off-the-shelve" components is puzzling although confirmed via repeated interactions. Note that (Table 13) the total weight of the HXs units is essentially the same between these suppliers. Given the 15-years life expectancy of the Al Plate Fin HXs compared to 30-years for the Ti HXs and the similarity of costs estimates we will only consider the latter option.

Given that the cost of CHART Al. Plate Fin HXs is not lower than those of Ti. Plate Frame, with twice as long life expectancy, Alfa Laval and Kelvion should be considered at this stage of development. *It must be noted that the cost differential (84/26.8 ≈ 3) is incomprehensible but at this stage of development we must consider both and provide* ***CC*** *($/kW) and* ***LCOE*** *($/kWh) ranges*[11].

Table 13 provides a summary of the information obtained from the potential suppliers of HXs for a 10 MW-net (ΔT = 21.5 ºC) CC-OTEC plants. It must be emphasized that for the first generation of OTEC plants the necessity of having to interconnect in parallel numerous units that are currently manufactured for other applications will be challenging. Alfa Laval, for example, indicated that having to use 48 Evaporator units and 36 Condenser units for the 10 MW plant was *"not a good fit for their equipment".*

Note that in the case of Alfa Laval and Kelvion their total weights are similar. These companies indicated that depending on potential additional orders they could ensemble their plates into larger single units such that installations would be less cumbersome but at first the cost would be similar. Although for the sake of completeness in Chapter 4 we estimate the cost of electricity for both 10 and 50 MW plants we do not consider having to interconnect five times more units in the case of the larger plant as reasonable.

This is the most challenging aspect in the commercialization of CC-OTEC and another reason for having to first implement a demonstration plant sized at about 5 MW.

[11] The HXs costs extrapolated from the historical record correspond to *Kelvion's* current estimates.

Supplier	Evp Basic Unit	" m³ "	Unit Wgth	Number	Eve Total	Cod Basic Unit	m^3	Unit Wgth	Number	Cnd Total
Kelvion	*2.13m x 0.9m x 1.39m*	*2.7*	*3.9 ton*	*141*	*556 tonnes*	*2.13m x 0.9m x 2.3m*	*4.4*	*5 ton*	*74*	*370 tonnes*
Alfa Laval	*4.93m x 1.69m x 3.12m*	*26*	*12 ton*	*48*	*570 tonnes*	*5.82m x 1.13m x 3.39m*	*22*	*10 ton*	*36*	*367 tonnes*
Xenesys	*1.1m x 1.5m x 3.2m*	*5.3*	*11 ton*	*80*	*880 tonnes*	*1.1m x 1.5m x 3.2m*	*5.3*	*11 ton*	*120*	*1,320 tonnes*
Fives Cryo	1.3m x 1.46m x 3.3m	6.3	10 ton	32	320 tonnes	1.3m x 1.77m x 4.3m	9.9	15 ton	32	480 tonnes
Chart	1.2m x 4.4m x 2.4m	13	19 ton	64	1,203 tonnes	1.2m x 6.4m x 2.4m	18.9	26 ton	64	1,674 tonnes

** The "volume" entry in m^3 is provided as guidance to estimate 1st generation volume requirements in the HXs Plantship compartment.*
** Alfa Laval and Kelvion inputs are for "of-the-shelve" Titanium Plate Frame HXs resulting in numerous units with interconnections challenges. As OTEC is implemented and orders are placed they would design larger units to minimize installation requirements for later generations.*

** Xenesys is also Ti Plate Frame with manufacturing capabilities for an ≈ 1 MW plant. Their factory would require expansion to supply 10 MW. Note that the Xenesys entry indicates much higher weights and the condenser heavier than the evaporator.*

** Fives Cryo and Chart are Aluminum Plate Fin. Chart based their information in "off-the-shelve" units while Fives Cryo would require R&D.*
** Chart confirmed their information indicating the highest weights entry*

Table 13.- Dimensions and Weights of 10 MW-net CC-OTEC Heat Exchangers.

3.7 Ammonia Pumps

Using the Specifications from Appendices 2 and 3, we were able to obtain current quotes from *Dickow* for the NH_3 pumps required for the CC-OTEC plants under consideration.

We have positive field experience operating their pumps. *Dickow* pumps have the motor shaft magnetically coupled to the impeller shaft across a stainless enclosure, which means that there are no moving process fluid seals to fail and leak.

The total costs given in Table 14 exclude Freight and Installation costs.

Class	NH_3 Feed Pumps MMRs 250/400	NH_3 Recirc. Pumps MMRs 250/320	Total Cost
10 MW net	4 @ $285K	6 @ $368K	$653K
50 MW net	20 @ $1,537K	30 @ $1,837K	$3,374K

- Clyde Union could not meet our Specifications.

Table 14.- Anhydrous Ammonia (NH_3) Pumps by Dickow.

To these estimates we must add transportation costs from the factory to a "generic" site, assembly, and installation costs. Similar costs must also be added for all the components listed in all the sections of Chapter 3.

3.8 Closed Cycle Expander Generator (Turbine Generator)

After a long search for current information we were able to get a quote from *Atlas Copco*. The largest Radial Turbo Expander unit they manufacture corresponds to 5.8 MW at the generator terminal. This unit can be delivered 65 weeks after the order is placed. The cost at the factory would be $4 to $5 M. We estimate 3 units for the 10 MW class and 15 units for the 50 MW class.

NH_3 Turbine Generator

CC-OTEC Class Electricity Generation Mode ΔT= 21.5 ºC	**TG System Cost at Atlas Copco Factory (2023)**
Atlas Copco Unit: 5.8 MW-gross at generator	4.5 $M
16 MW-gross (10 MW-net)	13.5 $M
80 MW-gross (50 MW-net)	67.5 $M

- Siemens (nowadays includes Alstom) could not meet our Specifications;
- Rotoflow, Baker Hughes, Energent, Mitsubishi, Toshiba: no replies.

Table 15.- NH_3 Turbine (Expander) Generator by Atlas Copco.

Table 15 provides the costs estimated for the TGs. To these estimates we must add transportation costs from the factory to a "generic" site, assembly, and installation costs. Similar cost also must be added for all the components listed in all the sections of Chapter 3.

It is interesting to note that our archival cost estimates, obtained over the years from *ROTOFLOW* based on units available at different times, extrapolate to current estimates for the 10 MW-net and 50 MW-net designs of $12.2 M and $43.8 M respectively. Herein we use the current estimates from *Atlas Copco*.

For future reference consider the following relationships derived from our analyses through the years:

Turbine (Expander) Power output (kW) = k x Pressure Drop x NH_3 Mass Flow Rate
Typical Generator Efficiency = 0.93

For the Atlas Copco current information and our parameters in Appendix 2 (10 MW-net):

- **Pwr_{turb} = 0.135 x ΔP(kPa) x dm/dt (kg/s)**
- Pwr_{turb} = 0.135 x 232 kPa x 550 kg/s = 17,226 kW
- Pwr_{gen} = 17,226 x 0.93 = 16,020 kW-gross

Figure 9 represents the saturated conditions that must prevail in a CC-OTEC turbine. These confirmed values are nowadays readily available on the Internet, but we like to refer to the original publication from: W.C. Reynolds (1979) *Thermodynamic Properties in SI for 40 Substances*, Stanford University.

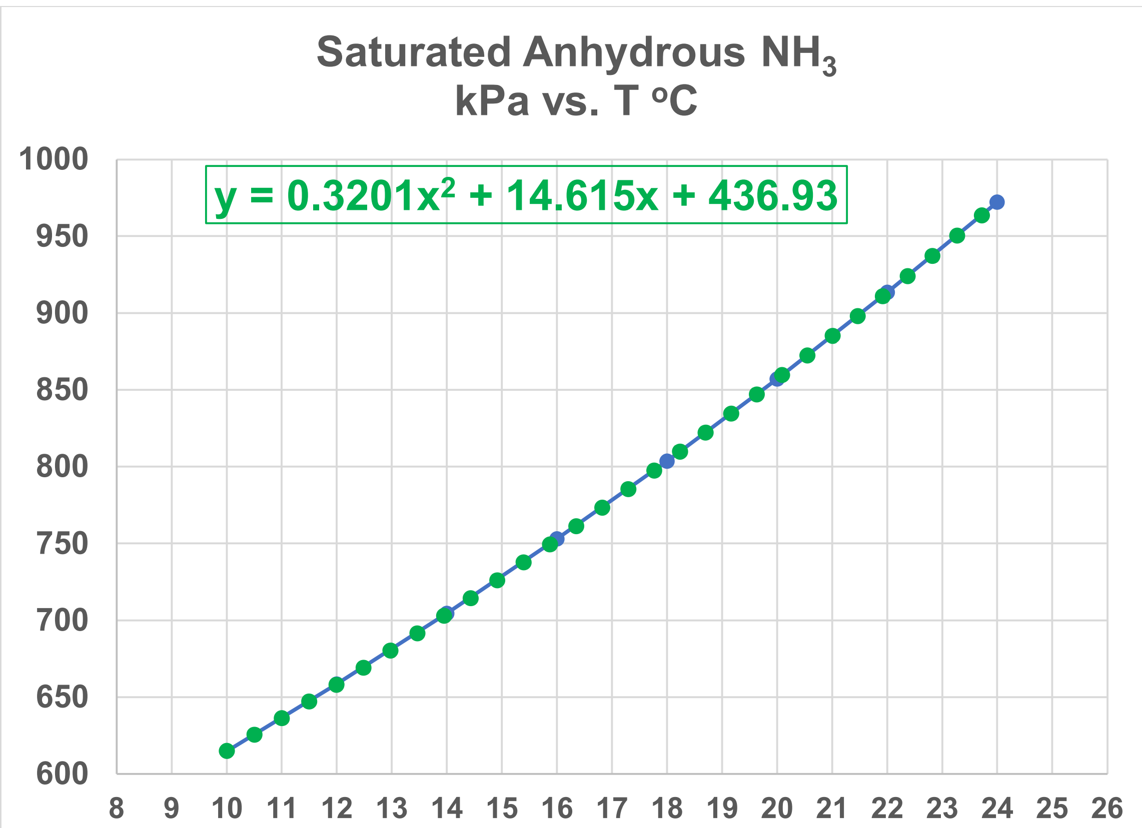

Figure 9.- Saturated Anhydrous Ammonia (NH3): The CC-OTEC Working Fluid.

Our design ΔT of 21.5 ºC corresponds to average conditions off Hawaii. For locations closer to the equator the increase in surface water temperatures will yield higher power outputs. For example, keeping the NH_3 mass flow rate constant at 550 kg/s and the cold seawater temperature at 4.5 ºC the pressure of the saturated working fluid at the turbine inlet will change following the data in Figure 9 yielding a different value of ΔP and consequently a higher net output as indicated in Table 16. In the OTEC region along the Equator with surface water temperatures at 29 ºC the output will increase to ≥14 MW from 10 MW. These values are comparable to those shown in Table 3 following more precise analysis.

ΔT ºC	ΔP kPa	Net Power Increase
26 - 4.5= 21.5	232 (design)	1
22.5	261	1.12
23.5	290	1.25
24.5	320	1.38
25.5	350	1.51

Table 16.- Empirical Power Increase at Atlas Copco Expander Exit due to variation in working fluid saturated temperature (Fig. 9) at inlet and outlet with corresponding variation in pressure. The mass flow rate of NH_3 is kept constant. Compare to the results tabulated in Table 3 under strict Heat & Mass Balance analysis.

3.9 Open Cycle Heat Exchangers (Flash Evaporator and Condensers)

The design and capital cost estimates of the Flash Evaporator and Surface Condenser are based on design work we conducted for a 1.8 MW gross OC-OTEC plant incorporating lessons learned during the 5-years operating the 250 kW Experimental Plant (Appendix 6). Design information is found in Sections 5 and 6 (pp. 28-34, Appendix 6) and our extrapolated 2023 cost estimate of $1.7 M and $4.6 M are found in Section 9 (p. 38).

OC-OTEC Class ΔT= 21.5 ºC	Evaporator System Cost at Factory (2023)	Condenser System Cost at Factory (2023)
1.8 MW-gross	1.7 $M	4.6 $M
16 MW-gross (10 MW-net)	15.3 $M	41.4 $M
80 MW-gross (50 MW-net)	76.5 $M	207 $M

Table 17.- OC-OTEC Flash Evaporator and Surface Condenser Cost Estimates based on our previous Experimental work.

Table 17 provides the costs estimated for the OC-OTEC Flash Evaporator and Surface Condenser systems with the condensers manufactured by a company like Alfa Laval. It is reasonable, given the cost differential between Alfa Laval and Kelvion in the case of CC-OTEC (Section 3.6), to expect that the OC-OTEC surface condensers for the 16 MW-gross case could be manufactured for $23 M instead of $41.4 M. To these estimates we must add assembly and installation costs. Similar costs also must be added for all the components listed in all the sections of Chapter 3.

3.10 Vacuum Pumps (Non-Condensables Gas Removal for OC-OTEC)

After numerous inquiries we were able to finally identify *Edwards* (a brand within the Vacuum Division of *Atlas Copco*.) as a potential supplier of the Vacuum Pumps system required for the OC-OTEC non-condensables gas removal system. Our Specifications were based on our design of a 1.8 MW-gross plant (Appendix 6, pp 35-37).

OC-OTEC	Vacuum Pumps System Cost at Factory (2023)
1.8 MW-gross/1.3 MW-net (ΔT= 21.5 ºC)	3.45 ± 0.25 $M
16 MW-gross/10 MW-net (ΔT= 21.5 ºC)	30.7 ± 2.23 $M
80 MW-gross/50 MW-net (ΔT= 21.5 ºC)	153.2 ± 11.1$M

Table 18.- OC-OTEC Vacuum Compressors by Edwards.

Table 18 provides the costs estimated for the Vacuum Compressors for OC-OTEC with Surface-Condensers (SC).

To these estimates we must add transportation costs from the factory to a "generic" site, assembly, and installation costs. Similar cost also must be added for all the components listed in all the sections of Chapter 3.

3.11 Open Cycle Turbine Generator

Using information obtained 20 years ago (Appendix 6, pp 26-28) we tried to solicit an update from *Mitsubishi Heavy Industries, Ltd*. (MHI) but unfortunately, we were not able to get a response even with the support of Japanese OTEC researchers. We also contacted *Siemens* given their current expertise with Geothermal and Nuclear power plants. Unfortunately, they don't have a current design that meets our Specifications. Not having a current cost estimate means that we had to assume the extrapolated cost from our 1.8 MW gross design for a unit delivered at the factory: 5.9 $M (Appendix 6 page 37). The following Table provides the cost estimates used herein.

Basic Unit: 1.8 MW-gross	10 MW-net (16 MW-gross)	50 MW-net (80 MW-gross)
5.9 $M	53.1 $M (9 units)	265.5 $M (45 units)

Table 19.- OC-OTEC Turbine Generators from Historical Records. No current manufacturer was identified.

Table 19 provides our archival costs estimated for the OC-OTEC TG units. To these estimates we must add transportation costs from the factory to a "generic" site, assembly, and installation costs. Similar costs also must be added for all the components listed in all the sections of Chapter 3.

4.0 Levelized Cost of Electricity

The analytical model available (Appendix 4) to estimate the Levelized Cost of Electricity (LCOE) production is used to assess scenarios under which OTEC might be competitive with current technologies. First, the OTEC capital cost, expressed in $/kW-net, is estimated (Chapter 3). Subsequently, the relative cost of producing electricity ($/kWh), offset when applicable by the desalinated water production revenue, is estimated to determine the scenarios (*i.e., electricity cost and cost of desalinated water production*) under which OTEC could be competitive.

The worldwide current cost of Reversed Osmosis (RO) desalinated water from plants sized at 2,000 to 6,000 m^3/day ranges from 1 to 1.5 $/$m^3$. There are some larger plants generating as much as 900,000 m^3/day that can generate at 0.5 $/$m^3$. Herein when analyzing the cost effectiveness of OC-OTEC plants we take credit for the desalinated water at 1.5 $/$m^3$ to evaluate the equivalent LCOE.

In Hawai'i, for example, the wholesale cost of electricity generation is ≈ 60% of the rate charged to residential consumers by the State Power Company (40% account for transmission & distribution infrastructure, maintenance, and profit). The June 2023 retail charge is 0.35 $/kWh such that the current target for an OTEC plant as an Independent Power Producer is 60% of the retail, i.e.: 0.21 $/kWh.

Another reference point is that for Utilities that use primarily liquid petroleum fuels the cost component is 0.02 $/kWh for each $13 of the cost of a 42 US gallons barrel. Although currently the cost of a barrel at a major location is ≈ $80, in remote locations (SIDS and Military Bases) the cost is doubled due to transportation costs such that the fuel component cost alone is ≈ 0.25 $/kWh. The commercialization target for OTEC LCOE ($/kWh) can, therefore, be taken as ≤ 0,25 $/kWh once we progress beyond the first generation of commercial OTEC plants.

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

The total LCOE is determined by adding the amortized annual capital-loan repayment divided by the annual production ($/kWh) to the annual levelized cost incurred due to operations, maintenance, repair, and equipment repair and eventual replacement (OMR&R) divided by the annual electricity production ($/kWh). It must be noted that environmental credits, tax credits and profit are excluded in this definition.

The Levelized Cost of Electricity Generation (LCOE) is formally estimated as follows (with further details in Appendix 4):

LCOE ($/kWh) = Capital Cost Amortization + Levelized OMR&R

1st Year: **O**perations & **M**aintenance ~ staff of 20;
Repair & **R**eplacement ~ (CC)/(life expectancy years)
e.g., Heat exchangers life expectancy: Ti HXs 30 years & Al HXs 15 years

CC and OMR&R: Europe/Japan/USA/South Korea equipment
with USA labor rates. No cost reduction speculations

- **C**apital **R**ecovery **F**actor (CRF): CRF = [I x(1 + I)N]/[(1+I)N -1]
- 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;
- **P**resent **W**orth **F**actor (PWF): PWF = [(1 +ER)/(I – ER)]/[1 – {(1 + ER)/(1 + I)}N]
- Annual **E**scalation (Inflation) **R**ate (ER): 3% constant herein *(N.B. over the last 20-years, for example, the average USA Manufacturing-Price-Index was 2.65 %);*
- **E**xpenses **L**evelizing **F**actor (ELF): ELF = PWF x CRF
- 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;
- 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 COE OMR&R; The value given here excludes environmental credits, tax credits and profit.

The following Tables provide our current estimates for first generation plants. Levelized costs were estimated under two loan scenarios: 8%, 15-year commercial loan (Table 20); and 2.5%, 20-year concessionary loan (Table 21) from a development bank (e.g., ADB, WB). All cases considered a fixed inflation rate of 3%. Based on this and previous work and because a generic site is considered the first year OMR&R is defined as 5.5% of the Capital Cost.

Under the specified Commercial Loan, excluding profits and credits, the breakeven point (defined as: levelized annual costs = annual revenue) for the 50 MW class CC-OTEC plants is given by a 15-year power-purchase-agreement for at least $0.26/kWh (Kelvion HXs) and as much as $0.38/kWh (Alfa Laval HXs as given in Table 22).

In the case of the 50 MW class OC-OTEC plant the breakeven point, with credit of 1.5 $/m^3 for the desalinated water, is given by a 15-year power-purchase-agreement for at least $0.36/kWh (Table 23).

15-years Commercial Loan @ 8% Interest with 3 % Annual Inflation for OMR&R

Class	CC ($/kW)	OMR&R[12] (% CC)	LCOE[13] ($/kWh)	Desalinated Water (@ 1.5 $/m³)
10 MW CC (w/ Alfa Laval)	27,012	5.5 %	**0.615** *(0.390 + 0.225)*	Not Applicable
10 MW CC (w/ Kelvion)	21,606	"	**0.492** *(0.312 + 0.180)*	Not Applicable
10 MW OC (with SC)	33,962	"	**0.618**	23,690 m³/day @$1.5/m³
50 MW CC (w/ Alfa Laval)	16,578	"	**0.378** *(0.240 + 0.138)*	Not Applicable
50 MW CC (w/ Kelvion)	11,223	"	**0.256** *(0.162 + 0.093)*	Not Applicable
50 MW OC (with SC)	22,722	"	**0.362**	118,450 m³/day @$1.5/m³
100 MW CC (w/ Alfa Laval)	13,023	"	**0.297** *(0.188 + 0.108)*	Not Applicable
100 MW CC (w/ Kelvion)	8,817	"	**0.201** *(0.127 + 0.073)*	Not Applicable

Table 20.- OTEC Current LCOE Estimates with 8 % - 15 years Commercial Loan. For the record, estimates for CC-OTEC 100 MW-class are included although not currently feasible due to the excessive number of "off-the-shelve" HXs and Seawater Pumps that would be required.

20-years Concessionary Loan @ 2.5% Interest with 3 % Annual Inflation for OMR&R

Class	CC ($/kW)	OMR&R (% CC)	LCOE ($/kWh)	Desalinated Water (@ 1.5 $/m3)
10 MW CC (w/ Alfa Laval)	27,012	5.5 %	**0.462** *(0.214 + 0.248)*	Not Applicable
10 MW CC (w/ Kelvion)	21,606	"	**0.370** *(0.171 + 0.199)*	Not Applicable
10 MW OC (with SC)	33,962	"	**0.424**	23,690 m³/day @$1.5/m³
50 MW CC (w/ Alfa Laval)	16,578	"	**0.284** *(0.132 + 0.152)*	Not Applicable
50 MW CC (w/ Kelvion)	11,223	"	**0.192** *(0.089 + 0.103)*	Not Applicable
50 MW OC (with SC)	22,722	"	**0.233**	118,450 m³/day @$1.5/m³

Table 21.- OTEC LCOE Estimates with 2.5 % - 20 years Concessionary Loan that might be available for future OTEC generations. Not currently applicable.

[12] Given that we are considering a generic site and from this and previous studies we take the first year Operations, Maintenance, Repairs & Replacement amount as 5.5% of the Capital Cost . Published values of OMR&R from numerous locations range between 4.9% and 5.9 % of the CC.
[13] Under the total amount ($/kWh) the amount towards capital payment is added to the amount towards OMR&R

Previous work (Ref. 2-4) that continues to be applicable identified two distinct markets: (i) industrialized nations; and (ii) small island developing states (SIDS) with modest needs for power and fresh water. For example, although currently the first generation plants are not cost competitive, 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.

To be cost competitive, OTEC Plantships of at least 50 MW capacity would be required for sites with a larger population base. These would be moored a few kilometers from land, transmitting the electricity to shore via submarine power cables. Although currently not cost competitive, the Plantships could also house OC-OTEC systems and transport the desalinated water produced via flexible pipes.

It was also previously 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 ≤ 5MW (e.g., Appendix 6).

The use of energy carriers (e.g.: Hydrogen, Ammonia) to transport OTEC energy generated in floating plants, drifting in tropical waters, was determined to be technically feasible but requiring increases in the cost of fossil fuels equivalent to $400/barrel to be cost competitive.

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. In the USA, for example, the range of all estimates is equivalent to adding from $80/barrel to over $400/barrel (equivalent to adding from 0.12 to 0.6 $/kWh). Accounting for these externalities is not the modus operandi but might eventually help the development and expand the applicability of OTEC, but in the interim the scenarios discussed here should be considered as the market entry point.

It must be recognized that the power industry only invests in plants whose designs are based on similar plants with an operational record. It is, therefore, once more concluded that before OTEC can be commercialized, a prototypical (pilot) plant would have to be built and operated to obtain the information required to design commercial systems and to gain the confidence of the financial community.

Yes, 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.

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):	$886.92 M	16578 $/kW
1st Year OMR&R:	$48.78 M	*5.5% of CC*
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):	103.619 $M	"Annual Amortization"
COE_{CC} : Fixed CC Component of COE	0.240 $/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):	59.741 $M	"Annual Levelized OMR&R "
$COE_{OMR\&R}$: Levelized OMR&R Component of COE	0.138 $/kWh	
Total (CC + OMR&R) Levelized Annual Cost of Electricity Production:	163.359 $M	

Total Levelized Cost of Electricity (no profit; no environmental or tax credits):	
$COE = COE_{CC} + COE_{OMR\&R}$	0.378 $/kWh

Table 22.- First Generation 50 MW-class CC-OTEC: 2023 Levelized Cost of Electricity Production with Commercial Loans yield an Upper Limit of 0.378 $/kWh. With potentially less expensive HXs the LCOE would be 0.256 $/kWh.

Current-Dollar Levelization (constant annual cost)

Inputs in Blue		Output Red
System Net Name Plate:	53.50 MW	*SOA Components*
System Availability:	92.3%	*Experimental Plant*
Site Annual Average Capacity Factor:	100.0%	*Design Selection*
Annual Electricity Production:	432,609 MWh	
Daily Desalinated Water Production	31.29 MGD	US Gallons= 3.785 liters
	118,450 m^3/day	
Installed Cost (CC):	$1,215.63 M	22722 $/kW
Yearly OMR&R:	$65.04 M	
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):	142.021 $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):	79.648 $M	"Annual Levelized OMR&R"
Total (CC + OMR&R) Annual Cost of Electricity and Water Production:	221.669 $M	
		Rates
Breakeven Annual Sales (no Profit, no credits)		
Electricity	156.605 $M	0.362 $/kWh
Water	65.108 $M	5.7 $/kgallon
Total Annual Sales	221.713 $M	

Table 23.- First Generation 50 MW-class OC-OTEC: 2023 Breakeven Electricity and Water Rates Required with Commercial Loan would be 0.362 $/kWh and 1.5 $/m^3 (5.7 $/kgallon).

5.0 Conclusions

The major conclusion of this work continues to be that there is a market for OTEC plants that produce electricity and desalinated water, however, operational data must be obtained by building and operating demonstration Plantships scaled down from sizes identified as potentially world-wide cost effective. OTEC could be envisioned as a "*Bridge to 2050 Carbon-Neutral Goals*". The major challenge continues to be:

> *How to finance relatively high capital investments that must be balanced by the expected yet to be demonstrated low operational costs?*

This report was commissioned to update the economic viability of OTEC for the generation of electricity and desalinated water by reassessing specific cases under which both Closed Cycle and Open Cycle plants (CC-OTEC and OC-OTEC) could be competitive considering the following classes (defined for $\Delta T = 21.5\ ^{o}C$): (i) 1 MW land-based plants; (ii) 10 MW and (iii) 50 MW Plantship operating offshore connected via submarine power cable to land. For this purpose we estimate the corresponding LCOE ($/kWh) required to collect enough funds for loan repayment and to cover costs for Operations, Maintenance, Repair & Replacement (OMR&R) without Environmental Credits or profits. That is, the Breakeven cost.

It must be noted that some published references of land-based systems do not include all costs under the assumption that the seawater systems will be covered by others such that their cost estimates are not all inclusive.

Experimental plants in Hawaii, Japan and South Korea have confirmed that with proper design no Green House Gasses are emitted during operations, but no credit is taken pending establishment of international/national agreements.

Given that at this developmental stage we must consider generic sites for the floating plants operating throughout the OTEC region, only ship-shaped vessels were considered. For land-based plants bathymetric conditions off Keahole Pt. Hawaii were assumed to estimate the costs associated with the seawater pipes.

Moored plants would transmit the electricity/desalinated water to shore; and eventually Drifting plants would generate the electricity and desalinated water required to generate and store NH_3 or H_2 as the fuels of the future in the post fossil fuels era. These products could be shipped to land or provide fuel filling stations for commercial shipping lines or Navy vessels away from land.

In addition, there are other potential Plantship applications. OTEC, for example, could provide the electricity required for site support of Oil and Gas Platforms off Brasil. Another promising 1st Generation application is for drifting Plantships along Equatorial waters (mild environment with maximum ΔT) supporting energy intensive technologies/applications (e.g., high-density computing) that can operate remotely. These referred to as Demand-Response OTEC (DROTEC) have been proposed by OceanBit (Oceanbitenergy.com).

It was determined that the major updated Capital Cost differences are due to:

- The marked decrease over the last 25 years in fabrication cost ($/tonnage) of ship shaped vessels indicates that it is reasonable to expect that the cost of OTEC ship shaped vessels will be about 35 % lower than the extrapolated historical estimates.

- High-Density-Polyethylene-Pipes (HDPE) pipes are currently available in larger diameters of appropriate thickness (3 m i.d.) such that they can be used as the cold-water-pipe (CWP) for a 5 MW plant and in bundles for the 10 MW (2 pipes) and the 50 MW (8 pipes) resulting in relatively lower costs.

LCOEs ($/kWh) were estimated using the current Capital Costs and for a reasonable Commercial loan (15 years @ 8%); and for the record: Concessionary loans available from Development Banks for Developing Nations (20 years @ 2.5%)[14].

Furthermore, the major technical, economic, environmental, and political issues related to the implementation of OTEC systems can still be summarized as follows:

Technical
One of the major engineering challenges associated with the first generation of Plantships (e.g.,10 to 50 MW) relying on adapting equipment designed and implemented for other applications, is that some subsystems will require multiple units linked together. Most noticeable are the cases with seawater pumps (“low-head high flowrate”) and CC-OTEC HXs and OC-OTEC TGs.

No additional major technical issues remain for the implementation of OTEC; although, it must be emphasized that site specific Engineering Design processes incorporating Operations, Maintenance, Repair and Replacement (OMR&R) Protocols must be incorporated into the final design process. In addition, the selection of a site must consider the human and equipment infrastructure required for installation and operations. This is extremely important when considering remote locations and Small Island Developing States (SIDS).

Economics
Except for relatively small land-based plants (< 5 MW) serving SIDS, commercial size (i.e., potentially cost competitive) Plantships sized at about 50 MW and above are the world-wide future. These might eventually be competitive for: (i) electricity and desalinated water generation onboard Plantships moored offshore transmitting the products to shore; and eventually (ii) NH_3 or H_2 generation away from shore in drifting Plantships.

There might also be 1st Generation applications for drifting Plantships along Equatorial waters (mild environment with maximum ΔT) supporting energy intensive technologies/applications that can operate remotely.

[14] Concessionary loans are not available for first generation technologies but are included for future consideration because the OTEC resource is appropriate in the EEZ of some Developing Nations.

Under the assumption that certain components will be identified or redesigned to minimize the number of units required (e.g., seawater pumps; CC-OTEC HXs; and OC-OTEC TGs) and considering sites with average seawater temperature differential (ΔT) of 21.5 ºC, the 2023 updated LCOEs ($/kWh) with first generation plants implemented with commercial loans are:

1.36 MW-net Land Based OC-OTEC:	**0.59 $/kWh** with credit for 2,450 m^3/day of Desalinated Water @ 1.5 $/$m^3$;
10 MW OC-OTEC Plantship:	**0.62 $/kWh** with credit for 23,690 m^3/day of Desalinated Water @ 1.5 $/$m^3$;
50 MW OC-OTEC Plantship:	**0.36 $/kWh** with credit for 118,450 m^3/day of Desalinated Water @ 1.5 $/$m^3$;
1.36 MW Land Based CC-OTEC:	**0.64 $/kWh** (no desalinated water credit).
10 MW CC-OTEC Plantship:	**0.55 ± 0.06 $/kWh;**
50 MW CC-OTEC Plantship:	**0.32 ± 0.06 $/kWh;**
100 MW-CC-OTEC Plantship:	**0.25 ± 0.05 $/kWh.**

The CC-OTEC upper limit is with Alfa Laval HXs and the lower limit with Kelvion HXs. The 100 MW case is included although currently not feasible for the 1st generation due to the excessive number of units required for the seawater-pumps and HXs systems.

It must be noted that for sites with higher ΔT the net output increases such that for a location with ΔT of 24.5 ºC will yield ≈ 40% higher outputs such that the LCOE would be about 30% lower.

Clearly, these first generation LCOEs are challenging without environmental credits or subsidies. One might speculate, based on the implementation of similar technologies, that later generation designs will reach cost reductions of about 30%.

To minimize Financial Risks associated with the implementation of commercial size Plantships, a pilot plant sized at about 5 MW, representing a scale version of a commercial size plant, must be implemented, and tested for at least one year. This step is dependent on government financing and will require a budget of as much as $164 M.

Perhaps a lesson can be learned from the successful commercialization of Wind Energy that has been achieved due to consistent government funding of pre-commercial projects (with first generation LCOEs much higher than the rates estimated herein for OTEC) 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.

Environment

It is theoretically feasible to envision, with acceptable environmental impact, the decades long world-wide implementation of as many as 50,000 Plantships sized at 100 MW each (5 TW). The annual energy generation from these plants: *5TW x* 8760 hrs. of electrical energy represent a substantial contribution to the current worldwide primary energy consumption: 18 TW x 8760 hrs.

Political

The implementation of the required pre-commercial OTEC plantship depends on Government or "Angel" Patient Financing because the electricity generated will not be cost competitive at the ≈ 5 MW size. This step from final engineering design to electricity generation will take 4 to 5 years and is required before proceeding with the implementation of commercial sized Plantships.

The first Commercial Plantship (≥ 50 MW) will be operational 5 years after the pre-commercial plant before income generation.

New Developments

Drifting Plantships could also house data centers or other applications that would use the OTEC electricity on-board and transmit data to land stations via satellite connections. We are aware of a project designed to house Application Specific Integrated Circuits (ASIC) in a drifting Plantship along equatorial waters (no hurricanes and the highest feasible surface water temperatures within the OTEC region). The 10 MW (@ ΔT = 21.5 ºC) plantship operating along this equatorial region would generate at least 40% more electricity in an annual basis because of the higher temperature differences therein. Moreover, because a drifting plantship does not require a submarine power cable or a mooring system the electricity generated would be cost competitive compared with an ASIC operation on land.

Furthermore, the technical challenges referring to the major systems can be summarized as follows:

OTEC Vessel

At this developmental stage we must consider generic sites for the floating plants operating throughout the OTEC region, therefore, only ship-shaped vessels were considered. It must be noted that, for example, Semisubmersible or Spar vessels will at least double the costs estimated herein for the ship shaped vessels.

Cold Water Pipe

Current developments in the manufacturing of High-Density-Polyethylene-Pipes (HDPE) lead us to the selection of pipe bundles. HDPE pipes are currently available in larger diameters of appropriate thickness (3 m i.d.) such that they can be used as the cold-water-pipe (CWP) for a 5 MW plant (the dream baseline for a demonstration plant) and in bundles for the 10 MW (2 pipes) and the 50 MW (8 pipes) resulting in relatively lower costs. Depending on design specific environmental (waves and currents) conditions the CWPs might need to be attached using a gimbal to decouple pitch and roll vessel motions. The full-length CWPs bundles should be towed horizontally and upended at the site where the plantship is already positioned.

Due to CWPs installation considerations the size of OTEC land-based plants should be *sized at less than about 5 MW.*

Mooring System
For this report considering generic OTEC sites we opted to only consider Spread Moorings. It must be noted that locations requiring Turret Moorings would double the cost estimated for the baseline Spread Moorings.

Submarine Power Cable
Consider cables available from Prysmian.

Seawater Pumps
Consider pumps available from Flygt (Xylem). It must be noted, however, that due to the required "Low Head-High Flow Rate" the number of "off-the-shelve" Warm Water Pumps is challenging (28 units for the 10 MW-class and 140 units for the 50 MW-class). Manufacturers will consider implementing bigger pumps once a real market is available.

Closed Cycle Heat Exchangers
Several suppliers of heat exchangers for CC-OTEC were identified. As a baseline two well established manufacturers of Titanium Plate-Frame with off-the-shelve units meeting our Specifications and appropriate manufacturing capabilities were selected. However, currently numerous units with interconnection challenges would be required. Alfa Laval, for example, would require 48 Evaporator units and 36 Condenser units for the 10 MW-class plant (5x for the 50 MW-class). Kelvion would require 141 Evaporator units and 74 Condenser units. The total weight of the HXs units is essentially the same between these suppliers. These companies indicated that as OTEC is implemented they would design bigger units minimizing the number of interconnections for future generations. This is the most challenging aspect in the commercialization of CC-OTEC and another reason for having to first implement a demonstration plant sized at about 5 MW.

The marked cost differential between quotes from Alfa Laval and Kelvion is puzzling although confirmed via repeated correspondence (N.B., the lower cost estimate from Kelvion agrees with the extrapolated historical record). At this stage of development we must consider both and provide CC ($/kW) and LCOE ($/kWh) ranges.

Ammonia Pumps
Using our Specifications we were able to obtain current quotes from Dickow for the NH_3 pumps required for the CC-OTEC plants under consideration.

Closed Cycle Expander Generator (Turbine Generator)
After a long search for current information we were able to get a quote from Atlas Copco for an appropriate off-the-shelve unit. We would require 3 units for the 10 MW class and 15 units for the 50 MW class.

Open Cycle Heat Exchangers (Flash Evaporator and Condensers)
The design and capital cost estimates of the Flash Evaporator and Surface Condenser are based on design work we conducted for a 1.8 MW gross OC-OTEC plant incorporating lessons learned during the 5-years operating the 250 kW Experimental Plant.

Vacuum Pumps (Non-Condensables Gas Removal for OC-OTEC)
After numerous inquiries we were able to finally identify Edwards (a brand within the Vacuum Division of Atlas Copco.) as a potential supplier of the Vacuum Pumps system required for the OC-OTEC non-condensables gas removal system. Their basic unit meets the Specifications for our 1.8 MW-gross OC-OTEC plant with nine units required for our 10 MW net design and forty-five for our 50 MW-net concept.

Open Cycle Turbine Generator
We were not able to identify a current supplier of the TG required for OC-OTEC and, therefore, had to assume the extrapolated cost from our 1.8 MW gross historical design.

6.0 Main References

1) Nihous G.C. et al (2018), *"An Evaluation of the Large-Scale Implementation of Ocean Thermal Energy Conversion (OTEC) Using an Ocean General Circulation Model with Low-Complexity Atmospheric Feedback Effects",* Journal of Marine Science and Engineering.

2) Vega, L.A. (2014), *"Wave energy conversion and ocean thermal energy conversion potential in developing member countries*" (138 pages), Mandaluyong City, Philippines: Asian Development Bank. {See Appendices 1, 2 & 5}

3) Vega, L.A. (2010), *"Economics of Ocean Thermal Energy Conversion (OTEC): An Update"*, Offshore Technology Conference (OTC 21016), May 2010. {includes description of EXCEL file}

4) Vega L.A. (1992*), "Economics of Ocean Thermal Energy Conversion (OTEC)"* in R.J. Seymour, ed. Ocean Energy Recovery: The State of the Art, American Society of Civil Engineers, New York. {the original contribution.}

Appendix 1: Request for Quotes Form Letter

The following letter was used to solicit quotes based on our specifications:

Date -------

Aloha ---------------,

To update the capital costs estimated for the implementation of OTEC Plants sized at 1, 10 and 50 MWe we have documented the preliminary designs of the seawater supply pipes and platforms that could house the OTEC power block (heat exchangers and turbine generators). The heat and mass balances (H&M) of the power blocks for these systems have been documented using models validated with field data obtained with experimental plants sized between 50 and 250 kWe and operated over multiple years.

The 10 MWe and 50 MWe plants consist of:

- *Barge shaped vessels (referred to as "Plantships") deployed 10 to 100 km offshore in water depths of about 1,100 m to house the MW sized Power Block and connections to submarine power cables connected to land;*
- *Mooring positioning and control via a Single Point Moor (e.g., FPSO Platforms) with dynamic positioning thrusters and power (electrical) swivel;*
- *Associated submarine power cable;*
- *Relatively large diameter pipes for the transport of deep ocean "cold water" from depths of 1,000 m to the Plantship as well as the return water pipe to depths of 120 m (below the oceanic photic layer). Associated relatively low head/high volume seawater pumps are installed in moon pools onboard the Plantship;*
- *Power Block consisting of heat exchangers (evaporators and condensers) and associated MW-sized turbine-generators with associated working fluid (NH_3) pumps.*

We would appreciate your cost estimate for the specific components that your company manufactures. The attached RFQ outlines our request:

> *Here insert titles of the pertinent RFQs for….*

For your general information, we are also attaching the complete RFQ package for all components.

Please note that OTEC's Economy of Scale has been previously documented indicating the need to consider plants sized at 50 to 100 MW to achieve cost effective world-wide implementation with smaller plants for small-island-developing-states (SIDS). It has also been demonstrated with relatively small plants that OTEC generates electricity without GHG emissions.

Currently and finally there is world-wide consensus about the need to implement technologies to generate electricity and fuels without GHG emissions and with new funding from national governments and international development agencies it might finally be possible to implement appropriately sized OTEC plants.

Further information is found in a 10-year-old report that only needs to be updated to include current capital costs (the aim of this request). I wrote this report for the Asian Development

Bank (ADB) considering, in Section 2 (pp. 14-32), only member countries classified as developing states. I included Appendix 1 (pp. 33-55) to provide technical information that continues to be accurate:

> *Vega, L.A. (2014), "Wave energy conversion and ocean thermal energy conversion potential in developing member countries" (138 pages), Mandaluyong City, Philippines: Asian Development Bank.*

Your information will be appreciated.

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Appendix 2

Conceptual Specifications: 10 MW-net CC-OTEC Plantship

Luis A. Vega, Ph.D.

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Ship Shaped Platform

A ship shaped platform (Plantship) is selected for the 10 MWe CC-OTEC Class. The displacement and dimensions are summarized in the following Table with simple sketches of the side and top views given in page 2. A single FRP CWP (i.d. 3.9 m) is shown based on historical data. However, current work leads to the selection of two (2) HDPE pipes in a bundle (i.d. 3 m each). The platform includes bow and stern with bilge keels and flare. The platform is not necessarily self-propelled and could be towed and stationed 10 to 100 km offshore in water depths of about 1100 m.

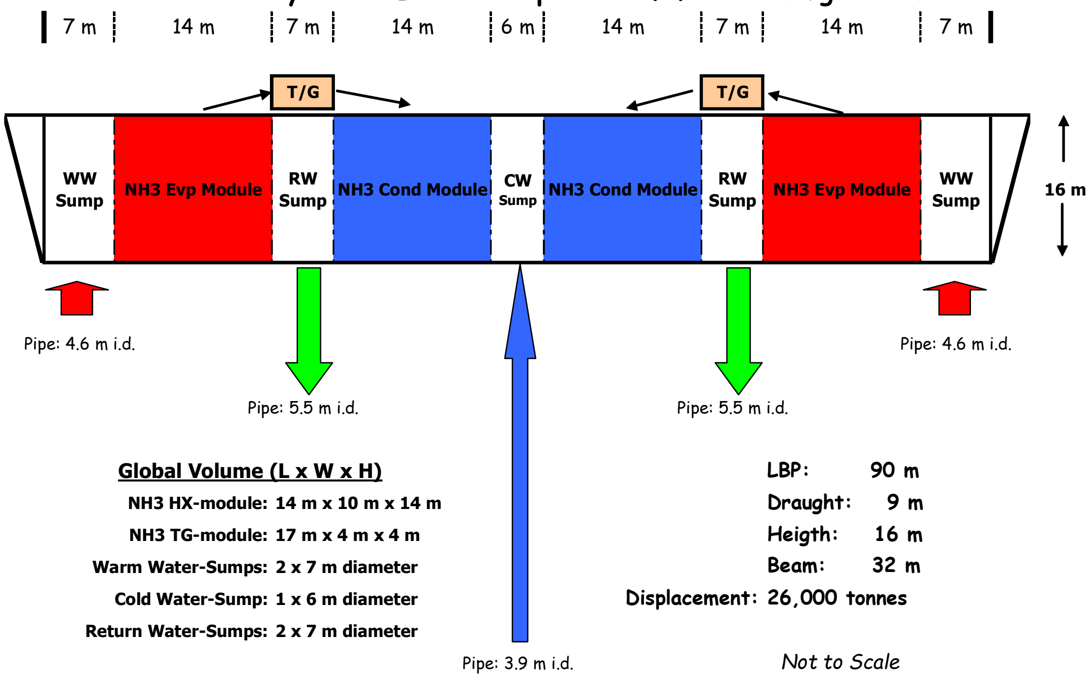
Mooring positioning and control are via a Single Point Moor (e.g., FPSO Platforms) with Dynamic Positioning Thrusters and Power (Electrical) Swivel. A submarine power cable will transmit electricity to a shore station.

Operational Displacement (C_b=0.95)	26,000 tonnes (metric tons)
Operational DWT	18,980 tonnes
Hull Material	Steel
Station Keeping	e.g., Multiple point mooring system or single point moor with power swivel for submarine power cable. Vessel, for example, is towed to station and during operations position keeping is assisted with 4 x 1,000 kW Azimuthal Thrusters
Length at Waterline	90 m
Bow and Stern	40 m Diameter Circular Sections at both ends of the straight Hull
Beam	32 m
Operational Draught	9 m
Depth (center)	16 m
Depth (bow & stern)	21 m
Seawater Sumps: 1 cold water; 2 warm water; and 2 mixed return	4 x 7 m diameter 1 x 6 m diameter

For an OC-OTEC system the overall length would be 80 m; the beam 74m with the same depth and operational draught resulting in a displacement of 53,400 tonnes.

Appendix 2

Side View Closed-Cycle-OTEC Plantship: Two of four 4 MWgross Modules



Global Volume (L x W x H)

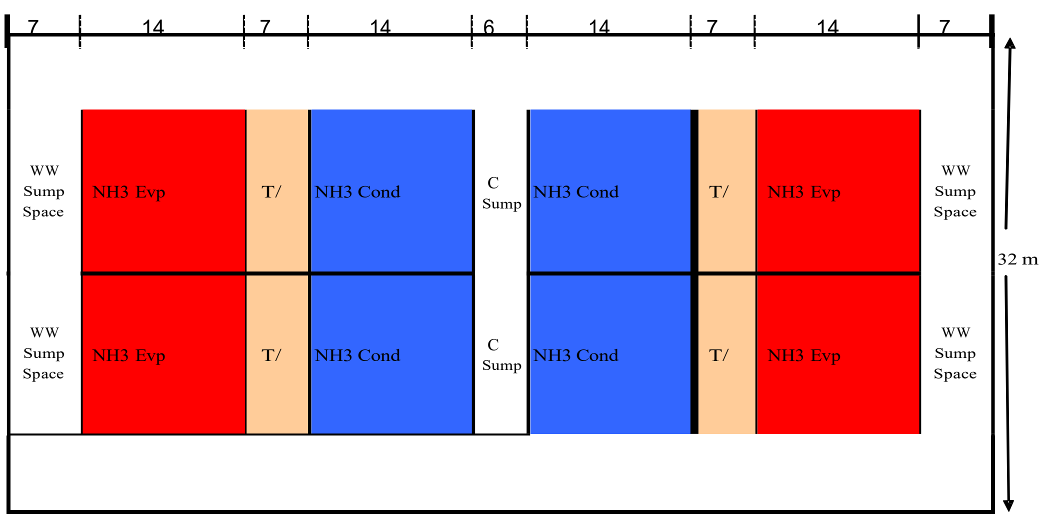
NH3 HX-module: 14 m x 10 m x 14 m
NH3 TG-module: 17 m x 4 m x 4 m
Warm Water-Sumps: 2 x 7 m diameter
Cold Water-Sump: 1 x 6 m diameter
Return Water-Sumps: 2 x 7 m diameter

LBP: 90 m
Draught: 9 m
Heigth: 16 m
Beam: 32 m
Displacement: 26,000 tonnes

Not to Scale

Broken Lines indicate space overlap.

Top View CC-OTEC Plantship: Four of four 4 MW Modules



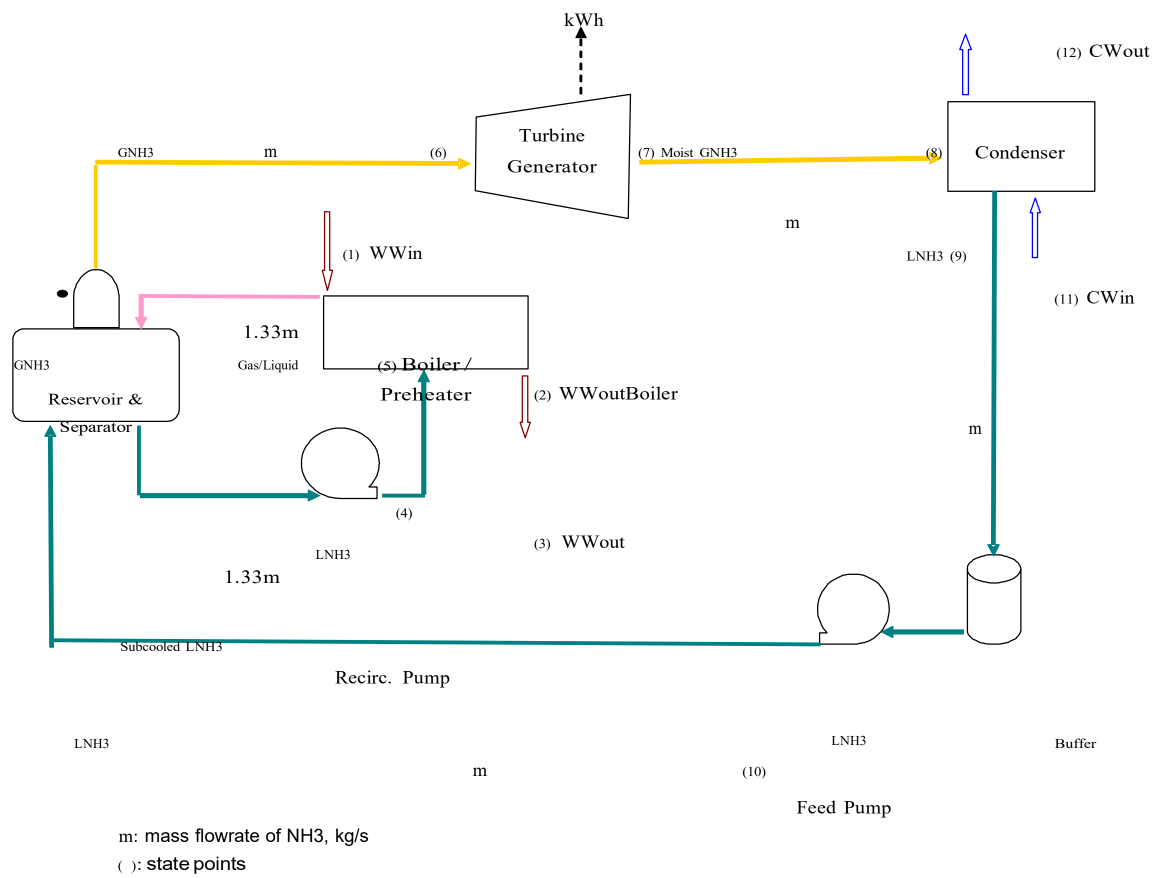
Global Volume (L x W x H)

NH3 HX-	14 m x 10 m x 14
NH3 TG-	17 m x 4 m x 4
Warm Water-	2 x 7 m diameter
Cold Water-	1 x 6 m diameter
Return Water-	2 x 7 m diameter

LBP: 90 m
Draught: 9 m
Height: 16 m
Beam: 32m
Displacement 26,000 tonnes

Not to scale

10 MWe CC-OTEC Power Block Performance Specifications



Process Flow Diagram for Electricity Production Mode

Appendix 2

Anhydrous Ammonia Turbine-Generator Specifications

	Specifications	Manufacturer Parameters
Total Output Required	16 MWe (Megawatt electricity at generator terminals)	
Rated Output per unit	2 x 8 MWe; or 4 x 4 MWe	
No. of Units	Four (4) or Two (2)	
Working Fluid	NH_3	
Total NH_3 Flow Rate	550 kg/s divided equally between units	
(P_6) Inlet Pressure	890 kPa saturated gaseous NH_3	
(T_6) Inlet Temp.	21.2 ^{o}C	
(h_6) Inlet Enthalpy	1606.6 kJ/kg	
(P_7) Outlet Pressure	658 kPa two-phase NH_3	
Outlet Quality (% NH_3 gas)	98%	
(T_7) Outlet Temp.	12.0 ^{o}C	
(h_7) Outlet Enthalpy	1576 kJ/kg	
Preferred Enclosure	Totally Enclosed Fan Cooled	
Preferred Rated Voltage	480 VAC, 3-phase	
Rated Speed	3,600 or 1,800 rpm	
Rated Frequency	60 Hz	
Turbine Efficiency	> 75%	
Generator Efficiency	> 95%	
Voltage Regulation	+/- 0.5%	

Information to be provided by T-G Manufacturer

Provide/Confirm Parameters Listed Above	
Bearing System provide info about lubricated and magnetic bearing options	
Overall Dimensions per unit include turbine, generator, lube oil skid & control panel	
Overall Weight per unit include turbine, generator, lube oil skid & control panel	
Space requirement for Maintenance:	
Manufacturing Time Required:	
Cost FOB Factory:	
Service Life:	

Appendix 2

Anhydrous Ammonia Heat Exchangers (HXs) Specifications

General

Preferred Type	Due to space optimization compact HXs like Plate Frame or Plate Fin are preferred; however T&S are acceptable
Preferred Materials	• Titanium (life expectancy: 30 years) • Bare Aluminum Al-3003 Alloy (not Alclad) for the water-side (life expectancy: 15 years)

Condenser

	Specifications	Manufacturer Parameters
No. of Condenser Units given by number of T-G units available	Four (4); or Two (2)	
Total NH3 Flow Rate	550 kg/s divided equally between units	
Target ΔP NH_3 side (Goal)	12 kPa	
Total Cold Seawater Flow ϱ = 1027 kg/m^3 ; Cp = 4 kJ/kg °C	28,450 kg/s divided equally between units	
Target ΔP Water side (Goal)	15 kPa	
(T_{11}) Seawater Inlet Temp.	4.5 °C	
(T_{12}) Seawater Outlet Temp.	10.3 °C	
(h_8) Enthalpy Condenser In	1576 kJ/kg	
(h_9) Enthalpy Condenser Out	379 kJ/kg	
(T_8) NH_3 Inlet Temp.	11.9 °C	
NH_3 Inlet Quality	0.98	
(P_8) NH_3 Inlet Pressure	657 kPa	
(T_9) LNH_3 Outlet Temperature	11.4 °C	
(P_9) NH_3 Outlet Pressure	645 kPa	
Latent Heat Condensation, f(P_8)	1217 kJ/kg	
Pinch Point, (T_9 – T_{12})	1.1°C	
Heat Duty NH3 Side	656,680 kJ/s	
Heat Duty Water Side	660,540 kJ/s	

Evaporator: Integrated Preheater and Boiler or Separate Units

	Specifications	Manufacturer Parameters
No. of Evaporator Units given by number of T-G units available	Four (4), or Two (2)	
Total NH3 Flow Rate	730 kg/s (= 1.33 x 550 kg/s) divided equally between units	
Target ΔP NH_3 side (Goal)	17 kPa	
Total Warm Seawater Flow ϱ = 1022 kg/m^3 ; Cp = 4 kJ/kg °C	54,000 kg/s divided equally between units	
Target ΔP Water side (Goal)	10 kPa	
(T_1) Seawater Inlet Temp.	26.0 °C	
(T_3) Seawater Outlet Temp.	22.9 °C	
(h_4) Enthalpy Evaporator In	379.6 kJ/kg	
(h_6) Enthalpy Evaporator Out	1606.6 kJ/kg	
Evaporator Global Heat Duty	670,200 kJ/s	
PREHEATER	PREHEATER	PREHEATER
Preheater: to raise temperature of subcooled liquid NH_3 (T_4) to temperature (T_5) of saturated liquid ammonia (LNH_3) at inlet pressure		
(T_4) NH_3 Inlet Temp.	11.5 °C	
(P_4) NH_3 Inlet Pressure	907.4 kPa	
(T_5) NH_3 Outlet Temp.	21.8 °C	
BOILER	BOILER	BOILER
Boiler: to produce gaseous ammonia (GNH3). Output expected to be about 75% gas/ 25% liquid requiring an external mist eliminator or separator		
(T_5) NH_3 Inlet Temp.	21.8 °C	
(P_5) NH_3 Inlet Pressure	907.4 kPa	
(T_6) NH_3 Outlet Temp.	21.2 °C	
(P_6) NH_3 Outlet Pressure	890.4 kPa	
Latent Heat Evaporation	1180.8 kJ/kg	
(T_1) Water Inlet Temp.	26.0 °C	
(T_2) Water Out of Boiler	23.0 °C	
Boiler Pinch Point, (T_2 – T_5)	1.2 °C	
Boiler Heat Duty NH3 Side	649,450 kJ/s	
Boiler Heat Duty Water Side	648,590 kJ/s	

Appendix 2

Information to be provided by Condenser Manufacturer

Provide/Confirm Parameters Listed Above	
Type	
Material	
Overall Dimensions per unit	
Overall Weight per unit	
Space requirement for Maintenance:	
Manufacturing Time Required:	
Cost FOB Factory:	
Service Life:	

Information to be provided by Evaporator Manufacturer

Provide/Confirm Parameters Listed Above	
Type	
Material	
Overall Dimensions per unit	
Overall Weight per unit	
Space requirement for Maintenance:	
Manufacturing Time Required:	
Cost FOB Factory:	
Service Life:	

Appendix 2

Liquid Anhydrous Ammonia (LNH3) Pumps Specifications

	Specifications	Manufacturer Parameters
Voltage	480 V/60 Hz/ 3-phase	
FEED PUMP	FEED PUMP	FEED PUMP
Total LNH3 Flow Rate	550 kg/s divided equally between units	
No. of Feed Pumps	Four (4); or Two (2) with fraction of flow and ΔP = 275 kPa, (P_{10} - P_9)	
(P_9) Inlet Pressure	645 kPa	
(T_9) Inlet Temperature	11.4 °C	
Inlet Density, f(T_9)	620 kg/m^3	
(h_9) Inlet Enthalpy	379.1 kJ/kg	
(P_{10}) Outlet Pressure	919 kPa	
(h_{10}) Outlet Enthalpy	379.6 kJ/kg	
Pump Overall Efficiency	>72%	
Target Total Power Consumption	< 340 kW	
RECIRCULATION PUMP	RECIRC. PUMP	RECIRC. PUMP
Total LNH3 Flow Rate	730 kg/s (= 1.33 x 550 kg/s) divided equally between units	
No. of Feed Pumps	Four (4); or Two (2) with fraction of flow and ΔP = 17 kPa, (P_4 - P_6)	
(P_6) Inlet Pressure	890 kPa	
(P_4) Outlet Pressure	907 kPa	
(T_4) Temperature	11.5 °C	
Density	620 kg/m^3	
Pump Overall Efficiency	>72%	
Target Total Power Consumption	< 28 kW	

Information to be provided by LNH3 Pumps Manufacturer

Provide/Confirm Parameters Listed Above	
Overall Dimensions per unit	
Overall Weight per unit	
Space requirement for Maintenance:	
Manufacturing Time Required:	
Cost FOB Factory:	
Service Life:	

Seawater Pumps Specifications

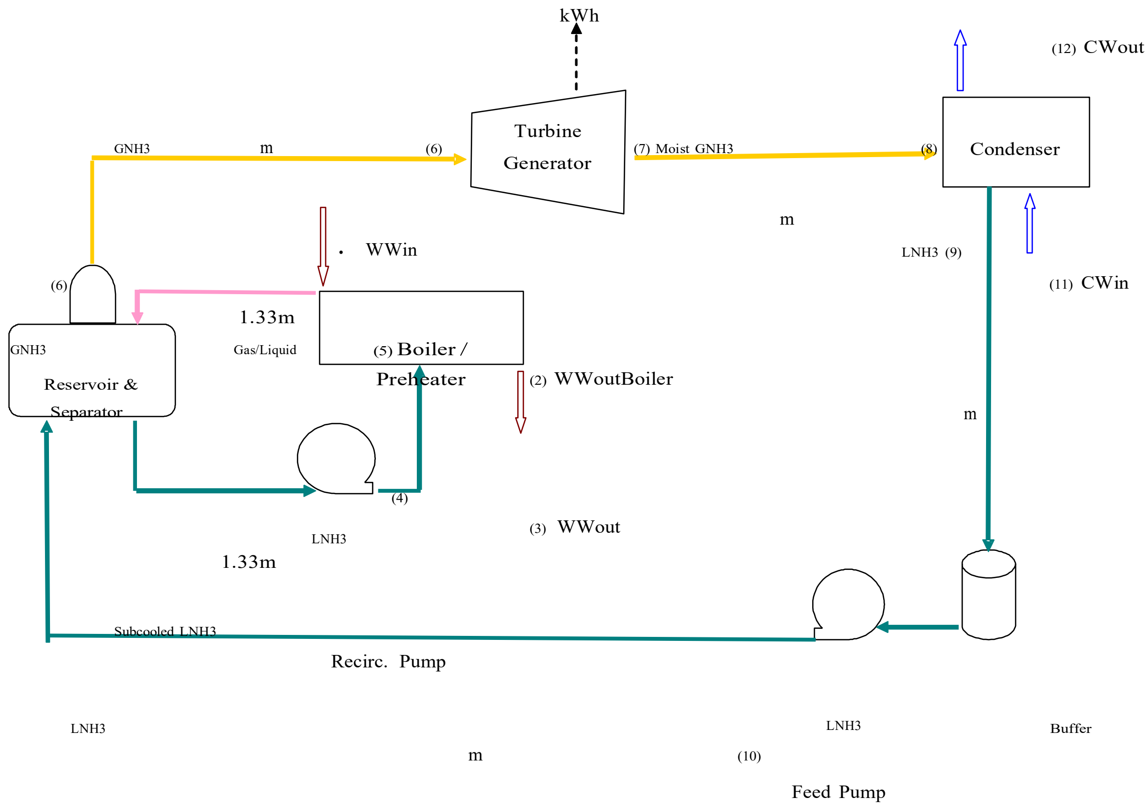
	Specifications	Manufacturer Parameters
Voltage	480 V/60 Hz/ 3-phase	
Type	Submersible Positioned 10 m below sea level at bottom of flooded sump that is connected to large diameter pipe(s) extending either 20 m below sea level to draw warm seawater; or 1,000 m below sea level to draw cold seawater.	
Material	Cast Iron, epoxy-coated wetted parts, external zinc anodes	
WARM SEAWATER PUMP(S)		
Total Seawater Flow Rate	54,000 kg/s	
Specific Gravity	1.022	
(T_1) Seawater Temp.	26.0 °C	
Total Head	3 m	
Target Pump/Motor Efficiency	> 72%	
Maximum Power Consumption	<2,170 kW	
No. of Pumps	TBD by supplier	
COLD SEAWATER PUMP(S)		
Total Seawater Flow Rate	28,450 kg/s	
Specific Gravity	1.027	
(T_{11}) Seawater Temp.	4.5 °C	
Total Head	7.2 m	
Target Pump/Motor Efficiency	> 72%	
Maximum Power Consumption	<2,770 kW	
No. of Pumps	TBD by supplier	

Information to be provided by Seawater Pumps Manufacturer

Provide/Confirm Parameters Listed Above	
Overall Dimensions per unit	
Overall Weight per unit	
Space requirement for Maintenance:	
Time Required for Manufacturing:	
Cost FOB Factory:	
Service Life:	

Heat and Mass Balance: 10 MWe-net CC-OTEC

The H&M balance keyed to the following diagram is given in pages 11-13.



m: mass flowrate of NH3, kg/s
( ): state points

Process Flow Diagram for Electricity Production Mode

Appendix 2

Heat & Mass Balance 10 MW OTEC Electricity Mode						
	Case:	15.936	MW-gross	TG-Terminals		
		10.658	MW-net			
Twwi	T1	26.0	°C	1022.7	kg/m^3	
Tcwi	T11	4.5	°C	1027.3	kg/m^3	
ΔT	(T1 - T11)	21.5	°C			
Mcw		28,447	kg/s	1,773	kg/s/ MW-gross	
Mww		54,049	kg/s	1.9	Mww/Mcw	
Cp seawater		4	kJ/(kg-deg)			
MNH3 Turbine		550	kg/s	34.3	kg/s /MW-gross	
MNH3Recirculating/Feed		1.3				
Boiler Pinch Point	T2 - T5	1.2	°C	Goal		
Cdsr Pinch Point	T9 - T12	1.1	°C	Goal		
P evp	P6 - P4	17	kPa	Assumption		
P cndsr	P8 - P9	12	kPa			
Quality Vapor out Turbine		0.98				
Generator Efficiency		95.0%				

Evaporator (Preheater & Boiler & Mist Eliminator) Module						
TwwEvpout	T3	22.9	°C			
TwwBoilerout	T2	23.0	°C			
TSubcooledLNH3	T4	11.5	°C			
Enthalpy into Evprt	h4	379.6	kJ/kg			
PLNH3 Preheater	P4	907.4	P4 = P5, negligible losses			
TLNH3 into Boiler	T5	21.8	°C			
PLNH3 into Boiler	P5	907.4	kPa			
PGNH3 out Boiler	P6	890.4	kPa			
TGNH3 out Boiler	T6	21.2	°C			
Enthalpy out of Evprt	h6	1606.6	kJ/kg			
HEAT ADDED	h6 - h4	1227.0	kJ/kg			
Latent Heat Evaporation	hfg (T6)	1180.8	kJ/kg			
Heat Duty Boiler NH3 side		649,448	kJ/s			
Heat Duty Boiler water side		648,588	kJ/s			
Overall Heat Duty Evprt		670,208	kJ/s	Includes Pre-Heater Heat Duty		

Appendix 2

	Turbine Module					
PGNH3 into Turbine	P6	890.4	kPa			
TGNH3 into Turbine	T6	21.2	°C			
T 2-phase out Turbine	T7	12.0	°C			
P 2-phase out Turbine	P7	658.3	kPa			
Enthalpy out of Turbine	h7	1576.1	kJ/kg			
TURBINE WORK	h6 - h7	30.5	kJ/kg			
Gross Power from	kWgross	15,936	for generator efficiency as given above			

	Condenser Module					
P NH3 into Cndsr	P8	656.9	small losses (1.4 kPa) turbine to cndsr			
T NH3 into Cndsr	T8	11.9	°C			
Enthalpy into Cndsr	h8	1576.1	kJ/kg			
Latent Heat Condensation	hfg(P8)	1217.2	kJ/kg			
PLNH3 out Cndsr	P9	644.9	kPa			
Enthalpy out Cndsr	h9	379.1	kJ/kg			
TLNH3 out Cndsr	T9	11.4	°C			
HEAT REJECTED	h8-h9	1197.0	kJ/kg			
Tcw out cndsr	T12	10.3	°C			
Heat Duty Cndsr NH3side		656,684	kJ/s			
Heat Duty Cndsr waterside		660,539	kJ/s			

		Feed Pump				
Inlet Pressure	P9	644.9	kPa			
Enthalpy inlet Pump	h9	379.1	kJ/kg			
Outlet Pressure	P10	919.4	kPa			
Enthalpy outlet pump	h10	379.6	kJ/kg			
PUMP WORK	h10 - h9	0.5	kJ/kg			
MLNH3		550	kg/s			

Appendix 2

Heat Added + Pump Work	1227.5
Heat Rejected + Turbine Work	1227.5
Ratio	1.0

LNH3 Pumps Power, kW		368.0
Feed Flow, kg/s		550.0
Feed P	P10 - P9	274.5
LNH3 Density, kg/l	at T9	0.62
Pump Efficiency		0.72
Feed Power Consumption, kW		340.0
Recirculating Flow		733.3
Recirc. P	P4 - P6	17
LNH3 Density, kg/l	at T6	0.61
Pump Efficiency		0.72
Rcir Power Consumption, kW		28.0

Water Pumps						
	Density Head	K-factor	f-factor	HX	Total	Efficiency
Cold Water Head, m	1.1	1.4	2.03	1.4	6.0	0.72
Warm Water Head, m	0	0.7	0.01	1.1	1.7	0.72
Discharge Loop Head, m	0	1.2	0.03	0.0	1.2	0.72
CW Pump, kW	2,780					
WW Pump, kW	2,130					
Total Seawater System	4,910					

Total Parasitics, kW	5,278

Conceptual Specifications: 50 MW-net CC-OTEC Plantship

Luis A. Vega, Ph.D.

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Barge Shaped Platform

A 120,600 tonnes (metric ton) steel barge with bow and stern including bilge keels and flare has been selected for the CC- OTEC system. The plantship will be stationed 10 km to 100 km offshore from a location to be selected in water depths of at least 1100 m.

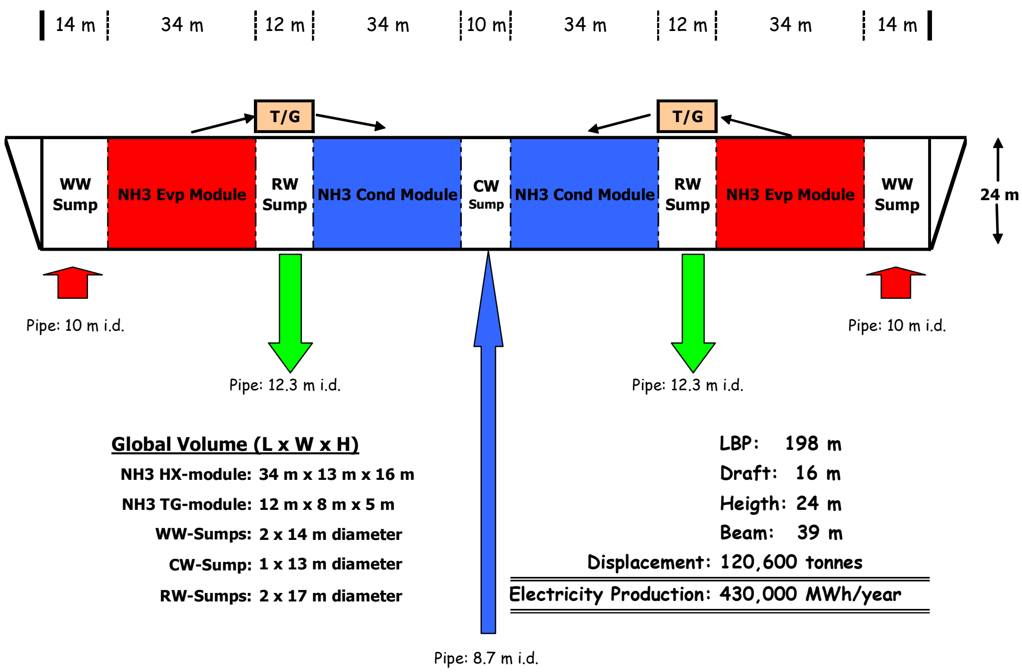
A single FRP CWP (i.d. 8.7 m) is shown on page 2 based on historical data. However, current work leads to the cost-effective selection of eight (8) HDPE pipes in a bundle (i.d. 3 m each). A submarine power cable will transmit electricity to a shore station.

Operational Displacement (C_b=0.95)	120,600 tonnes
Operational DWT	88,038 tonnes
Hull Material	Steel
Station Keeping	e.g., Multiple point mooring system or single point moor with power swivel for submarine power cable. Vessel, for example, is towed to station and during operations position keeping is assisted with 4 x 2200 kW Azimuthal Thrusters
Length at Waterline	198 m
Bow and Stern	40 m Diameter Circular Sections at both ends of the straight Hull
Beam	39 m
Operational Draught	16 m
Depth (center)	24 m
Seawater Sumps: 1 cold water; 2 warm water; and 2 mixed return	1 x 12.3 m diameter 2 x 14 m diameter 2 x 17 m diameter

For an OC-OTEC system the overall length would be 176 m; the beam 90 m with the same depth and operational draught resulting in a displacement 247,400 tonnes.

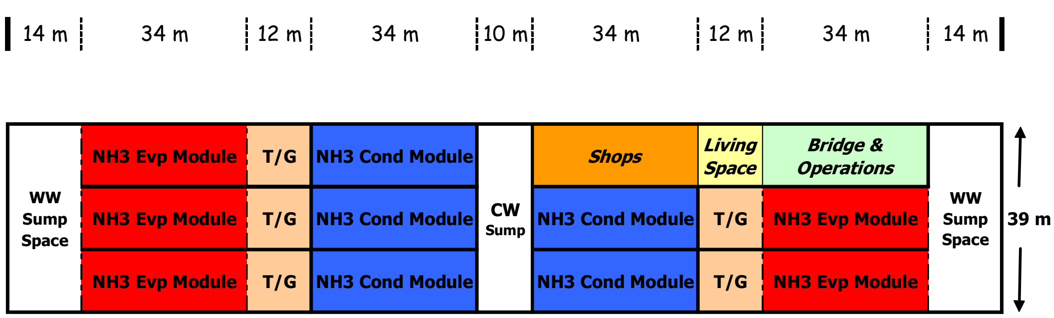
Appendix 3

Side View Closed-Cycle-OTEC Plantship: Two of Five 16 MWgross Modules



Broken Lines indicate space overlap.

TopView Closed-Cycle-OTEC Plantship: Five x 16MWgross Modules

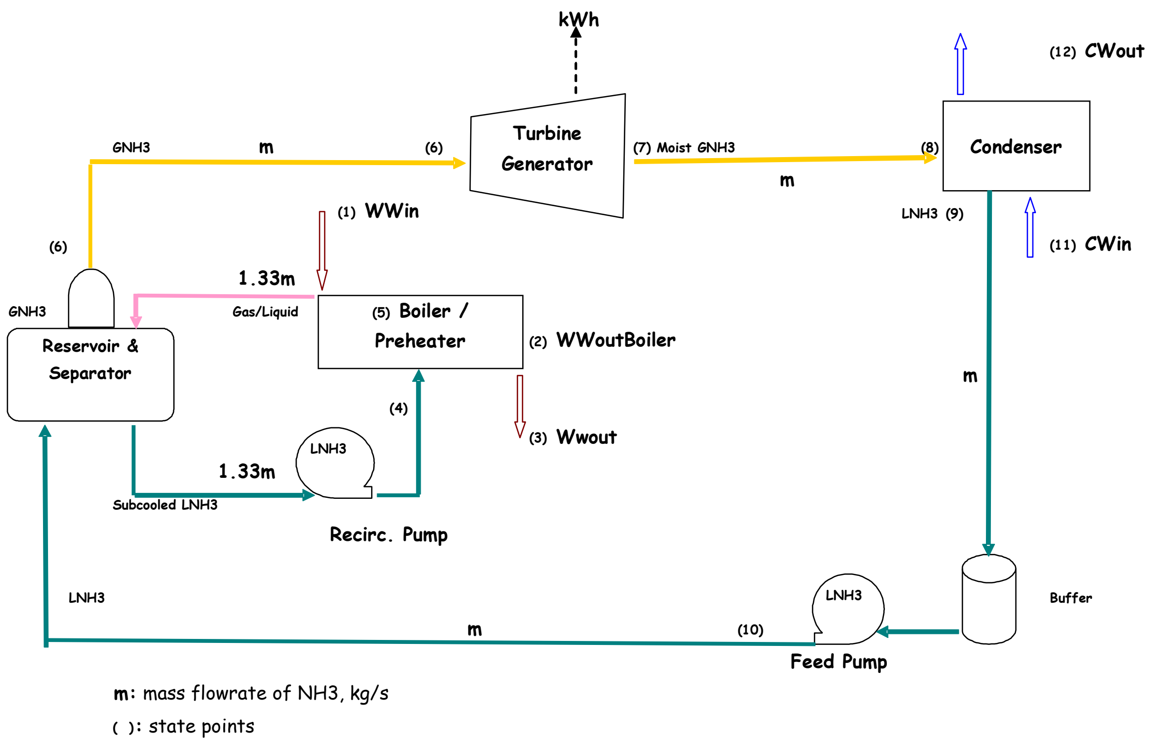


Global Volume (L x W x H)

NH3 HX-module: 34 m x 13 m x 16 m
NH3 TG-module: 12 m x 8 m x 5 m
WW-Sumps: 2 x 14 m diameter
CW-Sump: 1 x 13 m diameter
RW-Sumps: 2 x 17 m diameter

LBP: 198 m
Draft: 16 m
Heigth: 24 m
Beam: 39 m
Displacement: 120,600 tonnes
Electricity Production: 430,000 MWh/year

50 MWe CC-OTEC Power Block Performance Specifications



Process Flow Diagram for Electricity Production Mode

Anhydrous Ammonia Turbine-Generator Specifications

	Specifications	Manufacturer Parameters
Total Output Required	80 MWe (megawatt electricity at generator terminals)	
Rated Output per unit	8 MWe; or 4 MWe	
No. of Units	Ten (10) or Twenty (20)	
Working Fluid	NH_3	
Total NH_3 Flow Rate	2,750 kg/s divided equally between units	
(P_6) Inlet Pressure	890 kPa saturated gaseous NH_3	
(T_6) Inlet Temp.	21.2 °C	
(h_6) Inlet Enthalpy	1606.6 kJ/kg	
(P_7) Outlet Pressure	658 kPa two-phase NH_3	
Outlet Quality (% NH_3 gas)	98%	
(T_7) Outlet Temp.	12.0 °C	
(h_7) Outlet Enthalpy	1576 kJ/kg	
Preferred Enclosure	Totally Enclosed Fan Cooled	
Preferred Rated Voltage	480 VAC, 3-phase	
Rated Speed	3,600 or 1,800 rpm	
Rated Frequency	60 Hz	
Turbine Efficiency	> 75%	
Generator Efficiency	> 95%	
Voltage Regulation	+/- 0.5%	

Information to be provided by T-G Manufacturer

Provide/Confirm Parameters Listed Above	
Bearing System provide info about lubricated and magnetic bearing options	
Overall Dimensions per unit include turbine, generator, lube oil skid & control panel	
Overall Weight per unit include turbine, generator, lube oil skid & control panel	
Space requirement for Maintenance:	
Manufacturing Time Required:	
Cost FOB Factory:	
Service Life:	

Appendix 3

Anhydrous Ammonia Heat Exchangers (HXs) Specifications

General

Preferred Type	Due to space limitations relatively compact HXs like Plate Frame or Plate Fin are preferred; however T&S are acceptable.
Preferred Materials	- Titanium (life expectancy: 30 years) - Bare Aluminum Al-3003 Alloy (not Alclad) for the water-side (life expectancy: 15 years)

Condenser

	Specifications	Manufacturer Parameters
No. of Condenser Units given by number of T-G units available	Ten (10) or Twenty (20)	
Total NH3 Flow Rate	2,750 kg/s divided equally between units	
Target ΔP NH_3 side **(Goal)**	12 kPa	
Total Cold Seawater Flow ρ = 1027 kg/m^3 ; Cp = 4 kJ/kg °C	142,300 kg/s divided equally between units	
Target ΔP Water side **(Goal)**	15 kPa	
(T_{11}) Seawater Inlet Temp.	4.5 °C	
(T_{12}) Seawater Outlet Temp.	10.3 °C	
(h_8) Enthalpy Condenser In	1576 kJ/kg	
(h_9) Enthalpy Condenser Out	379 kJ/kg	
(T_8) NH_3 Inlet Temp.	11.9 °C	
NH_3 Inlet Quality	0.98	
(P_8) NH_3 Inlet Pressure	657 kPa	
(T_9) NH_3 Outlet Temperature	11.4 °C	
(P_9) NH_3 Outlet Pressure	645 kPa	
Latent Heat Condensation, f(P_8)	1217 kJ/kg	
Pinch Point, (T_9 – T_{12})	1.1 °C	
Heat Duty NH3 Side	3,275,000 kJ/s	
Heat Duty Water Side	3,300,000 kJ/s	

Appendix 3
Evaporator: Integrated Preheater and Boiler or Separate Units

	Specifications	Manufacturer Parameters
No. of Evaporator Units given by number of T-G units available	Ten (10) or Twenty (20)	
Total NH3 Flow Rate	3660 kg/s (= 1.33 x 2750 kg/s) divided equally between units	
Target ΔP NH_3 side **(Goal)**	17 kPa	
Total Warm Seawater Flow ρ = 1022 kg/m^3 ; Cp = 4 kJ/kg °C	270,400 kg/s divided equally between units	
Target ΔP Water side **(Goal)**	10 kPa	
(T_1) Seawater Inlet Temp.	26.0 °C	
(T_3) Seawater Outlet Temp.	22.9 °C	
(h_4) Enthalpy Evaporator In	379.6 kJ/kg	
(h_6) Enthalpy Evaporator Out	1606.6 kJ/kg	
Evaporator Global Heat Duty	3,353,000 kJ/s	
PREHEATER	PREHEATER	PREHEATER
Preheater: to raise temperature of subcooled liquid NH_3 (T_4) to temperature (T_5) of saturated liquid ammonia (LNH_3) at inlet pressure		
(T_4) NH_3 Inlet Temp.	11.5 °C	
(P_4) NH_3 Inlet Pressure	907.4 kPa	
(T_5) NH_3 Outlet Temp.	21.8 °C	
BOILER	BOILER	BOILER
Boiler: to produce gaseous ammonia (GNH3). Output expected to be about 75% gas/ 25% liquid requiring an external mist eliminator or separator		
(T_5) NH_3 Inlet Temp.	21.8 °C	
(P_5) NH_3 Inlet Pressure	907.4 kPa	
(T_6) NH_3 Outlet Temp.	21.2 °C	
(P_6) NH_3 Outlet Pressure	890.4 kPa	
Latent Heat Evaporation	1180.8 kJ/kg	
(T_1) Water Inlet Temp.	26.0 °C	
(T_2) Water Out of Boiler	23.0 °C	
Boiler Pinch Point, (T_2 – T_5)	1.2 °C	
Boiler Heat Duty NH3 Side	3,240,000 kJ/s	
Boiler Heat Duty Water Side	3,245,000 kJ/s	

Appendix 3

Information to be provided by Condenser Manufacturer

Provide/Confirm Parameters Listed Above	
Type	
Material	
Overall Dimensions per unit	
Overall Weight per unit	
Space requirement for Maintenance:	
Manufacturing Time Required:	
Cost FOB Factory	
Service Life:	

Information to be provided by Evaporator Manufacturer

Provide/Confirm Parameters Listed Above	
Type	
Material	
Overall Dimensions per unit	
Overall Weight per unit	
Space requirement for Maintenance:	
Manufacturing Time Required:	
Cost FOB Factory:	
Service Life:	

Appendix 3

Liquid Anhydrous Ammonia (LNH3) Pumps Specifications

	Specifications	Manufacturer Parameters
Voltage	480 V/60 Hz/ 3-phase	
FEED PUMP	FEED PUMP	FEED PUMP
Total LNH3 Flow Rate	2750 kg/s divided equally between units	
No. of Feed Pumps	Twenty (20); or Ten (10) with fraction of flow and ΔP = 275 kPa, ($P_{10} - P_9$)	
(P_9) Inlet Pressure	645 kPa	
(T_9) Inlet Temperature	11.4 °C	
Inlet Density, f(T_9)	620 kg/m^3	
(h_9) Inlet Enthalpy	379.1 kJ/kg	
(P_{10}) Outlet Pressure	919 kPa	
(h_{10}) Outlet Enthalpy	379.6 kJ/kg	
Pump Overall Efficiency	>72%	
Target Total Power Consumption	< 1690 kW	
RECIRCULATION PUMP	RECIRC. PUMP	RECIRC. PUMP
Total LNH3 Flow Rate	3660 kg/s (= 1.33 x 2750 kg/s) divided equally between units	
No. of Feed Pumps	Twenty (20); or Ten (10) with fraction of flow and ΔP = 17 kPa, ($P_4 - P_6$)	
(P_6) Inlet Pressure	890 kPa	
(P_4) Outlet Pressure	907 kPa	
(T_4) Temperature	11.5 °C	
Density	620 kg/m^3	
Pump Overall Efficiency	>72%	
Target Total Power Consumption	< 140 kW	

Information to be provided by LNH3 Pumps Manufacturer

Provide/Confirm Parameters Listed Above	
Overall Dimensions per unit	
Overall Weight per unit	
Space requirement for Maintenance:	
Manufacturing Time Required:	
Cost FOB Factory:	
Service Life:	

Appendix 3
Seawater Pumps Specifications

	Specifications	Manufacturer Parameters
Voltage	480 V/60 Hz/ 3-phase	
Type	Submersible Positioned 20 m below sea level at bottom of flooded sump that is connected to large diameter pipe(s) extending either 20 m below sea level to draw warm seawater; or 1,000 m below sea level to draw cold seawater.	
Material	Cast Iron, epoxy-coated wetted parts, external zinc anodes	
WARM SEAWATER PUMP(S)		
Total Seawater Flow Rate	270,400 kg/s	
Specific Gravity	1.022	
(T_1) Seawater Temp.	26.0 °C	
Total Head	3 m	
Target Pump/Motor Efficiency	> 72%	
Maximum Power Consumption	<10,840 kW	
No. of Pumps	TBD by supplier	
COLD SEAWATER PUMP(S)		
Total Seawater Flow Rate	142,300 kg/s	
Specific Gravity	1.027	
(T_{11}) Seawater Temp.	4.5 °C	
Total Head	7.2 m	
Target Pump/Motor Efficiency	> 72%	
Maximum Power Consumption	<13,850 kW	
No. of Pumps	TBD by supplier	

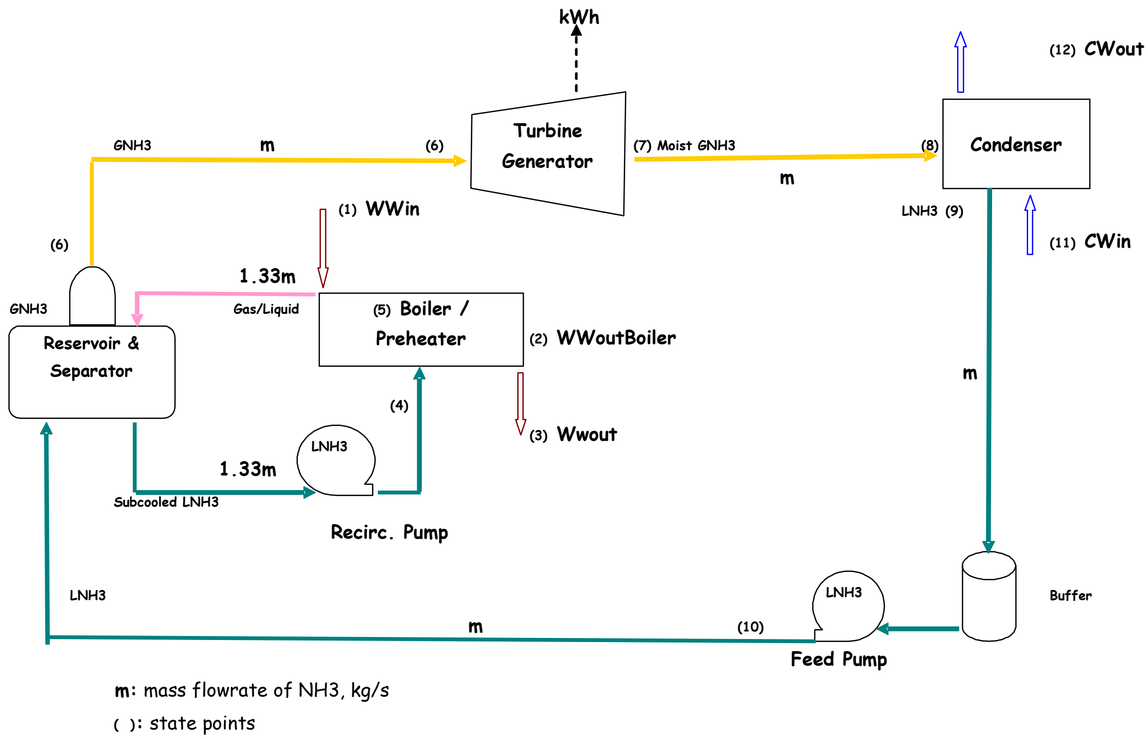
Information to be provided by Seawater Pumps Manufacturer

Provide/Confirm Parameters Listed Above	
Overall Dimensions per unit	
Overall Weight per unit	
Space requirement for Maintenance:	
Construction Time Required:	
Cost FOB Factory:	
Service Life:	

Appendix 3

Heat and Mass Balance: 50 MWe-net CC-OTEC

The H&M balance keyed to the following diagram is given in pages 11-13.



Process Flow Diagram for Electricity Production Mode

Appendix 3

Heat & Mass Balance 50 MW OTEC Electricity Mode						
	Case:	80.000	MW-gross	10 x 8 MW gross T-G		
		53.482	**MW-net**			
Twwi	T1	**26.0**	deg C	1022.7	kg/m^3	
Tcwi	T11	**4.5**	deg C	1027.3	kg/m^3	
ΔT	(T1 - T11)	21.5	deg C			
Mcw		**142,306**	**kg/s**	1,779	kg/s/ MW-gross	
Mww		**270,381**	**kg/s**	1.9	Mww/Mcw	
Cp seawater		4	kJ/(kg-deg)			
MNH3 Turbine		**2,743**	**kg/s**	34.3	kg/s /MW-gross	
MNH3Recirculating/Feed		1.3				
Boiler Pinch Point	T2 - T5	1.2	deg C			
Cdsr Pinch Point	T9 - T12	1.0	deg C			
DP evp	P6 - P4	17.0	kPa	could easily be twice		
DP cndsr	P8 - P9	12.0	kPa	these DP values.		
Quality Vapor out Turbine	¬	0.98				
Generator Efficiency		95.0%				

Evaporator (Preheater & Boiler & Mist Eliminator) Module						
TwwEvpout	T3	22.9				
TwwBoilerout	T2	23.0				
TSubcooledLNH3	T4	11.5				
Enthalpy into Evprt	h4	379.6				
PLNH3 Preheater	P4	907.4				
TLNH3 into Boiler	T5	21.8				
PLNH3 into Boiler	P5	907.4				
PGNH3 out Boiler	P6	890.4				
TGNH3 out Boiler	T6	21.2				
Enthalpy out of Evprt	h6	1606.6				
HEAT ADDED	h6 - h4	1227.0	kJ/kg			
Latent Heat Evaporation	hfg(T6)	1180.8				
Heat Duty Boiler NH3 side		**3,239,212**	**kJ/s**			
Heat Duty Boiler water side		**3,244,573**	**kJ/s**			
Imbalance NH3/Water		*0.998*				
Overall Heat Duty Evprt		**3,352,726**	**kJ/s**			

Appendix 3

	Turbine Module					
PGNH3 into Turbine	P6	890.4				
TGNH3 into Turbine	T6	21.2				
T 2-phase out Turbine	T7	12.0				
P 2-phase out Turbine	P7	658.3				
Enthalpy out of Turbine	h7	1576.1				
TURBINE WORK	h6 - h7	30.5	kJ/kg			
Gross Power	**kWgross**	**79,442**	for generator efficiency as given above			
	Condenser Module					
P NH3 into Cndsr	P8	656.9				
T NH3 into Cndsr	T8	11.9				
Enthalpy into Cndsr	h8	1576.1				
Latent Heat Condensation	hfg(P8)	1217.2	kJ/kg			
PLNH3 out Cndsr	P9	644.9				
Enthalpy out Cndsr	h9	379.1				
TLNH3 out Cndsr	T9	11.4				
HEAT REJECTED	**h8-h9**	1197.0				
Tcw out cndsr	T12	10.3				
Check Pinch Point	T9 - T12	1.1				
Heat Duty Cndsr NH3side		**3,275,302**	**kJ/s**			
Heat Duty Cndsr waterside		**3,304,342**	**kJ/s**			
Imbalance NH3/Water		*0.991*				

		Feed Pump				
Inlet Pressure	P9	644.9	outlet condenser			
Enthalpy inlet Pump	h9	379.1	same as cndrs outlet			
Outlet Pressure	P10	919.4	about 12 kPa higher than pressure at preheater			
Enthalpy outlet pump	h10	379.6	same as inlet evaporator h4			
PUMP WORK	h10 - h9	0.5				
MLNH3, kg/s		2743.2				

Appendix 3

Cycle Balance	
Heat Added + Pump Work	**1227.5**
Heat Rejected + Turbine Work	**1227.5**
Ratio	*1.0*

LNH3 Pumps Power, kW		**1828**
Feed Flow, kg/s		**2743**
Feed DP	P10 - P9	274.5
LNH3 Density, kg/l	at T9	0.62
Pump Efficiency		0.72
Power Consumption, kW		1687
Recirculating Flow, kg/s		**3658**
Recirc. DP	P4 - P6	17.0
LNH3 Density, kg/l	at T6	0.61
Pump Efficiency		0.72
Power Consumption, kW		142

		Water Pumps				
	Density Head	K-factor	f-factor	HX	Total	Efficiency
Cold Water Head, m	1.09	1.4	2.03	1.43	5.95	0.72
Warm Water Head, m	0	0.66	0.01	1.07	1.74	0.72
Discharge Loop Head, m	0	1.18	0.03	0	1.21	0.72
CW Pump, kW	**13,849**					
WW Pump, kW	**10,841**					
Total Seawater Pumps, kW	**24,690**					

Total Parasitics, kW	26,518

Levelized Cost of Electricity (LCOE: $/kWh)

Luis A. Vega, Ph.D.

Conventional Production of Electricity

The thermal efficiency (η) of well-maintained conventional steam power plants, fired with fossil fuels can be as high as 36%. This implies that only 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, η = 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, unfortunately 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 Cost of a (42 U.S. gallons) Barrel 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 such that, for example, with a price of $62 per metric ton 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 Operations, Maintenance, Repair and Replacement (OMR&R.)

These parameters are summarized here because Electric Utilities in the USA, for example, consider that electrical power generated by independent power producers (IPPs) should be purchased at a rate derived solely from the cost of the fuel they use. That is, they are willing to only purchase electricity from IPPs for the COE_{fuel}

Conventional Production of Desalinated Water from Seawater

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. Current, freshwater production by RO costs **1 ± 0.5 $/m^3** (3.8 ± 1.9 $/kgallon).

OTEC 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 Appendix 5, for example, the following terms are defined:

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

System (equipment) Availability: 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%);

Site Annual (resource) Capacity Factor: 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;

Annual Electricity Production (MWh): Name Plate x Availability x Capacity Factor x 8760;

Daily Desalinated Water Production (MGD; m^3/day): Used for OC-OTEC systems;

Installed Cost (Capital Cost, CC): This is the amount (given in million dollars) of the loan: derived from the cost estimate {given in $/kW} times the Name Plate;

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

Interest (I): From the loan terms

Escalation (Inflation) Rate: taken at a constant 3% herein *(N.B. over the last 20-years, for example, the average USA Manufacturing-Price-Index was 2.65 %);*

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 or concessionary loans) although the OTEC system is designed for a 30-year useful life. Some components are replaced in 15-year intervals (e.g., pumps; Turbines) others require 30-year intervals (e.g., Titanium heat exchangers);

Under Capital Payment (loan amortization):

Capital Recovery Factor (CRF):

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

such that for parameters in Appendix 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):

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

such that for parameters given in Table 4 (Appendix 5) the PWF is 10.48 years;

Expenses Levelizing Factor (ELF):

ELF = PWF x CRF

such that for the parameters given in Appendix 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 Appendix 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 $COE_{OMR\&R}$. The value given here excludes environmental credits, tax credits and profit.

OTEC State of the Art (2013)[15]

OTEC Technology

In 1881 D'Arsonval documented a concept to use the relatively warm (24 °C to 30 °C) surface water of the tropical oceans to vaporize pressurized ammonia through a heat exchanger (i.e., evaporator) and use the resulting vapor to drive a turbine-generator. The cold ocean water transported (upwelled) to the surface from 800 m to 1000 m depths, with temperatures ranging from 8 °C to 4 °C, would condense the ammonia vapor through another heat exchanger (i.e., condenser). D'Arsonval concept is grounded in the thermodynamic Rankine cycle used to study steam (vapor) power plants. Because the ammonia circulates in a closed loop, this concept has been named closed-cycle OTEC (CC-OTEC). The basic process diagram for CC-OTEC is depicted in Figure 1.

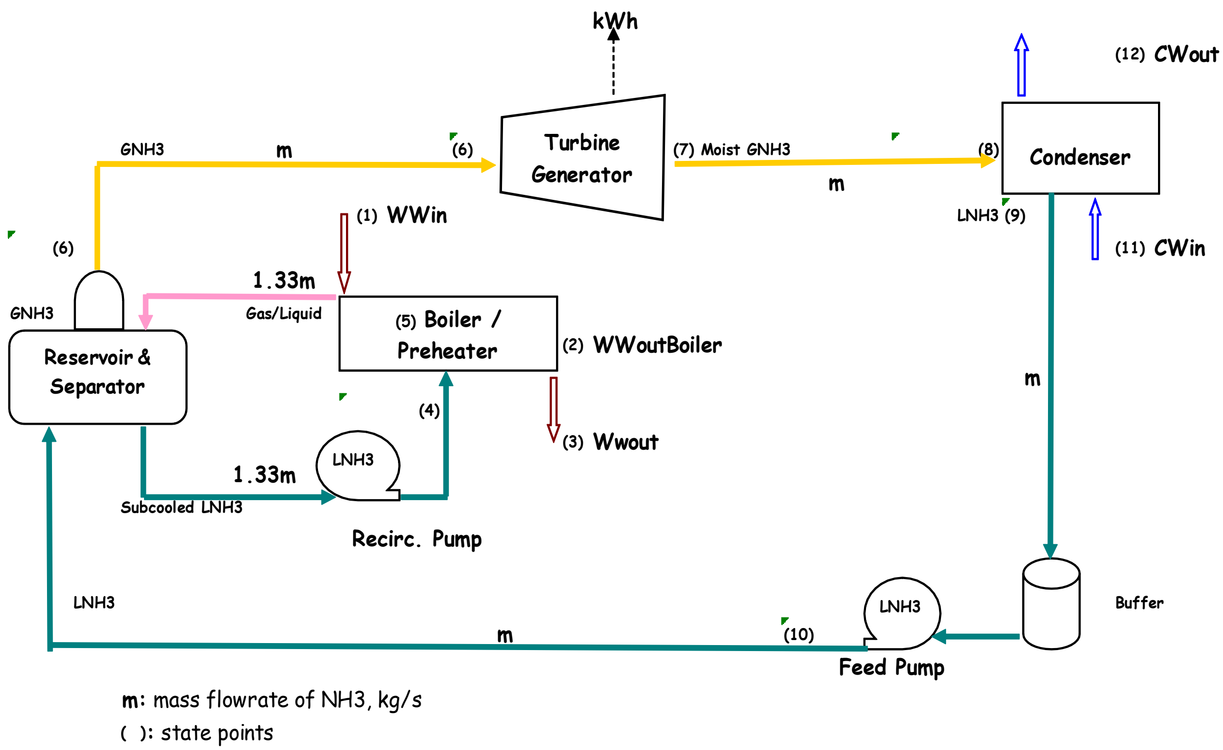


Figure 1.- Closed-Cycle OTEC Process Flow Diagram.

D'Arsonval's concept was demonstrated in 1979, when the state of Hawaii and a consortium of U.S. companies produced more than 50 kW of gross power, with a net output of up to 18 kW from a small plant mounted on a barge off Hawaii. Subsequently, a 100 kW gross power, land-based plant was operated in the island nation of Nauru by a consortium of Japanese companies. These plants were operated for a few months to demonstrate the concept. They were too small to be scaled to commercial size systems (Ref. 1).

[15] Reproduced from previous publications by Luis A. Vega, Ph.D.

Forty years after D'Arsonval, Georges Claude, another French inventor, proposed to use the ocean water as the working fluid. In Claude's cycle the surface water is flash-evaporated in a vacuum chamber. The resulting low-pressure steam is used to drive a turbine-generator and the relatively colder deep seawater is used to condense the steam after it has passed through the turbine. This cycle can, therefore, be configured to produce desalinated water as well as electricity. Claude's cycle is also referred to as open-cycle OTEC (OC-OTEC) because the working fluid flows once through the system. The basic process diagram for OC-OTEC is depicted in Figure 2.

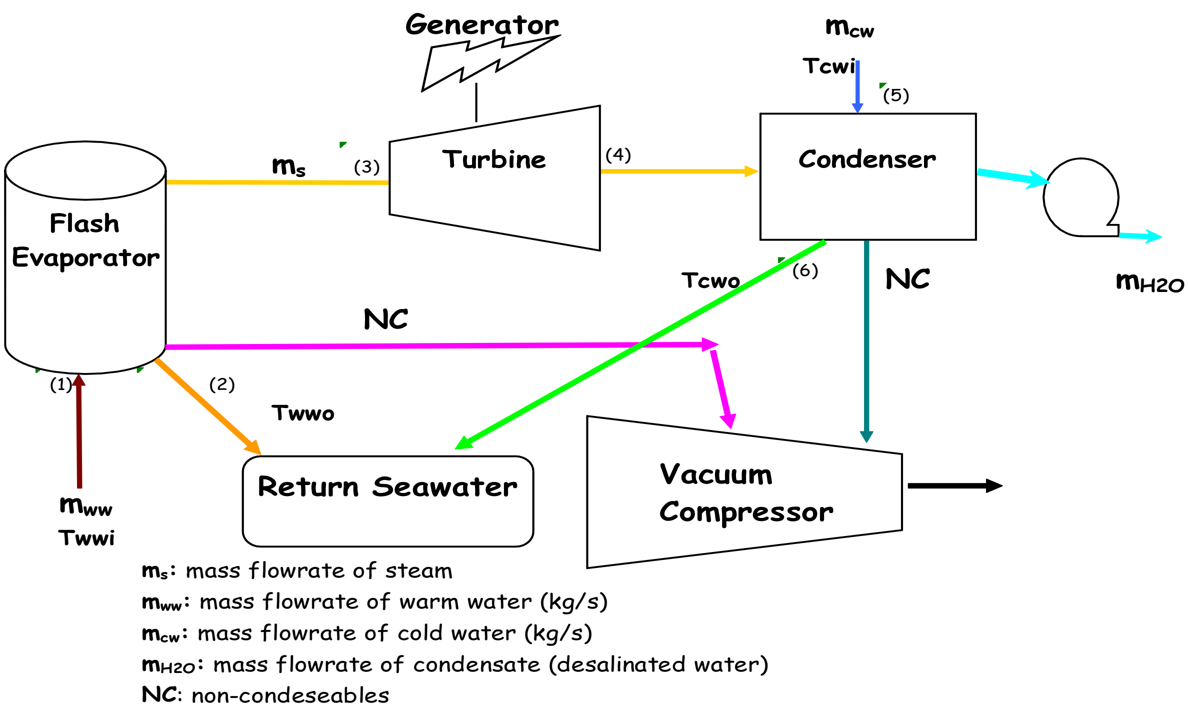


Figure 2.- Open-Cycle OTEC Process Flow Diagram.

Claude demonstrated this cycle in Cuba (1930) with a small land-based plant making use of a direct contact condenser (DCC). Therefore, desalinated water was not a by-product. The plant failed to achieve net power production because of a poor site selection (e.g., thermal resource) and a mismatch of the power and seawater systems. However, the plant did operate for several weeks.

Claude, subsequently, designed a 2.2 MW floating plant for the production of up to 2000 tons of ice (this was prior to the wide availability of household refrigerators) for the city of Rio de Janeiro in Brazil. Claude housed his power plant in a ship (i.e., plantship), about 100 km offshore. Unfortunately, he failed in his numerous attempts to install the vertical long pipe required to transport the deep ocean water to the ship (the cold water pipe, CWP) and had to abandon his enterprise in 1935. His failure can be attributed to the absence of the offshore industry, and ocean engineering expertise presently available. His biggest technological challenge was the at-sea installation of a CWP. This situation is markedly different now that there is a proven record in the installation of several pipes during experimental operations.

The next step towards answering questions related to operation of OTEC plants was the installation of a small OC-OTEC land-based experimental facility in Hawaii (Figure 3) by a team led by the author (Ref. 7). The turbine-generator was designed for an output of 210 kW for 26 °C warm surface water and a deep water temperature of 6 °C. A small fraction (10 percent) of the steam produced was diverted to a surface condenser for the production of desalinated water. The experimental plant was successfully operated for six years (1993-1998). The highest production rates achieved were 255 kW (gross) with a corresponding net power of 103 kW and 0.4 l/ s of desalinated water. These are world records for OTEC.

Figure 3.- 210 kW OC-OTEC Experimental Apparatus (Vega et al, 1993-1998).

A two-stage OTEC hybrid cycle, wherein electricity is produced in a first-stage (closed cycle) followed by water production in a second-stage, has been proposed to maximize the use of the thermal resource available to produce water and electricity (Ref. 1). In the second-stage, the temperature difference available in the seawater effluents from an OTEC plant (e.g., 12 °C) is used to produce desalinated water through a system consisting of a 1 evaporator and a surface condenser (basically, an open cycle without a turbine-generator). In the case of an open cycle plant, the addition of a second-stage results in doubling water production.

The use of the cold deep water as the chiller fluid in air conditioning (AC) systems was proposed and implemented (Ref. 9). It has been demonstrated that these systems, referred to as Seawater Air Conditioning (SWAC), provide significant energy conservation and have been installed independently of OTEC.

OTEC energy could be transported via chemical, thermal and electrochemical carriers. The technical evaluation of non-electrical carriers leads, for example, to the consideration of hydrogen produced using electricity and desalinated water generated with OTEC technology. The product would be transported, from the OTEC plantship located at distances of about 1,500 km (selected to represent the nominal distance from the tropical oceans to major industrialized centers throughout the world) to the port facility in liquid form to be primarily used as a transportation fuel. A 100 MW-net plantship can be configured to yield (by electrolysis) 1300 kg per hour of liquid hydrogen. Unfortunately, the production cost of liquid hydrogen delivered to the harbor would be equivalent to about $400 barrel-of-crude-oil (approximately four times present cost). The situation is similar for the other energy carriers considered (e.g., anhydrous ammonia). Presently, the only energy carrier that is cost-effective for OTEC energy is the submarine power cable. This situation would be different in future decades in the post fossil-fuels era.

A number of possible configurations for OTEC plants have been proposed. These range from floating plants to land-based plants, including shelf-mounted towers and other offshore structures. The primary candidate for commercial size plants appears to be the floating plant, positioned close to land, transmitting power to shore via a submarine power cable (Ref. 6).

Two decades ago, the detailed evaluation of economic feasibility and financial viability of OTEC revealed that, in general, plants would have to be sized at about 50 to 100 MW to produce cost competitive baseload electricity (Ref. 3). Smaller plants could be cost effective in some niche markets (Ref 16). It was also concluded that, although experimental work with relatively small plants had unambiguously demonstrated continuous production of electricity and desalinated water, it would be necessary to build a pre-commercial plant sized around 5 to 10 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 plants sized at less than 0.25 MW.

In the mid-90s an engineering team in Hawaii designed a 5 MW pre-commercial plant and made the information available in the public domain (Ref. 8). 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.

OTEC Limitations and Challenges

The performance of OTEC cycles is assessed with the same thermodynamic concepts used for conventional steam power plants. The major difference arises from the large quantities of warm and cold seawater required for heat transfer processes, resulting in the consumption of a portion of the power generated by the turbine-generator in the operation of pumps. The power required to pump seawater is determined accounting for the pipe-fluid frictional losses and in the case of the cold seawater for the density head, i.e., gravitational energy due to the differences in density between the heavier (colder) water inside the pipe and the surrounding water column. The seawater temperature rise, due to frictional losses, is negligible for practical designs.

The ideal energy conversion for 26 °C and 4 °C warm and cold seawaters is 8 percent. An actual OTEC plant will transfer heat irreversibly at various points in the cycle yielding an energy conversion of 3 to 4 percent. These values are small compared to efficiencies obtained for conventional power plants; however, OTEC uses a resource that is constantly renewed by the sun.

The thermal performance of CC-OTEC and OC-OTEC is comparable. As a reference we can consider a 10 MW CC-OTEC plant. The seawater flow rates are 27.7 m^3/s (28,450 kg/s), of 4.5 °C cold water drawn from a depth of 1,000 m; and 52.8 m^3/s (54,000 kg/s) 26 °C warm water drawn from a depth of about 20 m, with an output of 16 MW at the generator terminals (P_{gross}) with 5.3 MW (P_{loss}) required to pump seawater and the working fluid (e.g., anhydrous ammonia) through the plant. The net output (P_{net}) would, therefore, be 10.7 MW. To keep pumping losses at ~ 30 % of P_{gross}, an average speed of less than 2 m/s is considered for the seawater flowing through the pipes transporting the seawater resource to the OTEC power block. OTEC design parameters are, therefore, generalized as follows:

- In-house or parasitic electrical loads P_{loss} represent about 30% of P_{gross} , such that the exportable power (P_{net}) is about 70% of P_{gross};
- A cold water flow rate (Q_{cw}) of 2.7 m^3/s is required per MW_{net};
- The optimal warm water flow rate (Q_{ww}) is about 1.9 x Q_{cw}.

P_{gross} is proportional to the square of the temperature differential (ΔT) and the seawater flow rate, such that:

$$P_{net} = P_{gross} - P_{loss} = \beta Q_{cw}(\Delta T)^2 - P_{loss}$$

where, β and P_{loss} are system specific. Considering nominal values it can be shown that a 1 °C change in ΔT leads to a change of approximately 15% in P_{net}.

In summary, in the absence of seawater flow rate constraints, extractable power can be characterized by providing ΔT estimates.

The design and installation of a cost-effective pipe to transport large quantities of cold water to the surface (i.e., cold water pipe, CWP) presented an engineering challenge of significant magnitude complicated by a lack of evolutionary experience. This challenge was met in the USA with a program relying on computer-aided analytical studies integrated with laboratory and at-sea tests. The greatest outcome achieved has been the design, fabrication, transportation, deployment and test at-sea of an instrumented 2.4 m diameter, 120 m long, fiberglass reinforced plastic (FRP) sandwich construction pipe attached to a barge (Ref. 1). The data obtained was used to validate the design technology developed for pipes suspended from floating OTEC plants. This type of pipe is recommended for floating OTEC plants.

For land-based plants, there is a validated design for high-density polyethylene pipes of diameter less than about 2 m (Ref. 10). In the case of larger diameter pipes offshore techniques used to deploy large, segmented pipes made of steel, concrete or FRP are applicable. Pressurized pipes made of reinforced elastomeric fabrics (e.g., soft pipes), with pumps located at the cold-water intake, seem to offer the most innovative alternative to conventional concepts. However, the operability of pumps in 800 m to 1000 m water depths over extended periods must be verified and the inspection, maintenance and repair (IM&R) constraints established before soft pipes can be used in practical designs.

Other components for OTEC floating plants that present engineering challenges are the position keeping system and the attachment of the submarine power cable to the floating plant. Deep ocean-mooring systems, designed for water depths of more than 1000 m, or dynamic positioning thrusters developed by the offshore industry can be used for position keeping. The warm water intake and the mixed return water also provide the momentum necessary to position the surface vessel (Ref. 11). The offshore industry also provides the engineering and technological backgrounds required to design and install the riser for the submarine power cable.

The design of OTEC CWPs, mooring systems and the submarine power cable must take into consideration survivability loads as well as fatigue induced loads. The first kind is based on extreme environmental phenomena, with a relatively long return period, which might result in ultimate strength failure while the second kind might result in fatigue-induced failure through normal operations.

Important lessons learned from these experiences can be summarized as follows:

- All components must be considered in technical and economic assessments: *OTEC plants consist of several components or subsystems that must be integrated into a system;*
- The entire life cycle must be incorporated into design process;
- Equipment must be manufactured using commercially available practices in existing factories;
- Embellishment leads to negative consequences, creating credibility barriers for others and unrealistic expectations from the public.

Other significant lessons learned (or relearned) and observations from the perspective of an operator of the OTEC experimental plant facility were:

- Make the plant "user friendly" from the standpoint of troubleshooting, maintenance, repair and modification;
- Include technical field support from suppliers of major equipment, but be prepared to solve most problems on your own;
- Select equipment with excess capacity. It was appropriate to optimize design point performance but there will always be off-design operations requiring additional capacity;

- If equipment has moving parts evaluate the bearing system and ask potential supplier to provide references of successful application of their design before purchase;
- Consider the corrosive saltwater, condensate, and the typically harsh environment of OTEC sites when making design decisions, especially material selection and placement of mechanical and electrical equipment;
- Avoid metal components, but if unavoidable, use the hot-dip-galvanized process from a factory with proven quality control procedures.

OTEC Site Selection (taken from G. Nihous work)

As it is well known the OTEC concept utilizes the differences in temperature, ΔT, between the warm ($T_{ww} \sim 22$ °C to 29 °C) tropical surface waters, and the cold ($T_{cw} \sim 4$ °C to 5 °C) deep ocean waters available at depths of about 1,000 m, as the source of the thermal energy required.

Deep seawater flows from the Polar Regions. These polar waters, which represent up to 60% of all seawater, originate mainly from the Arctic for the Atlantic and North Pacific Oceans, and from the Antarctic (Weddell Sea) for all other major oceans. Therefore, T_{cw} 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_{cw} as nearly constant, with a value of 4°C to 5°C at 1000 m (Ref. 1, 5).

A desirable OTEC thermal resource of at least 20°C requires typical values of T_{ww} 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_{ww} 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. A careful OTEC site selection requires a comprehensive knowledge of local climate features inasmuch as they may affect T_{ww} 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 2005 version of the World Ocean Atlas (WOA05) compiled by the US National Ocean Data Center (NODC) represents an extremely valuable source of objectively analyzed statistical fields, including ocean temperature. The data includes long-term historical averages of variables that have been determined from all available oceanographic measurements. Monthly averages also are available. The data is provided with a resolution of one-quarter degree latitude by one-quarter degree longitude. The historical monthly averages of ΔT for February and August 2005 are depicted in Figures 4 and 5 respectively (Ref. 4). The annual average values are given in Figure 6. Values are color coded as indicated in the right-hand-side of the Figures.

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 freshwater plant outputs should match local consumption in orders of magnitude.

This brings out an interesting question about the size of the OTEC resource: *Could a massive deployment of this technology affect ocean temperatures on which the process itself depends? In other words, could OTEC be self-limiting?*

Recent analysis using a 3D oceanic general circulation model to account for the complex interplay between planetary heat fluxes and potentially large OTEC intakes and discharges spread over more than 100 million square kilometers confirmed a 30 TW maximum for global OTEC power production (Ref. 5). As OTEC flow rates increase, the erosion of vertical seawater temperature gradients is much slower in 3D ocean models, because any heat locally added to the system can be horizontally transported and re-distributed at a relatively fast rate. Another distinctive feature of the model results is the persistence of slightly cooler surface waters in the OTEC region. This is compensated, however, by a warming trend at higher latitudes. A boost of the planetary circulation responsible for the overall supply of deep cold seawater is also shown. A more modest OTEC scenario with a global potential of the order of 7 TW shows little impact (Ref. 5). It must be noted that the baseline commercial size OTEC plant is sized at 100 MW such that 70,000 plants would correspond to 7 TW.

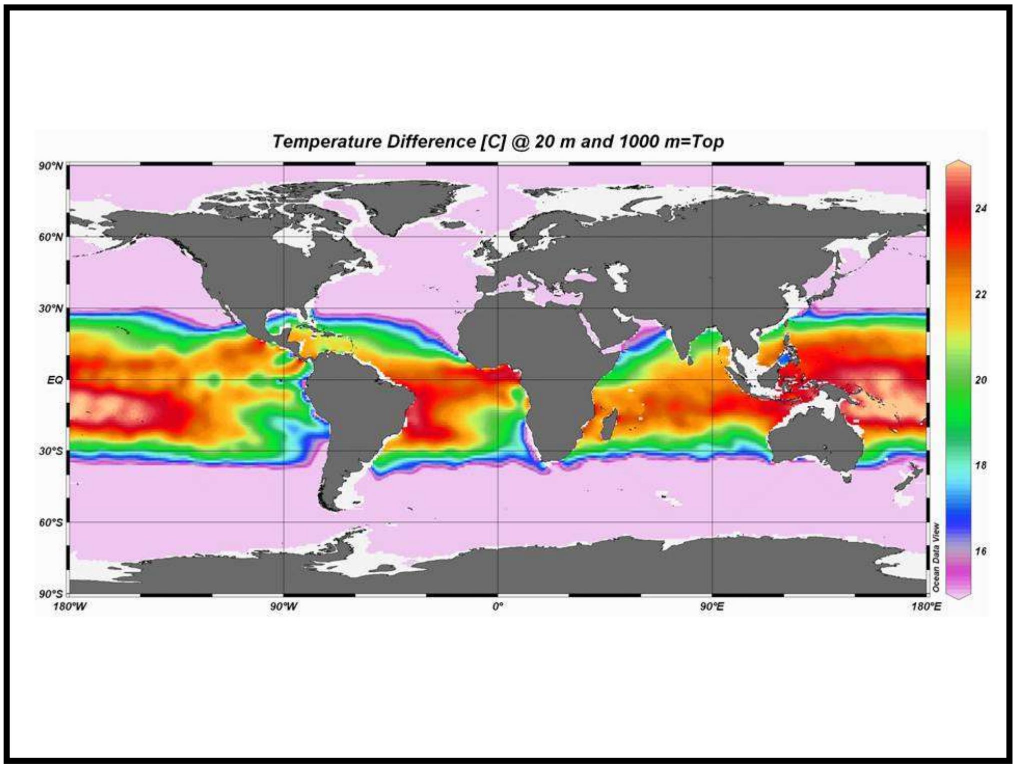


Figure 4.- Historical Monthly average of ∆T during February 2005 (Ref. 4)

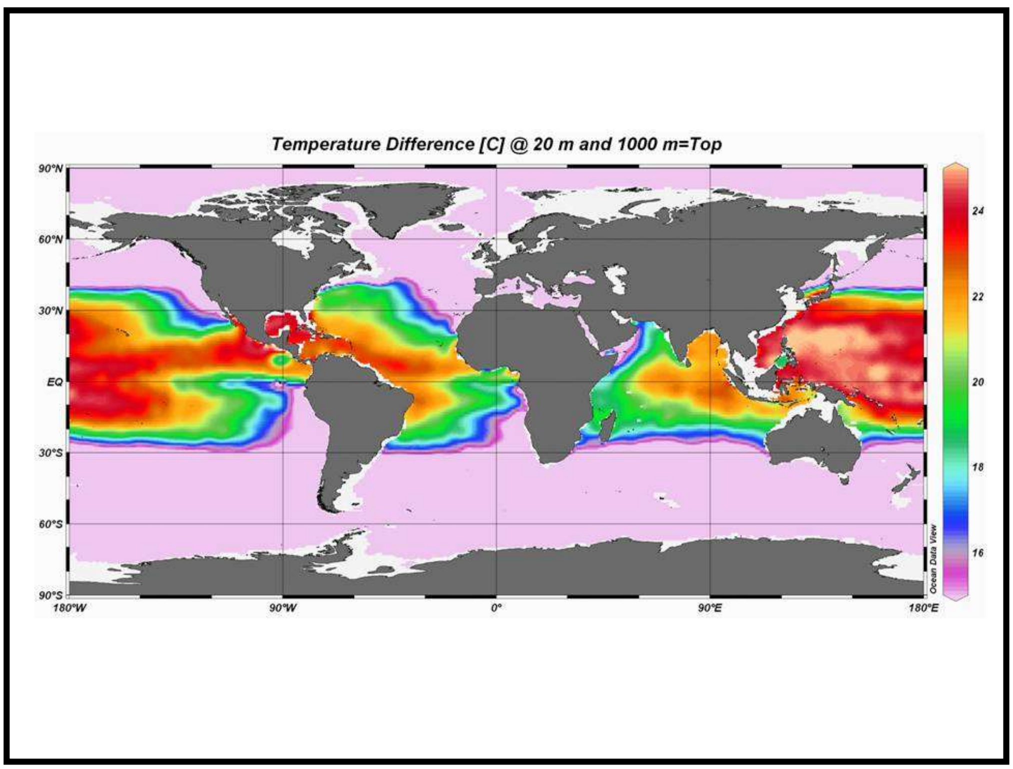


Figure 5.- Historical Monthly average of ∆T during August 2005 (Ref. 4).

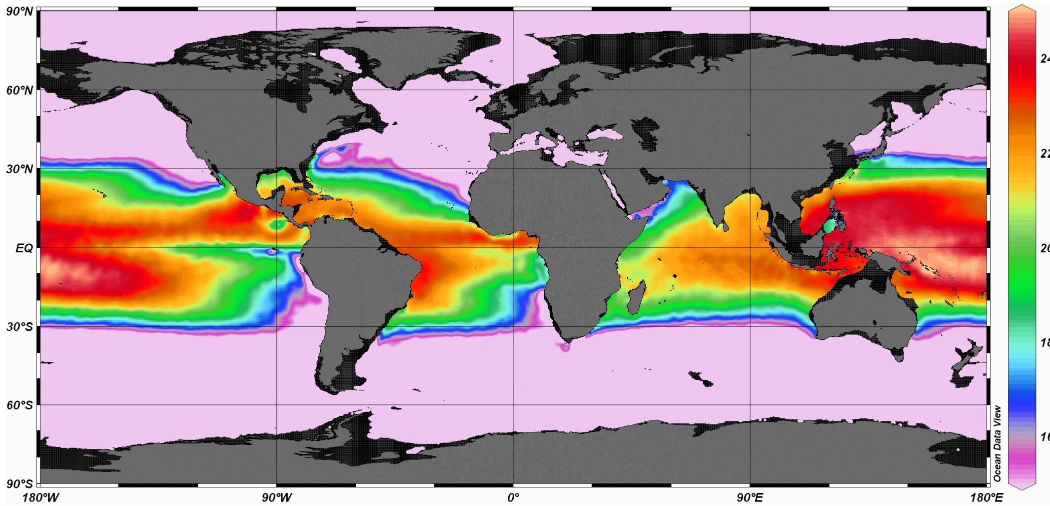


Figure 6. – Worldwide average ocean temperature differences (between 20 m and 1000 m water depths) from WOA 2005 (1/4°) data. The color palette is from 15°C to 25°C (Ref. 4).

Environmental Impact of OTEC

OTEC might offer a relatively benign power production technology, since the handling of hazardous substances is limited to the working fluid (e.g., ammonia for CC-OTEC), and no noxious by-products are generated. 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, and 500 for natural gas plants. For OC-OTEC plants, without proper water return piping connected to the vacuum compression system, it is at most ~ 1 % of the amount released by fuel oil plants. The value is negligible in the case of a CC-OTEC plant (Ref. 1, 12).

To have effective heat transfer it is necessary to protect the heat exchangers from biofouling. It has been determined that, with proper design, biofouling only occurs in CC-OTEC heat exchangers exposed to surface seawater. Therefore, it is only necessary to protect the CC-OTEC evaporators by, for example, intermittent chlorination (50-100 parts per billion chlorine for 1 hr/day). This amount, for example, is well below what is allowed under current USA regulations. The use of biocides and ammonia are similar to other human activities. If occupational health and safety regulations like those in effect in the USA are followed, working fluid and biocide emissions from a plant should be too low to detect outside the plant sites. Ammonia is used as a fertilizer and in ice skating rink refrigeration systems. Chlorine is used in municipal water treatment plants and in steam power plants. It must be emphasized that no chlorination is required in the OC-OTEC process (Ref. 1).

A sustained flow of cold, nutrient-rich, bacteria-free deep ocean water could cause sea surface temperature anomalies and biostimulation if resident times in the mixed layer and the euphotic zone respectively are long enough (i.e., upwelling). The euphotic zone is the upper layer of the ocean in which there is sufficient light for photosynthesis. This has been taken to mean the 1 percent-light-penetration depth (e.g., 120 m in Hawaiian waters). This is unduly conservative, because most biological activity requires radiation levels of at least 10 percent of the sea surface value. Since light intensity decreases exponentially with depth, the critical 10 percent-light-penetration depth corresponds to, for example, 60 m in Hawaiian waters.

The analyses of specific OTEC designs indicate that mixed seawater returned at depths of 60 m results in a dilution coefficient of 4 (i.e., 1 part OTEC effluent is mixed with 3 parts of the ambient seawater) and equilibrium (neutral buoyancy) depths below the mixed layer throughout the year. This water return depth also provides vertical separation, from the warm water intake at about 20 m, required to avoid reingestion into the plant. This value will vary as a function of ocean current conditions. It follows that the marine food web should be minimally affected and that persistent sea surface temperature anomalies should not be induced. These conclusions need to be confirmed with actual field measurements that could be performed with pilot plants.

Other potentially significant concerns are related to the construction phase. These are similar to those associated with the construction of any power plant, shipbuilding and the construction of offshore platforms. OTEC operations might affect commercial and recreational fishing. Fish will be attracted to the plant, potentially increasing fishing in the area. However, the losses of inshore fish eggs and larvae, as well as juvenile fish, due to impingement and entrainment and to the discharge of biocides may reduce fish populations. The net effect of OTEC operation on aquatic life would depend on the balance achieved between these two effects. Through adequate planning and coordination with the local community, recreational assets near an OTEC site may be enhanced.

To better understand the risks that these impacts pose, a site specific environmental baseline is required prior to installation. This baseline should include monitoring for presence and abundance of large and small biota, as well as the physical and chemical seawater characteristics. For certain impacts, a longer baseline may be desired to capture multi-year variability. Monitoring for changes to the baseline should occur during the operation phase and would provide information on how the facility is impacting the local environment. Physical, chemical, and biological criteria should be monitored, including: temperature; salinity; dissolved oxygen; pH; trace metals; and abundance, diversity, mortality and behavioral changes in plankton, fish, marine mammals, turtles, and other biota (Ref 18).

In summary, potential environmental impacts must be evaluated and all licensing and permitting requirements must be fulfilled. However, it is of extreme importance to understand that the only process that differentiates OTEC from other well established human activities and industries is the use of ocean water drawn from ~ 1,000 m depths and its return to the ocean below the photic zone. Given the intricate and dynamic nature of the ocean it is nearly impossible to determine with a high degree of certainty what would be the effect of such a process through basic research or the development of ecological theory. **The only way to evaluate the OTEC environmental differentiator is to obtain field data with a pilot plant operating with flow rates corresponding to at least a 5 MW plant. Such a plant must be operated and monitored through ongoing and adaptive experience for one to two continuous years, i.e., an adaptive management process.**

OTEC Operations: Environmental Impact Monitoring

The only aspect of OTEC operations that is unique and not found in other marine industries can be addressed by asking:

What might be the environmental impact of the redistribution of relatively large deep ocean seawater masses?

Another aspect that must be considered, although it is not unique to OTEC, is the entrainment of organisms through the seawater intake pipes and their impingement as they travel through the plant into the seawater discharge piping system.

To answer these questions, monitoring sampling during actual operations of OTEC plants is necessary to track primary productivity, organism's abundance and density, and entrainment and impingement. The most important directive is to establish a protocol for monitoring the environmental effect of plant operations. Numerical models provide a first step but only through field observations can the impact be quantified.

Vega et al have proposed that monitoring the following parameters, during the actual operation of OTEC plants, in relation to baseline conditions will suffice to reveal the impact of the effluent plume on the environment:

Nutrients and Biological	**Conductivity, Temperature and Depth (CTD) Casts**	**Carbonate Cycle**
Nitrate	**Temperature**	**Dissolved Inorganic Carbon**
Phosphate	**Salinity**	**pH**
Silicate	**Dissolved Oxygen**	Alkalinity
Chlorophyll a		

Furthermore, the following can be considered a *minimum* effective list of parameters to monitor at the depth where the discharge effluent has reached neutral buoyancy away from the plant:

- Chlorophyll a, Nitrate+Nitrite
- Temperature, Salinity, Dissolved Oxygen
- Dissolved Inorganic Carbon, pH

In addition, it has been proposed to determine the Genome displacement due to the deepwater displacement.

Marine life Entrainment and Impingement effects can be monitored by, for example, adapting the US Environmental Protection Agency (EPA) approved protocols for the operations of conventional power plants utilizing seawater for cooling processes.

Frequently asked questions about the OTEC environmental and social impact are:

Environmental		
Land Requirements for OTEC Plantships	What is the land requirement?	Land is only required for Electrical Substation with Transformers and submarine power cable landing. Less than 0.1 ha required per Plantship.
Ecological sensitivity	Is the land ecologically sensitive?	No because Plantship deployed at least 10 km offshore.
Pollution effects	How will operations affect local air, water and coastal/riparian quality?	None to relatively minimal.
Local Air Emissions	What are the annual air emissions (NO_x, SO_x, total PM)?	None.
Greenhouse Gas Emissions	What are the greenhouse gas emissions (CO_2)?	None with appropriate design as demonstrated with experimental plants.
Noise and light pollution	Will there be a signification source of noise or light pollution during operation?	Comparable to regular ship operations.
Accidents & Risks	What are the probabilities of accidents and the consequences?	Low to negligible in industrial safety practices are followed.
Other	Possible enhancement of Marine Food Web?	Only if somehow effluent is kept in the photic zone (depths of no more than about 100m). None under proper design of return/discharge pipes.
Social		
Employment Opportunities	What employment opportunities will be generated by construction or operation? What are the opportunities for local people to become part of the skilled labor force?	Need a crew of about 20 per Plantship.
Social Infrastructure	Can the facility be added to the existing social infrastructure? (housing, parks, tourism, roads)	Not Applicable (NA).
Research & Development Opportunities	Is there opportunity for technological innovation or research and development?	Ongoing.
Public Acceptance	What actions could be taken to educate the public about the facility/technology and/or green energy?	Public Announcements and Webpage.
Aesthetics	What steps will be taken to increase the aesthetics of the built environment?	NA
Future Growth	What is the potential for growth?	Could deploy thousands of OTEC plants throughout the World within national EEZs
International Collaboration	Is there an opportunity for international collaboration and/or foreign investment?	Yes.

OTEC State of the Art Components (2013)

The following Tables provide information about major OTEC components as of 2013.

COMPONENT: Cold Water Pipe (2013)

FIRST GENERATION BASELINE: FRP-Sandwich per NOAA/DOE 1980s Design and At-Sea Testing, with horizontal towing and upending in-situ; Gimbal connected. *See updated information in the main report. Since 2013 the diameter of HDPE pipelines has been increased such that, they are a cost effective alternative.*

TOPIC	STATE-OF-THE-ART:	ENGINEERING CHALLENGE
PROCESSES		
Fabrication:	Standard FRP	Syntactic Foam spraying
Deployment:	Tow tank tests led to model	Weather window
Construction:	See fabrication	None
Installation:	See deployment model	Weather window
OMR&R:	From marine risers	None
Environmental Monitoring:	“	“
Safe Operating Procedures:	“	“
Decommissioning:	Adapt from Marine Risers	Must incorporate into final design
RISKS ASSOCIATED WITH PROCESS FAILURE	A CWP failure is NOT an option. This is a single component.	Must design for 30-year useable life
COMPONENT VIABILITY	Proven	Need FRP fatigue data beyond 15-years
HURDLES/LIMITING FACTORS	None	“
DEVELOPMENT TIME FRAME	Technology ready but final design process, of entire plant, takes at least one-year	“

COMPONENT: Heat Exchangers (2013)

BASELINE: Aluminum Plate-Fin Evaporator and Condenser manufactured by, for example CHART

TOPIC	**STATE-OF-THE-ART:**	**ENGINEERING CHALLENGE**
PROCESSES		
Fabrication:	Standard	Must get manufacturer involved in design
Deployment:	Installed on shipyard	None
Construction:	See fabrication	“
Installation:	See deployment	“
OMR&R:		
Environmental Monitoring:	Standard NH_3 Industry	“
Safe Operating Procedures:	“	
Decommissioning:	Replace every 15-years & Recycle Al	“
RISKS ASSOCIATED WITH PROCESS FAILURE	Minimal because Modular Design of HXs & TG Combination.	“
COMPONENT VIABILITY	Proven	Replace every 15-years
HURDLES/LIMITING FACTORS	None	“
DEVELOPMENT TIME FRAME	Long-lead item (~ 18^{+} months). Technology ready but final design process, of entire plant, takes at least one-year	Must get manufacturer involved in design

COMPONENT: Mooring (2013)

BASELINE: Spread Mooring or Single Point Mooring with Power Swivel and Dynamic Thrusters

TOPIC	**STATE-OF-THE-ART:**	**ENGINEERING CHALLENGE**
PROCESSES		
Fabrication:	Standard for existing offshore platforms	None
Deployment:	“	“
Construction:	“	“
Installation:	“	“
OMR&R:		
Environmental Monitoring:	Standard for existing offshore platforms	“
Safe Operating Procedures:	“	“
Decommissioning:	Reversible process and Standard	“
RISKS ASSOCIATED WITH PROCESS FAILURE	None (other than power swivel, see submarine power cable)	“
COMPONENT VIABILITY	Proven	“
HURDLES/LIMITING FACTORS	None	“
DEVELOPMENT TIME FRAME	Long-lead item, technology ready but final design process, of entire plant, takes at least 1-year	“

COMPONENT: Pumps and Turbines (2013)

BASELINE: NH_3 Turbine from GE (ROTOFLOW) or Mitsubishi; and submersible Pumps from several manufacturers

TOPIC	**STATE-OF-THE-ART:**	**ENGINEERING CHALLENGE**
PROCESSES		
Fabrication:	- TG Standard to ~ 16 MW - Need multiple units to use SOA submersible pumps (low head-high flow).	None
Deployment:	Installed in shipyard	“
Construction:	“	“
Installation:	“	“
OMR&R:		
Environmental Monitoring:	Standard from NH3 Industry	“
Safe Operating Procedures:	“	“
Decommissioning:	Standard	“
RISKS ASSOCIATED WITH PROCESS FAILURE	None, modular design of HXS & TG combination.	“
COMPONENT VIABILITY	Proven	“
HURDLES/LIMITING FACTORS	None	“
DEVELOPMENT TIME FRAME	Long-lead items (~ 18 to 24^{+} months). Technology ready but final design process takes at least one-year	“

COMPONENT: Platform (2013)

BASELINE: Ship-Shaped Tanker or Container Ship

TOPIC	**STATE-OF-THE-ART:**	**ENGINEERING CHALLENGE**
PROCESSES		
Fabrication:	Standard tanker or container ship construction	Is lower capital cost of single hull construction allowed?
Deployment:	Shipyard	None
Construction:	“	“
Installation:	“	“
OMR&R:		
Environmental Monitoring:	Standard	“
Safe Operating Procedures:	Standard	“
Decommissioning:	Standard	“
RISKS ASSOCIATED WITH PROCESS FAILURE	None, not applicable	“
COMPONENT VIABILITY	Proven	“
HURDLES/LIMITING FACTORS	None	“
DEVELOPMENT TIME FRAME	Technology ready but final design process takes at least one-year	“

COMPONENT: Submarine Power Cable (2013)

BASELINE: Several manufacturers

TOPIC	**STATE-OF-THE-ART:**	**ENGINEERING CHALLENGE**
PROCESSES		
Fabrication:	Standard submarine power cables: (1) AC only with ethylene-propylene-rubber (EPR) insulation $V \leq 35$ kV; $P \leq 25$ MW and $L \leq 100$ km; (2) AC or DC with self-contained-fluid-filled (SCFF) insulation, $V \geq 138$ kV; $P \geq 100$ MW and $L < 50$ km; (3) DC only with paper-impregnated-lead-covered (PILC) insulation, $V < 450$ kV; $P < 500$ MW and $L < 200$ km.	Not scalable from pre-commercial to commercial
Deployment:	Standard and with mooring system	None
Construction:	Standard	“
Installation:	See Deployment	“
OMR&R:		
Environmental Monitoring:	Standard	“
Safe Operating Procedures:	“	“
Decommissioning:	“	“
RISKS ASSOCIATED WITH PROCESS FAILURE	Major risk because baseline includes only one cable.	Redundancy, conservative design.
COMPONENT VIABILITY	Proven	None
HURDLES/LIMITING FACTORS	None	“

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6) ***"Technical Readiness of Ocean Thermal Energy Conversion (OTEC)".*** National Oceanic and Atmospheric Administration (NOAA). University of New Hampshire, Durham, NH 27 pp and appendices" Coastal Response Research Center, 2009.

7) ***"Operation of a Small Open-Cycle OTEC Experimental Facility"*** L. Vega and D. Evans, in Proceedings of Oceanology International 94, Vol. 5, Brighton, UK, March 1994.

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LAND BASED OC-OTEC PLANT FOR THE PRODUCTION OF ELECTRICITY AND FRESH WATER:

Conceptual Definition and Design Considerations for Small Island Developing States (SIDS)

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Highlights Extracted for this OTEC Economics Report

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1.0 INTRODUCTION

This report provides the conceptual design for a land-based Open-Cycle Ocean Thermal Energy Conversion (OC-OTEC) plant rated at 1.8 MW (gross) with the net output varying as a function of configuration. Knowledge acquired by the author leading the team that operated the "250 kW OC-OTEC Experimental Apparatus" for six years (1993-1998) is incorporated. This experimental plant funded by the US Department of Energy is also referred to as the NPPE (Net-Power-Producing-Experiment).

A baseline 1.8 MW (gross) power output was selected, because it corresponded at the time to the biggest diameter (1.6 m OD) with appropriate wall thickness High-Density Polyethylene (HDPE) pipe that could be used as the Cold Water Pipe (CWP). This choice was, in turn, compatible with the operating conditions of the largest existing low-pressure steam turbines applicable to OC-OTEC. It should be noted that for larger plants, power modules could be configured in parallel[16]. The modularity argument, however, does not apply to the CWP because of its economy of scale due, mostly, to deployment cost considerations. Therefore, larger plants will use larger CWPs (e.g., power output ~ D^2)

The well-known site off the Natural Energy Laboratory of Hawaii Authority (NELHA) at Keahole Pt., on the West coast of the island of Hawaii, was adopted to represent resource and bottom bathymetry conditions applicable to some Small-Island-Developing-States (SIDS) with a steep seafloor and an appropriate thermal difference between deep seawater and surface seawater.

Because the effluent seawater streams leaving an OTEC plant exhibit a thermal difference of 10°C to 12°C we included an optional "second-stage", consisting of a flash evaporator and surface condenser to generate additional fresh (desalinated) water. In addition, some of the cold water resources can be used to support an air conditioning (AC) system providing considerable electrical energy savings. We consider a 300 room (300 AC Tons) hotel complex yielding a savings of 240 kW.

Two global design options with average temperature difference of 22 ºC between the warm (surface) and cold (deep) water streams were identified: (i) an OC-OTEC plant proper, with a net power production capability of 1.36 MW and freshwater production of 2450 m^3/day; and, (ii) an OC-OTEC plant fitted with a second-stage desalinated water unit, with a net power production capability of about 1.26 MW and a total freshwater production of 5670 m^3/day.

This report summarizes our global design effort to make OC-OTEC as close to being a state-of-the-art technology as it has ever been. Chapter 2 presents a summary of the overall practical plant design. Chapters 3 through 8 tentatively describe individual plant components in a more detailed, albeit succinct, manner. The tentative cost estimates for implementing the project are discussed in Chapter 9, and conclusions and recommendations are finally proposed in Chapter 10.

[16] Currently HDPE pipes of twice the 1.6 m diameter considered herein are available. A 3.2 m pipe can be used to supply the cold water for an ≈ 7 MW-gross OTEC plant consisting of four of the power blocks summarized herein.

2.0 DESIGN

The OC-OTEC plant is designed to meet the general performance guidelines listed below. For convenience and without the loss of generality, environmental conditions corresponding to Keahole Pt. are used. These conditions must be updated for other specific sites. It must be noted that bottom mounted HDPE pipelines have been operational for over 30 years at Keahole Pt.

Plant size: Was selected primarily by installation/deployment infrastructure limitations in SIDS.

Plant availability: Experience acquired during the operational phase of the 250 kW OC-OTEC Experimental Apparatus indicates that with proper OM&R the plant availability will be ≈ 92% (i.e., 28 to 30 days /year downtime for maintenance and repair). This value is used to determine the annual production of electricity and desalinated water.

Plant life: The design should provide a plant life of 30 years consistent with that of a utility plant.

Plant surviveability: The plant should be designed to survive the site-specific 100-year storm event and the 100-year predicted geological hazards (i.e., tsunamis, landslides, earthquakes, etc.).

Geophysical Conditions: Keahole Pt is situated on the Western coastline of the Island of Hawaii. Located in the district of North Kona, Keahole Pt is approximately 13 km North of the town of Kailua-Kona, 37 ocean or 42 road km South of the deep water port of Kawaihae and 5 km from the small boat harbor at Honokohua. Figure 2.1 shows the offshore bathymetry: At the shoreline, lava cliffs drop from an average of 3 m above mean sea level to 6 m below. A shallow shelf, 80 m wide, extends out to a depth of 15 m, where it grades into a 30-40° slope down to a depth of 80 m. At this depth the bottom levels off again (5-10°), forming a mid-depth shelf, 500 m wide. At the 150 m depth contour, the bottom rolls off into a 45-50° slope, which gradually becomes less steep. At the cold water intake depth of 1000 m, the bottom slope is 20°.

Wind Waves: The 100-year deep-water wave off Keahole Pt. is conservatively characterized by:

Significant Wave Height (Hs) & Period:	8.4 m / 18s
Maximum Wave Height:	15 m

Tsunamis: Due to the high level of seismic activity around the perimeter of the Pacific Basin, the Hawaiian archipelago is quite susceptible to the effects of tsunamis. Based on analysis of the advancement of the wavefront from the April 1, 1946 tsunami, as well as the heights reached by the waves at various locations around the island it is concluded that: in general, the height along the Western coast of Hawaii was between
2.1 m and 4.2 m although focusing of the wave at Upolu Point, on the North coast, raised the measured heights at this site to 12.2 m. From the values given for Kawaihae and Kailua, the height at Keahole Pt. would have been around 3.4 m, although the shape of the bottom contours indicates a tendency for focusing, and the level at this site may have been higher.

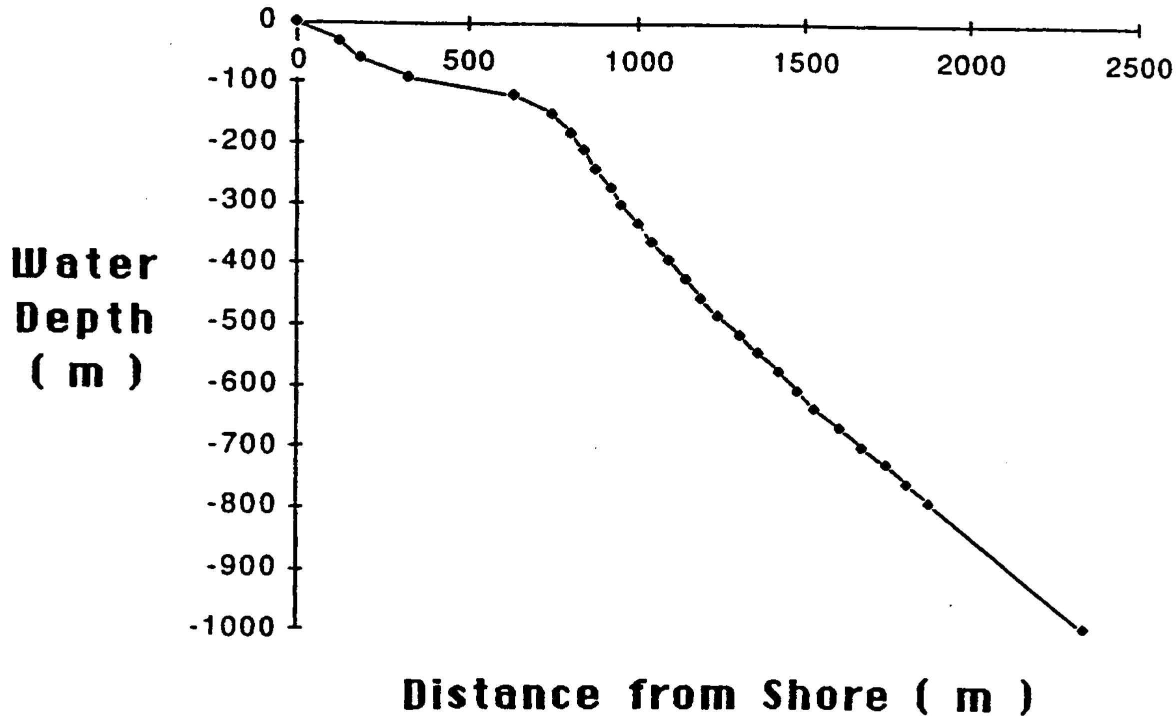


Figure 2.1- Keahole Point Bathymetric Profile

Tides: Tides in the vicinity of the Hawaiian archipelago are a mixed type with a dominant semi-diurnal constituent. The highest tide is taken as 0.61 m (2 feet) above MSL and the lowest tide as 0.37 m (1.2 feet) below MSL for a maximum range of < 1 m.

Current: Seawater current speed, at a given distance from the shore, decreases with depth. The following maximum ocean current profile was adapted for design survival purposes from available data. These unusually high speeds are induced by large eddies generated periodically between the islands of Hawaii and Maui.

Depth (m)	Maximum Current Speed (m/s)
0	1.00
85	0.73
115	0.67
150	0.63
205	0.58
290	0.55
350	0.54
440	0.49
550	0.44
>675	0.40

Water temperature: For design purposes the surface temperature (at 20 m depth) is defined as 26 °C ranging throughout the year between 24 °C and 28 °C. The cold water from 1000 m is taken at a constant value of 4 °C.

The extreme values recorded during the operational phase of the NPPE were 28.29 °C (8/94) and 24.01 °C (2/95). The cold seawater at the 670 m depth intake of the pipe used for the Experimental Apparatus ranged from 5.21 °C (10/94) to 6.64 °C (4/93). General conditions are shown in Figure 2.2 taken from:

https://www.hnei.hawaii.edu/hinmrec-reports/AnnualTempDiff.html

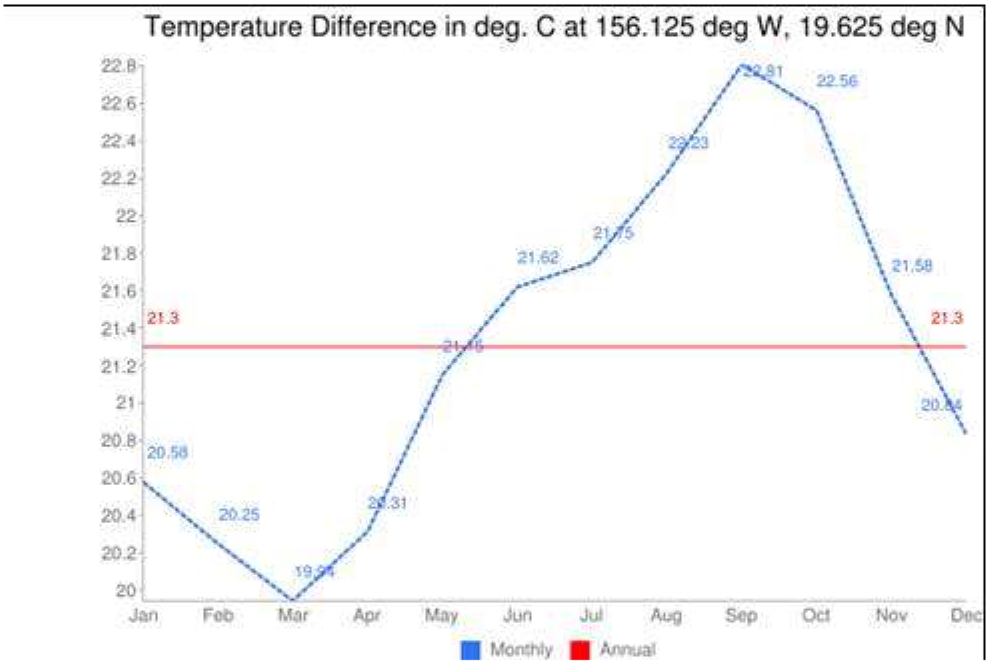


Figure 2.2 - Average monthly variations of temperature differences Between water depths of 20 m and 1000 m off Keahole Pt.

Water density: For the range of water temperatures discussed above the density of the surface water is defined as 1.023 g/cm^3 and that of the deep seawater as 1.027 g/cm^3. When pumping deep seawater through a conduit, the increase in density with depth results in a pressure loss in addition to the friction losses. This is referred to as density head.

Seismicity: The American Petroleum Institute Recommended Practice for Designing Planning and Constructing Fixed Offshore Structures recommends a seismic level of Zone 3 for the Island of Hawaii. This corresponds to an effective horizontal ground acceleration of 0.2g.

Design Description

The basic components of the 1.8 MW (gross) two-stage OC-OTEC plant are summarized and listed in Table 2.1. The baseline heat and mass balance diagram, in Figure 2.4, shows basic state parameters and fluid flow rates through the energy and freshwater production modules.

Cold seawater is supplied to the OTEC plant by a single HDPE, 1.6 m diameter - 2590 m long, pipe. The nearshore portion of the cold water pipe (CWP) is 120 m long and made of Fiberglass Reinforced Plastic (FRP) to account for high suction loads; it is rock-bolted to the seafloor. The rest of the CWP is the HDPE conduit.

The deep water segment extends from the intake, 1000 m below the ocean surface, to a water depth of 150 m over a 30° slope, whereas the intermediate depth segment is anchored on a 12° average slope. The baseline water velocity is 1.6 m/s.

Warm seawater is supplied to the OTEC plant by a single, 2.5 m inner diameter, 120 m long, FRP pipe rock-bolted to the seafloor. The baseline water velocity is 1.0 m/s.

The power plant consists of four major components:

- Evaporator
- Turbine
- Condenser
- Non-condensables Removal System

Warm water enters the low pressure evaporation chamber through an array of spouts where flashing occurs. Some water is vaporized whereas the remaining flow is drained to the discharge pool. The steam from the evaporator drives a turbine before entering a surface condenser. The condenser is cooled by deep seawater and produces freshwater condensate.

The evaporator is a carbon steel cylindrical vessel, 13.4 m diameter and 15.6 m high. It has a warm water inlet, warm water outlet and a steam outlet. A baffle plate divides the vessel into perseveration and evaporation chambers. The plate houses 122 vertical spouts to allow water to flash in the evaporator.

The steam turbine is a single rotor axial flow machine. The tip-to-tip diameter of the rotor is 5.65 m and the blade height 1.29 m.

The baseline condenser system uses tube & shell surface condensers designed and manufactured by Toshiba with envelope dimensions of 18.9 m x 12.7 m x 21m (L x H x W). Most of the steam (92%) is condensed into freshwater in the main unit; residual steam liquefies in the vent condenser.

The removal of non-condensable gases is performed by a compressor train which draws them from various locations in the power block. Presently there are two options: *(i) a train of commercially available positive displacement vacuum pumps; or (ii) a train of custom manufactured high speed centrifugal compressors with higher efficiency but limited life cycle information*.

The second stage freshwater production unit consists of an additional evaporator and surface condenser downstream of the (first stage) power system. This second stage allows a significant increase in the amount of fresh water produced.

Mixed effluent water is returned by gravity back to sea via a 3 m inner diameter FRP pipe. A return depth of 60 m is taken to minimize environmental impact. The pipe is 190 m long of which 120 m are rock-bolted to the seafloor.

Item	Major Components	Material	Description
Power Block Housing	Building	Concrete	63 m x 36 m x 24 m (height)
Seawater System	Cold Water Pipe	HDPE & FRP	1.6 m o.d., 2590 m long
	C W Pumps	C.I. Body, S.S. Impeller	2 active/1 backup @ 1.55 m^3/s, 8.2 m, 334 kW per pump (inline submersible)
	Warm Water Pipe	FRP	2.5 m i.d., 120 m long
	W W Pumps	C.I. Body, S.S. Impeller	3 active/2 backup @ 2 m^3/s, 3.5 m, 284 kW per pump
	Return Pipe	FRP	3 m i.d., 190 m long, 60 m depth Gravity discharge
Power System	Turbine (MHI)	Ni Cr Alloy, Steel Blades	Axial Flow, Single Rotor, 5.65 m wheel
	Evaporator	Coated C.S., or Concrete, PVC pipes	Cylindrical: 13.4 m diameter, 15.6 m height, 122 spouts
	Condenser	Steel, Al-Brass	T&SI, main: 18.9 m length, 12.7 m height, 21 m wide
	Vacuum Compressor Train	C.S or Al.	Predeaeration & Reinjection, (4 Stages from 1.1 to 30 kPA): PDP and/or Centrifugal

Table 2.1 - OC-OTEC Plant Major Subsystems

Heat and Mass Balance

The 6156 kg/sec of warm seawater at 26 °C are supplied via a 2.5 m ID FRP pipe (Figure 2.3). The pipe has an intake depth of 25 m and is 120 m long. Five inline submersible propeller type pumps (three operational, two stand by) supply the flow to an intake pool below the first stage evaporator. The intake pool has a nominal operating level of 2.78 m MSL. This level is selected to provide enough head in the mixed flow discharge pool for gravity return into the ocean.

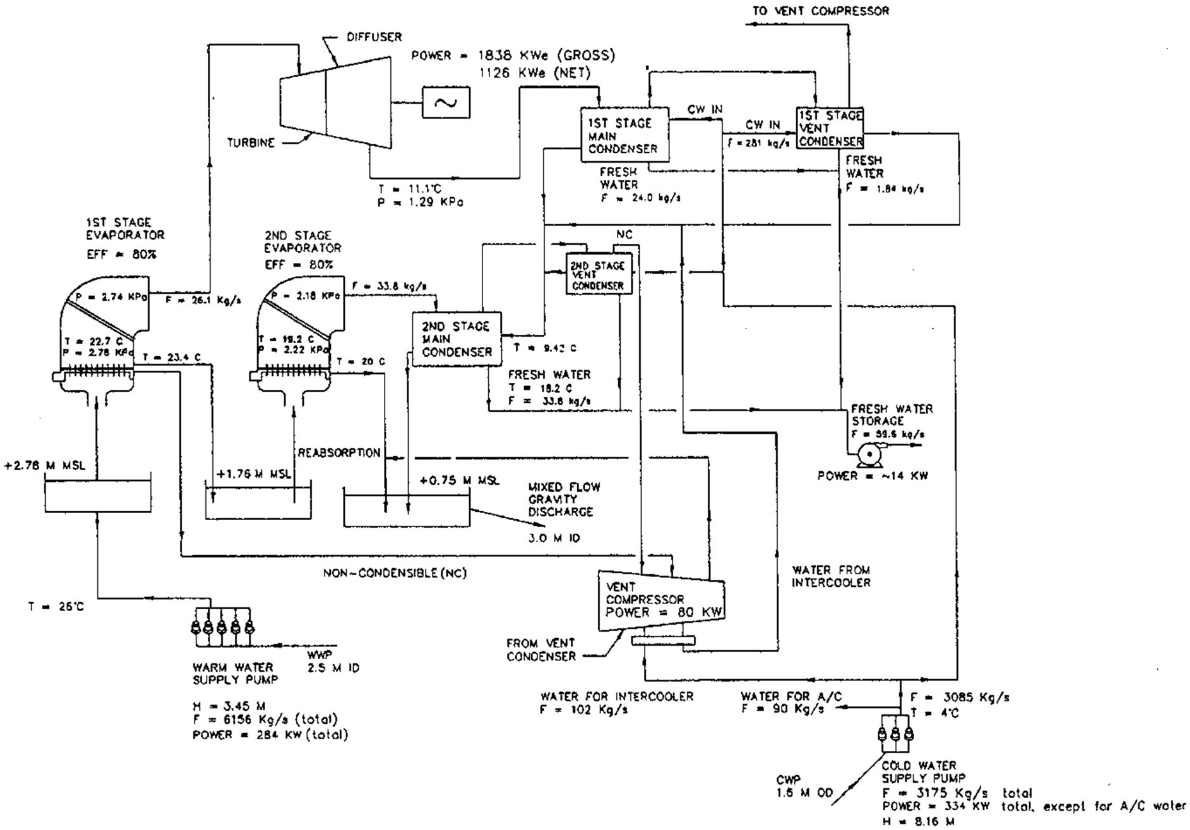


Figure 2.3 – Double Stage ≈ 1.8 MW-gross OC-OTEC: Heat & Mass Balance Diagram (final configuration yields 1260 kW-net & 5670 m^3/day).

Three inline submersible propeller type pumps (two operational, one standby) bring 3175 kg/s of cold seawater through a 1.6 m OD pipe from a depth of 1000 m. The pipe length is 2590 m. 3085 kg/s of 4 °C cold seawater is available for OTEC system whereas 90 kg/s is reserved for air-conditioning applications.

An upriser takes the warm water into the evaporator. A pre-deaeration nozzle removes a portion of non-condensables from the warm water accumulated below the spout plate. The evaporator spout plate has 122 spouts and the warm water flashes through the spouts into the evaporation chamber at a pressure of 2.76 kPa. A small fraction (26.08 kg/s) of supply water is flashed into steam and the rest is discharged into the first stage discharge pool at a temperature of 23.4 C. The discharge pool, at a level of 1.76 m MSL, also acts as the supply pool for the second stage evaporator. The evaporation pressure in the second stage is 2.22 kPa. No pre-deaeration is required in the second stage as the water has been deaerated in the first stage. The steam produced in the second stage evaporator is 33.8 kg/s. The effluent water from the second stage evaporator at 20 °C goes into the mixed water discharge pool.

Steam from the first stage evaporator enters the turbine at 2.74 kPa and leaves the turbine diffuser system at 1.29 kPa. The turbine generator system gives a gross output of 1838 kW. Steam exhaust from the turbine-diffuser (98% quality) system enters the first stage main surface condenser. The main condenser receives 2702 kg/s of cold seawater at 4 °C and condenses 92% of the incoming steam. The remaining 2.05 kg/s flow into the vent condenser. The vent condenser gets 281 kg/s of 4 °C cold seawater and condenses 1.84 kg/s. The remaining vapor (< 1% of steam produced in the evaporator) along with the non-condensables are evacuated by the vacuum compressor system.

The 33.8 kg/s of steam generated with the second stage, water production, evaporator is condensed in the second stage main condenser using the 9.4 °C seawater discharged from the first stage condenser (and the vacuum compressor system) as the coolant. The minimal amount of uncondensed steam goes to an optional vent condenser. A hook-up to the vacuum compressor system is provided to remove any non-condensables and water vapor from the second stage system.

Non-condensables and vapor from the first and second stage condenser systems enter the vacuum compressor system through a counter-current direct contact precooler. The precooler receives 4 °C cold seawater (out of 102 kg/s reserved for the compressor system) and ensures that the mixture temperature at the first stage inlet of the compressor system is not more than 5 °C and the entire vapor is condensed till its partial pressure becomes equal to the seawater saturation pressure at 5 °C. The basic compressor system has four stages with intercoolers in-between. The fourth stage compressor takes the non-condensables from warm water preparation in addition to the non-condensables from the third stage. The discharge from the fourth stage is re- injected at 30 kPa into the warm water effluent returning from the second stage evaporator. A fifth stage compressor can also be provided to bypass the re-injection scheme and discharge into the atmosphere. The fifth stage would require 35 kW in addition to the 80 kW required for the other stages. The first four stages are centrifugal whereas the fifth stage is positive displacement type. All coolers should be of the direct contact type.

Cold water effluent from the second stage condenser and warm water effluent from the second stage evaporator combine into a mixed discharge pool with the nominal level of 0.75 m MSL. A 3 m ID, 190 m long and 60 m deep pipe provides a gravity discharge recourse for the mixed water system.

The net power from the system, after subtracting 334 kW for cold water supply pumping (includes 9.5 kW for the water dedicated to an AC system), 284 kW for warm water supply pumping, 80 kW for compressor system, and 14 kW for desalinated water pumping from the gross power, is 1126 kW. The total desalinated water produced is 59.6 kg/s. Without second stage water production the combined pumping losses will be reduced by approximately 100 kW (net increase) and the desalinated water produced would be 25.8 kg/s.

Operational data obtained with the NPPE indicates that production of steam could be ~ 10% higher and, therefore, the power output and desalinated water production would be 1260 kW and 65.6 kg/s respectively. These values are used in Chapter 9.

Under design conditions, the warm water temperature has an average value of 26 °C and ranges between 24 °C and 28 °C and the cold water is given a constant value of 4 °C such that the variation of power output.

(given by 2 x gross power/(Tw - Tc)) is 164 kW/°C corresponding to a net output variation of ±328 kW throughout the year.

Although this discussion is important to the economic analysis of the OC-OTEC plant, future design efforts must concentrate in developing cost effective turbines fabricated of plastics and reliable bearing systems for the centrifugal pumps used in the vacuum compression system.

3.0 SEAWATER SYSTEMS: Cold Water Pipe

The detailed information presented here is applicable to the specific site at Keahole Pt., Hawaii but it is included here to emphasize the importance of planning an ***appropriate deployment scenario with experienced ocean engineers and adequate equipment.*** The author is aware of at least two attempted deployments of CWPs (in India and Hawaii) that resulted in catastrophic failure because these conditions were not followed for the sake of cost savings. In addition, the OTEC literature is plagued with well-intentioned conceptual designs for sites that do not incorporate these requirements into their cost estimates.

The use of a single-length 1.6 m diameter high density polyethylene (HDPE) conduit as the Cold Water Pipe (CWP) was our imposed design specification for the land based ~ 1.8 MW-gross OC-OTEC plant for SIDS with limited infrastructure. An intake depth of 1,000 m corresponding to a seawt6er temperature of 4 ºC was selected. A simultaneous tradeoff analysis was also performed to determine the optimal cold seawater velocity through the pipeline, 1.75 m/s. It should be noted that these results are design and site specific.

The following step, in the CWP design methodology, consists in estimating pipe wall thickness as a function of lengthwise coordinate (alternatively, the notion of dimensional ratio (DR), or ratio of outer diameter over thickness, is often used). This step and the previous fluid velocity optimization are interdependent, since pipe thickness affects friction losses, which in turn largely determine suction loads.

Given that polyethylene has a low modulus of elasticity, the critical collapse pressure corresponding to the onset of buckling under suction may be reached within the range of typical OTEC cold seawater flowrates (velocities). At the same time, thickness is limited by the HDPE extrusion process, and DRs as low as 22 are technically feasible, though they also represent a practical lower limit at present. The CWP wall structure corresponding to the optimal combination of intake depth and seawater velocity inside the CWP was determined based on three "basic" values of DR as follows (distances are length coordinates measured from intake):

- DR 32.5: from the cold seawater intake to 1210 m;
- DR 26: from 1210 m to 1770 m;
- DR 22: from 1770 m to 2470 m;
- FRP or concrete through the 120 m long near-shore zone.

Cold Water Pipe Optimization

Because the OTEC thermal resource is relatively small, with average temperature difference of the order of 22°C to 24°C , large water flow rates are necessary to ensure the feasibility of the OTEC concept. This analysis applies to both Open and Closed cycles. Moreover, the thermodynamically feasible power output of an OTEC plant is very sensitive to any change in the already small available temperature difference. Many ways to improve the efficiency of the OTEC cycle, however, such as increasing flow rates, or reaching down for deeper, colder seawater, concurrently increase the amount of parasitic power consumed to overcome larger line-friction and density-head losses. Because of this simultaneous increase in gross power and parasitic losses with deeper cold water intake or higher flow rates, a net power maximization is performed here. The following constraints are imposed by the choice of HDPE for the CWP:

- the outer diameter of the CWP is 1.6 m; therefore, flow rate variations become equivalent to velocity changes, prescribed values being defined at the intake;
- because polyethylene has a low modulus of elasticity, the critical collapse pressure corresponding to the onset of wall buckling under suction may be reached within the range of expected OTEC cold water velocities;
- one way to avoid pipe collapse, an increase in pipe thickness, is limited by the polyethylene extrusion process; a thickness of 0.07273 m, i.e., a ratio of outer diameter over thickness, or Dimensional Ratio (DR), of 22, is deemed technically feasible (for the 1.6 m pipe).

The optimization methodology proceeds in three steps:

1) A definition of the parameter matrix for which net power should be calculated, and compatible with the above constraints.

2) An actual determination of the net power produced by an OC-OTEC plant for the parameters defined at the first step.

3) The choice of a baseline configuration, corresponding to maximum net power output, and possible improvements based on cost effectiveness, technical feasibility, and basic loading constraints.

Three possible intake depths were chosen, 700, 850 and 1000 m. These depths correspond to approximate cold water temperatures of 6, 5 and 4°C, respectively, at Keahole Point.

CWP lengths are determined based on a simplified bathymetry (Figure 2.1) compatible with the input to the computer code used to calculate the pressure difference across the pipe wall: thus, an average slope of 12° is assumed from shore to a water depth of 150 m, and a slope of 30° is chosen for deeper waters. The three OTEC pipes are assumed to be buried in a 120 m long trench through the surf zone, and the pumps are located at the shoreline.

The goal here is to define a parametric range for cold water velocities in keeping with the constraints imposed by the 1.6 m diameter HDPE pipe.

A safety factor of at least 2.0 is applied between local calculated pressure differences across the CWP wall and local collapse pressures. For the sake of simplicity, three pipe sections corresponding to three different pipe thickness are iteratively defined for a prescribed water velocity.

First, the following high flow limits are sought:

- the maximum velocity such that a safety factor of 2.0 for the minimum DR (22) is obtained at the trench end (120 m offshore). In this case, the CWP material in the trench may have to be, say, FRP.
- the maximum velocity such that a safety factor of 2.0 for the minimum DR (22) is obtained at the pump inlet.

Then, at least one more (lower) velocity is considered, thus yielding a minimum 3 x 3 parametric matrix.

Net Power Optimization

Heat and mass balance calculations, and some basic cost estimates were performed as an input to a thermodynamic code. Power systems parameters were kept constant as much as possible to perform a meaningful sensitivity analysis. A warm water temperature of 25°C is selected for the first stages of the design process. From an operational standpoint, this conservative approach will ensure, for instance, that certain plant components such as heat exchangers be not undersized when the available thermal resource reaches a minimum.

Results are presented on Figure 3.1. Net power production is seen to be unambiguously higher with deeper cold water: the three curves corresponding to different intake depths are well decoupled and a value of 1000 m should be selected. Strictly speaking, however, one should ensure that the cost of reaching down to deeper cold water is not excessive: the baseline unit investment cost C, in $/kW, should decrease.

To better assess the effect of cold water velocity upon net power output, in the vicinity of a maximum, a few additional cases were added to the original matrix. For all three depths, a maximum power output was reached within the baseline velocity range, and the expected shift toward lower maximizing velocities as depth increases is noticeable. These results indicate that a lower pipe collapse safety factor, yielding higher allowable pumping velocities, would not imply an increase in net power production. Thinner pipes, however, could be utilized.

The absolute net power maximum shown on Figure 3.1 corresponds to an intake velocity of 1.75 m/s. This value is used with the submersible pump system for an intake pipe DR of 32.5. However, for a pumping system on land a lower value would be required to allow pumping all the way up to the pump station with a pipe collapse safety factor of at least 2.0.

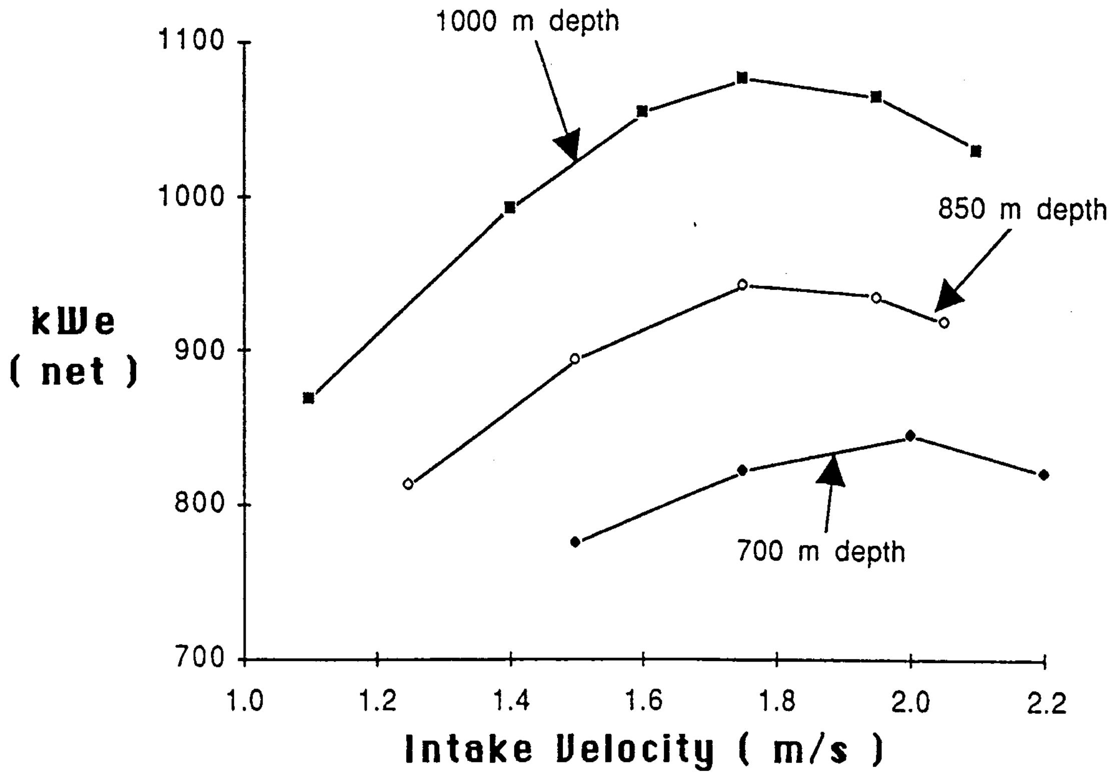


Figure 3.1 - Net Power Output as a Function of Cold Water Velocity and Intake Depth

In summary, the optimized values for the 1.6 m HOPE CWP, with submersible pumps, were selected as a water depth of 1000 m, and an intake velocity of 1.75 m/s.

CWP Anchoring

In summary, hydrodynamic loads are estimated to establish anchoring requirements for the bottom mounted CWP deployed in an environment corresponding to Keahole Point. The knowledge acquired in the installation of three HDPE conduits at NELHA, ranging in diameter from 0.3 m (12") to 1 m (40") and reaching down to water depths of about 700 m is incorporated into the design process. Various deployment and anchoring techniques were tested and refined through these three projects. The 1 m pipe was used to supply cold water to the “250 kW” Net-Power-Producing-Experiment (NPPE.)

The overall configuration of the CWP for the ~ 1.8 MW-gross OTEC Plant consists of an FRP rock-bolted nearshore section, about 120 m long, and of the offshore section. The latter is subdivided into a bottom-mounted subsection, through intermediate water depths (< 150 m), and a 1950 m long inverted catenary. Figure 2.1 represents a bathymetric profile at Keahole Point, where the site-specificity of the seafloor can be appreciated, with the sharp break in submarine slope where the suspended catenary begins, about 700 m from shore.

In the intermediate depth region, where the CWP would be held to the seafloor with gravity (deadweight) anchors, combined wave and current loading are assessed. Because of the presence of submarine slopes of about 30° on either side of the intermediate depth region, wave hydrodynamics are calculated with diffraction and refraction effects accounted for. A mathematical and numerical model has been specifically developed for this purpose. The computational domain is defined with Keahole Point bathymetric data as follows:

- for a horizontal distance of 150 m, extending offshore from a water depth of 25 m, a slope of 27°

- for a horizontal distance of 500 m, a slope of 5°

- down to a water depth of 250 m, a slope of 30°

The wave height and period used, respectively 15 m and 18 s, are estimated to be conservative.

Because the CWP diameter, 1.6 m, is much smaller than the wavelength, wave diffraction due to the pipe itself is negligible, and hydrodynamic forces are estimated with the Morison's equation.

Given that the pipe centerline is anchored near the seafloor, vertical components of fluid velocity and acceleration can be neglected, and no gap effect should be anticipated if a clearance more than the pipe diameter is provided.

Results indicate that different deep-water wave angles of incidence generate the largest loads at different locations. Moreover, a comparison of the forces acting on pipes of different diameters revealed that drag dominates inertia because loads exhibited proportionality to the ratio of pipe diameters. This point allows an easy determination of the anchoring requirements associated with the 3 m diameter Mixed Effluent Return Pipe (MERP) down to the return water depth of 60 m.

Requirements for deadweight may be evaluated from the knowledge of the maximum hydrodynamic force F_{Hmax} expected by writing a simple static equilibrium between seafloor friction force and sliding force; neglecting bottom-perpendicular lift, we obtain:

$$W = F_{Hmax} / \{ \mu^2 \cos^2\theta - \sin^2\theta \}^{1/2}$$

W: required anchor weight per unit length (N/m)
μ : seafloor friction coefficient
Θ : seafloor slope angle

Note that if μ is less than tanΘ, this type of anchor is not feasible. The steeper section of the bottom profile, with an average value Θ = 27º, consists of coral rubble and , μ may be taken as 0.7. For the flat sandy shelf that follows (Θ = 5º), a lower value for μ, 0.5, is appropriate.

The best design strategy consists in using concrete weights of standard sizes, spaced at variable distances to account for the dependence of W upon x. As an example, the 1.6 m CWP could be anchored with 5 tonnes concrete collars. With a concrete wet weight of approximately 1200 kg/m^3, a typical 5 tonnes collar anchor could be 3 m x 3.5 m x 0.4 m.

The long inverted (buoyant) catenary section of the cold water pipe is not sensitive to wave loading since it is anchored at depths more than 150 m. A static analysis of current-induced forces is therefore sufficient to evaluate anchoring requirements and catenary deflections. Moreover, apinned-pinned strength member may be considered flexible, or cablelike.

The net buoyancy of the 1.6 m CWP can be taken as 225 N/m, corresponding to a HDPE density of 0.92, a pipe dimensional ratio of 32 and an average seawater density of 1025 kg/m^3.

The following output was generated:

- suspended length: the actual catenary length including elastic stretching under tension;
- anchor point angles: the vertical angle is measured clockwise from horizontal, in a vertical plane containing the (straight) cable element;
- anchor point tensions;
- maximum datum clearance: this is the maximum vertical distance between any cable point and the datum, defined as the plane containing the two anchor points and the direction parallel to the shoreline;
- minimum radius of curvature.

Computations were performed for a 1000 m deep cold water intake, The determination of anchoring weights was based on seafloor friction alone, and an additional provision to prevent lift-off at the lower end was included. At the upper end, where weight requirements are higher because of the downslope component of the tension, this approach is conservative since the CWP is held by the weighted (bottom-anchored) section of the CWP; in addition, the detailed CWP design includes floats at the upper end which would reduce the downslope component of the tension.

Deadweight anchors made of reinforced concrete, and weighing 60 and 80 tonnes for, respectively, the lower and upper catenary touchdown points, were deemed adequate.

Deployment of the Offshore Section

The most challenging activity during the construction of a land based OTEC facility is the installation of the CWP. This Section outlines the installation of a 1.6 m HDPE CWP beyond the 120 m long near-shore section. The deployment technique is based on the surface tow and controlled flooding of the pipelines. It has been demonstrated by the successful deployment of a 1 m pipe at Keahole Pt. (NELHA).

It is assumed that assembly has been completed in the nearby Kawaihae Harbor (37 km from the site). Weather monitoring must be performed, as sea states should not exceed 3 during towing operations, and currents larger than 0.5 m/s should be avoided throughout deployment. The final schedule should provide some contingency options and reversibility whenever possible. Some equipment redundancy and a minimum exposure time at sea are desirable.

The following basic list, in conjunction with Figures 3.2 to 3.10, of the equipment required for the deployment of a 1.6 m pipe at Keahole Pt. is summarized here to illustrate the challenges that might be posed in some SIDS:

Crane barge: a moderate-size barge, at least 50 m long, with a 10 tonnes (metric tons) lifting capacity and a 3 to 4 point mooring capability to position itself right outside the trench (Point "T");

Anchor barge: it is used to lower the 80 tonnes upper catenary anchor down to 150 m water depth, and the 60 tonnes lower catenary anchor down to 1000 m water depth;

Tugs one medium-size tug will handle either barge (Tug #2); other tug(s) handling the CWP must be able to provide a combined Bollard pull of 120 tonnes for, say, three hours (Tug #1);

Pipe pontoons: because of the great pipe length at stake, it might be necessary to handle the 1950 m catenary in 2 or 3 sections; in that case, a low freeboard pontoon would permit the at-sea connection of the pipe section flanges;

Workboat: a small workboat, with approximately 1000 hp, an A-frame and winch capable of lifting 2 tonnes, and a towing winch for handling the anchor barge;

Compressors: two compressors, including backup, rated at 100 psi (- 7 bars) and 750 cfm (0.35 m^3/s) are needed to pressurize the pipes;

Crewboat: a relatively fast small craft used to transport personnel between the barges;

Picket boats: two small boats required to fend off traffic;

Pumps: three seawater pumps will deliver water at 50 psi (3.5 bars) to the end of the pipeline; flow rates of 0.3 m^3/s must be possible;

Pipe pig;

ROV or submersible: underwater inspection of the shallower region down to, at least, the transition to the catenary (Point "S") is desirable, which implies depth capabilities of about 200 m;

Dynamometer: the tension applied to the pipeline during deployment operations should be monitored within 5%;

Transponder system: the distance between the two catenary anchors must be carefully determined;

Navigation system: an electronic navigation system and properly lighted shore ranges will permit accurate positioning;

Communication system: VHF radios and a backup of multi-channel CB radios are recommended.

About one week prior to the deployment, various preparation tasks must be completed. At the shore end of the offshore pipeline, or Point "T", a wire rope sheave is placed on the trench concrete slab, upper anchor plates and a bridle are installed. In addition, the pumps and manifolds that will flood the pipeline, and located on a barge over Point "T", are set up with an accurate flowmeter. At the offshore end of the pipeline, on the offshore vessel, an air manifold with pressure gauge and compressor is used. The two large catenary anchors are lowered in shallow water. Vessel critical lifts and pulls need to be tested for several hours, as well as their positioning capability. An overnight check of the behavior of the pipe under hydrostatic pressure is performed, this task being more delicate for the weighted portion because it will sink to the bottom of the harbor. Pipeline bridles, shore end spool piece, additional buoyancy at intake, flanges and towing lights are installed. The anchor barge is equipped with bumpers to protect the pipeline.

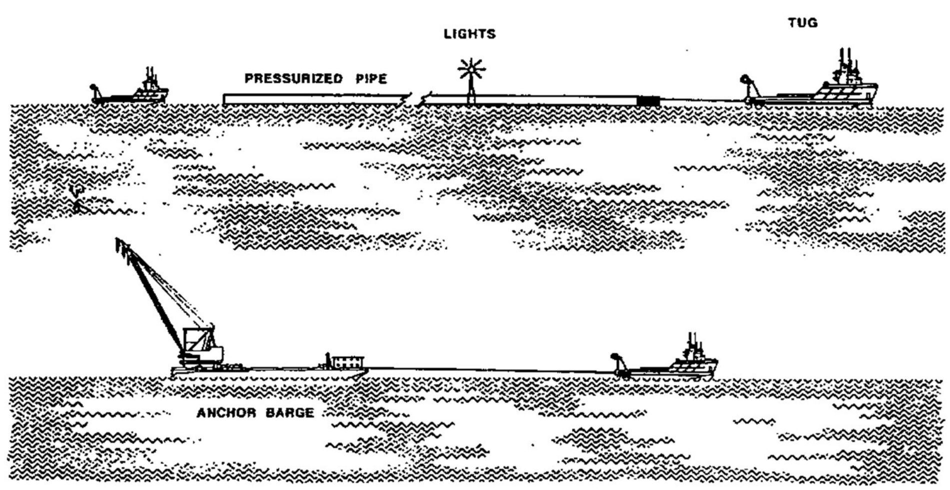
It is assumed, at this conceptual level, that the CWP comprises only two sections, labeled Phase I and Phase II. Under favorable weather and operational conditions, the deployment could be completed in four days, and the final near-shore connection in one day. Figures 3.2 to 3.10 illustrate the typical deployment sequence (Figures are shown for illustrative purposes only and are not drawn to scale.)

<u>Day 1</u>: the Phase I section of the pipe is towed from Kawaihae harbor to Keahole Point overnight (Fig. 3.2); meanwhile, the crane barge is positioned over Point T.

<u>Day 2</u>: the Phase I section of the pipe is attached to the bridle at Point T (Figure 3.3); the anchor barge picks up the upper catenary anchor and moors over Point S (Figure 3.4); the pipeline is maneuvered along the anchor barge and connected to the upper catenary anchor (Figure 3.5); position is maintained overnight;

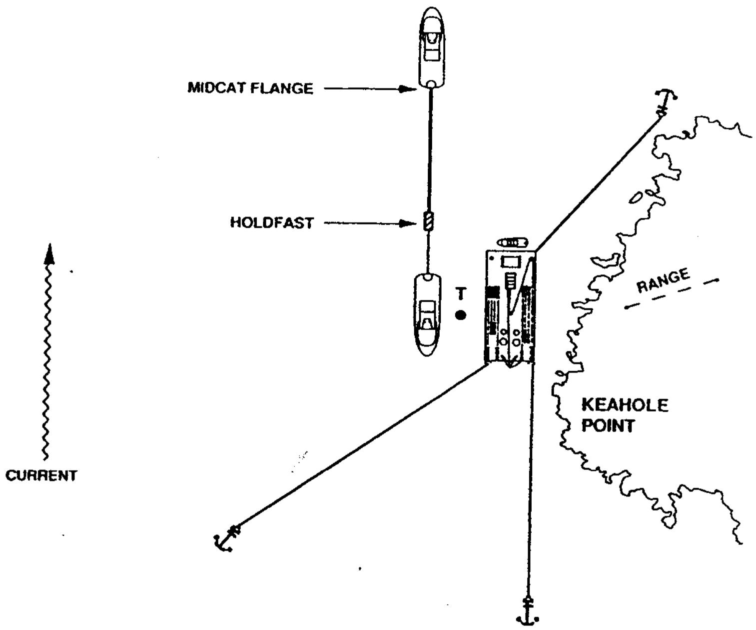
<u>Day 3</u>: the pipeline is flooded in the early morning, as illustrated on Figures 3.6 and 3.7; this operation is expected to last about 2 hours; at the end, the upper catenary anchor is lowered along with the pipeline (Figure 3.8); the Phase II section of the pipe is towed from Kawaihae harbor to Keahole Point;

<u>Day 4</u>: the two pipeline sections are mated (Figure 3.9), flooding of the CWP is completed and the bottom catenary anchor is lowered (Figure 3.10).



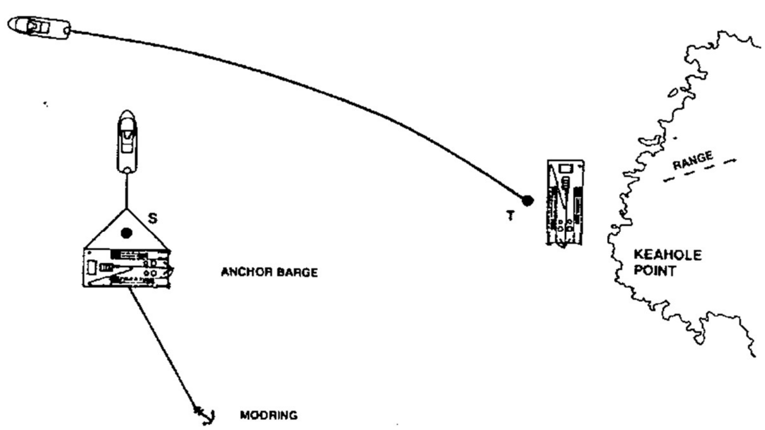
Towing Phase I Pipeline

Figure 3.2



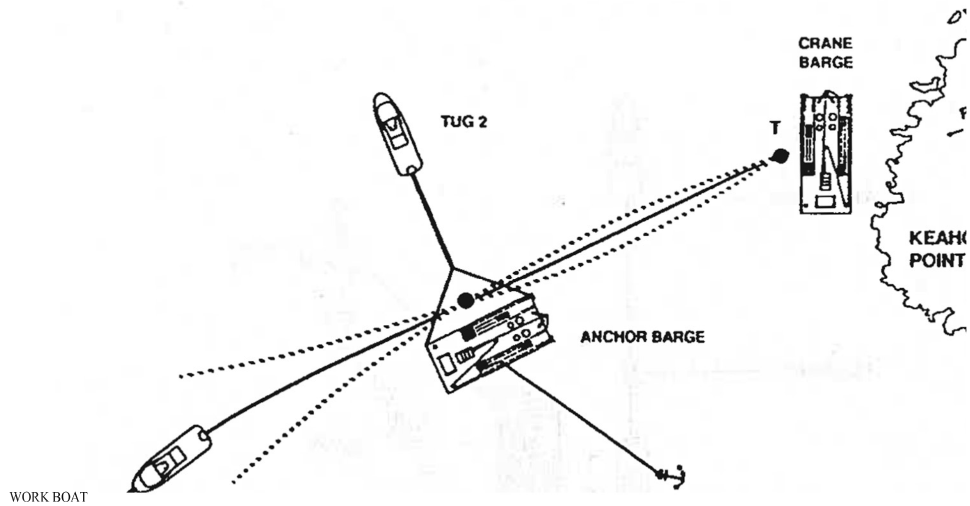
Alignment and Attachment of Pipe Section 1 to Point " T "

Figure 3.3



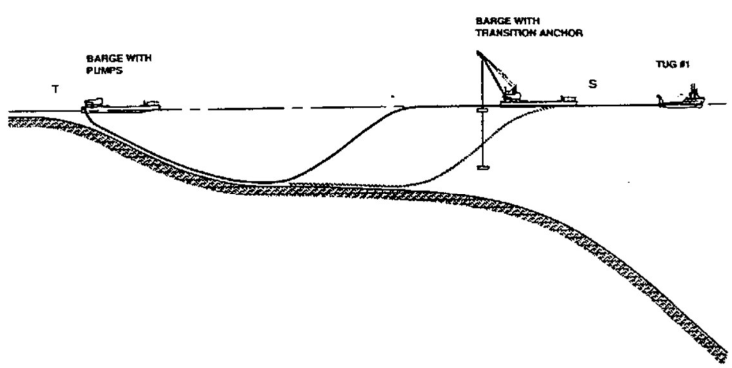
Positioning the Anchor Barge over Point " S "

Figure 3.4



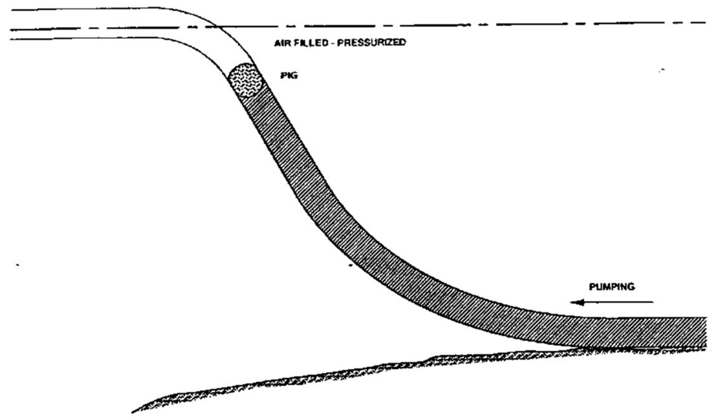
Maintaining the Pipe alongside the
Anchor Barge

Figure 3.5



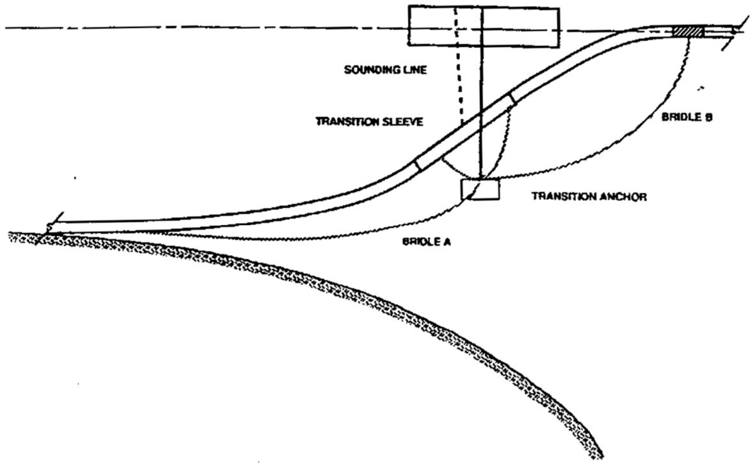
Flooding Phase I Pipeline

Figure 3.6



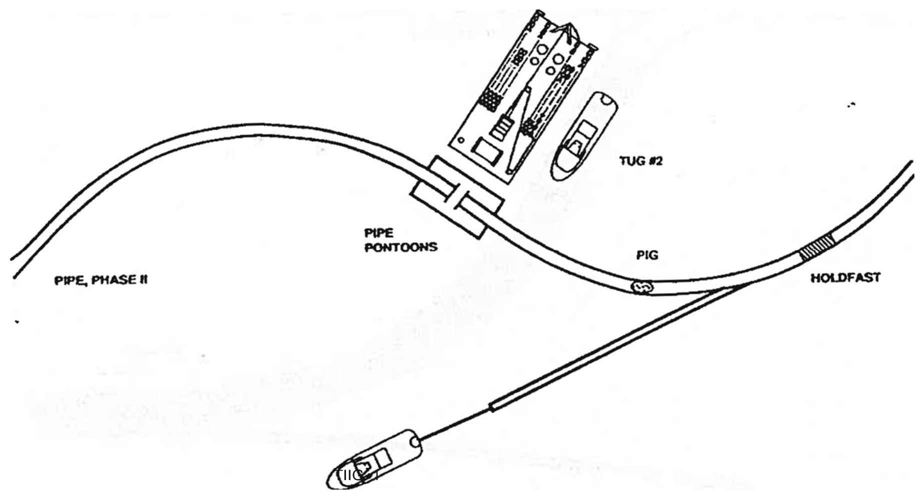
Flooding the Pipeline

Figure 3.7



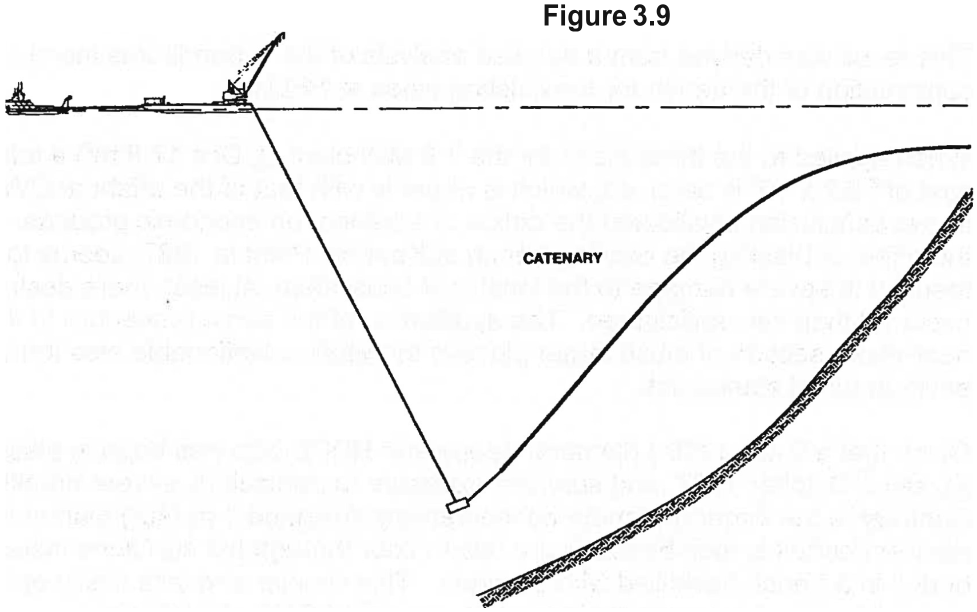
Lowering the Transition Anchor just ahead of the Pipeline

Figure 3.8



Mating Mid-Catenary Flange

Figure 3.9



Lowering Phase II
Pipeline

Figure 3.10

Warm Seawater Pipe

This 120 m long pipe feeds a warm seawater flow rate of about 6 m^3/s to the ~ 1.8 MW (gross) OC-OTEC plant. A 2.5 m FRP or concrete conduit is expected to be adequate through the surf zone, reaching the pump structure from a water depth of 25 m. As is the case for both CWP and MERP, and for reasons discussed below, the warm seawater pipe would be rock-bolted to the seafloor.

Following the design adopted for the 1 m diameter HDPE pipe installed at Keahole Pt. for the NPPE, the near-shore sections of the three OTEC pipes considered for the 1.8 MW (gross) OC-OTEC plant could be installed in a trench backfilled with concrete. After a careful assessment the specific expenses related to the 120 m long trench for the 1 m pipe were updated using the manufacturing price index in the USA it was found that the following current cost formula reflecting the volume proportionality of such costs as excavation and backfill, could be used (in Hawaii):

$$\text{Cost (\$/m)} = 9780\ \Sigma\ D^2$$

where $\Sigma\ D^2$ is the sum of the squared of the three pipe diameters and the cost is given per meter of length. When applied to the three pipes for the 1.8 MW plant ($\Sigma\ D^2 = 17.8\ m^2$) with a trench length also of 120 m a total current trench cost of $20 M is estimated. Because this value is equivalent to the cost of a 1.6 m CWP the option of a trench is questionable on economic grounds.

Moreover, the effect of blasting the existing trench at Keahole Point 30 years ago, seems to have resulted in severe damage to the local reef ecosystem; at least, more destruction occurred than was anticipated. The application of the same procedure to the near-shore section of much larger pipes is therefore questionable also from an environmental standpoint.

A 0.45 m (18") diameter deepwater HDPE pipe has been in place at Keahole Pt. since October 1987, and survived exposure to particularly severe breaking waves. Contrary to the larger and more conservatively designed 1 m (40") diameter pipe, this smaller conduit is rock-bolted to the ocean floor through the surf zone instead of being buried in a trench backfilled with concrete. This simpler and less costly option is taken as the baseline for the three pipes of the present OTEC plant design.

Mixed Effluent Return Pipe

After being utilized in the OTEC plant, warm and cold seawater streams must be returned to the ocean. At the conceptual design level, a Fiberglass Reinforced Plastic (FRP) Mixed Effluent Return Pipe (MERP), 3 m in diameter and reaching down to a water depth of 60 m, is selected.

The choice of a single MERP over two separate warm and cold seawater effluent return pipes was primarily motivated by the inclusion of a second desalination stage downstream of the OC-OTEC plant: thus, the residual temperature difference between the two waste seawater streams drops from about 10°C (single-stage plant) to about 5°C (two-stage plant), and the rationale for distinct discharges weakens considerably.

The ultimate argument for a return depth of 60 m is economic: the bathymetric profile at Keahole Point (Figure 2.1) would impose a severe cost penalty if depths beyond 60 m had to be reached, because the seafloor flattens at that point. Moreover, the plume equilibrium depth is expected to be located below the photic layer off Keahole Pt. Most biological activities require light intensity levels of about 10% of the sea-surface value. Since light intensity decreases exponentially with depth (extinction coefficient ≈ 0.3838 m^{-1}), the critical 10% threshold off Hawaii corresponds to a 60 m water depth.

At pipe exit, the jet spreads laterally in a fan-like fashion, with an angular opening between 70° and 100°, and centerline velocities decrease very rapidly through the jet phase, where most of the dilution of the effluents with ambient seawater takes place. Overall dilution coefficients of 4 are typical.

The 120 m long near-shore portion of the MERP would have to be rock-bolted to the seafloor, whereas the remaining 70 m section, between water depths of 25 m and 60 m, could rest on the seafloor by means of gravity anchors.

Seawater Pump Stations

The baseline pump station, with features like the existing structure built for the 1 m (40") diameter CWP, included an onshore sump, 32.5 m^2 in area, 9.5 m deep, and excavated in the basaltic lava rock found at Keahole Point. The cost estimate provided for the pump station, i.e., pump and sumps, extrapolated to present day costs would be \$12.5 x 10^6. Clearly an area for cost reduction is with the onshore sump and nearshore pipe trenching as discussed above.

The smaller 0.45 m (18") diameter CWP at Keahole Pt. uses pumps installed offshore, bolted to the seafloor at a depth of 10 m. Although maintenance may be more difficult for submerged pumps, the potential savings in deployment costs appeared to justify a thorough evaluation of this option for the 1.8 MW plant.

A survey of existing pumps operating in the marine environment led to the selection of pumps with a cast iron body, cathodic protection, and stainless steel impellers and shafts. In addition, the sharp drop-off, or cliff, at the Keahole Pt. shoreline, as well as the relatively high design seawater flow rate, suggested that shoreline pump stations might represent the most favorable configuration. Thus, drawbacks relative to the baseline design, such as trenching and digging, or to offshore pumps, i.e., their difficult maintenance, could be simultaneously avoided. Naturally, open-sump options were ruled out because extensive excavation would still be required, and their installation in the high surge zone appeared to be too risky. These preliminary considerations led to the practical concept of hard-piped pump stations using either dry-motor vertical or submersible pumps, as illustrated on Figure 3.11. Common features include large high-efficiency pumps, shallow pump submergence, a steel riser column, a shoreline concrete support, HDPE manifolds and check valves. An option consisting of 3 pumps in parallel (2 operational, 1 backup) was selected.

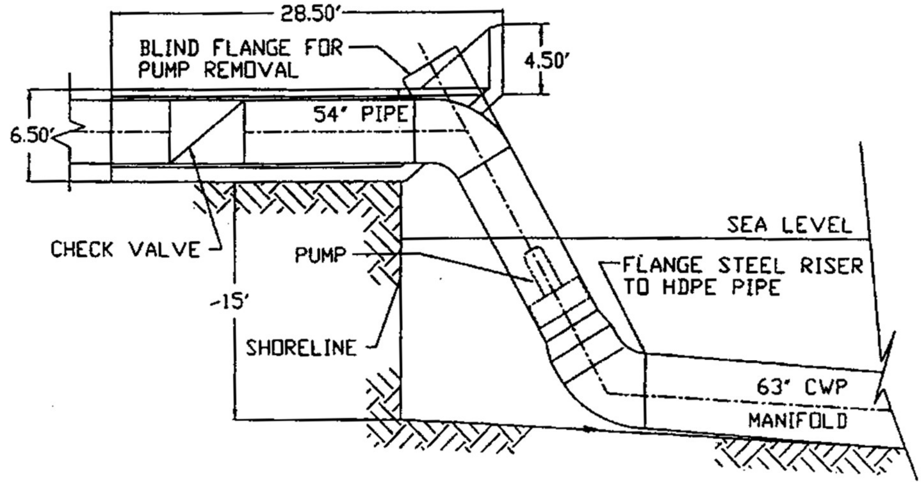


Figure 3.11 - Submersible Pump Station Elevation (dimensions in feet and inches)

Pumps of both dry-motor-vertical and submersible types were identified. Parasitic pumping power calculations were performed for all type-option combinations, with results within 10% of one another, ranging from 308 kW to 342 kW. Next, the question of pump dynamics was addressed, to evaluate startup and shutdown time scales, and to ensure that pump cavitation and CWP suction collapse be avoided. It should be noted that pump dynamic effects are more critical for inline systems, such as are discussed here, than for open-sump configurations, like the baseline: in the latter case, the long intake CWP, upstream of the pump, is effectively decoupled from the conduit feeding cold seawater through the OC-OTEC plant, downstream of the pump; in the former case, there is no dynamic buffering between water masses upstream and downstream of the pump. Typical time scales of 2 and 4 minutes were determined for, respectively, startup and shutdown, under reasonable assumptions for the pipe layout downstream of the pump and onshore.

The combination of two submersible pumps and one redundant unit proved to be the most economical. As stated before, it must be emphasized that the present results are site specific to some extent, and would be applicable to other OTEC sites only if the shoreline topography is similar to Keahole Pt.

Extrapolation of the present study to the case of the warm seawater pump station, for which the flow rate is about twice as large, but the overall pump head only one half, an additional cost reduction was deemed possible, with an overall cost savings of nearly $16M in present day costs compared to the original concept.

4.0 TURBINE

The OC-OTEC turbine must accommodate the high volumetric flow rates of steam that accompany the low system operating pressures. In the present 1.8 MW OTEC system, the specific volume, v [m^3/kg], of steam exiting the turbine will be between 2.5 to 5 times larger than v in conventional, large combustion or nuclear power stations.

The turbine area required to pass a unit mass flow of steam must be increased accordingly. Since volumetric flow capacity dictates the dimensions of a turbine rotor, size limitations of existing turbo-machinery impose a practical bound on the maximum power that may be generated by an OC-OTEC plant, unless modularity of power generation units be considered. While innovative turbine designs have been proposed to overcome these restrictions, the required development costs probably cannot be justified for first-generation plants.

Given the present funding status of OC-OTEC power systems, and the high development costs of innovative turbines, it was recognized that, wherever possible, existing turbine component designs should be adapted for use under OC-OTEC operating conditions.

The majority of conventional, stationary, steam power generation systems employ axial flow turbines. The results of earlier studies suggested that the last stages of low pressure turbines used in nuclear power plants might have adequate flow capacity to be used in the present application. These axial flow designs are produced by most major manufacturers and their performance and reliability have been verified by extensive field use. Although previously used primarily in propulsion and gas liquefaction systems, recent studies had demonstrated that radial inflow turbine designs also could be a viable option for OC-OTEC systems. Thus, the potential application of both axial flow and radial inflow turbines was investigated. Relevant turbine operating conditions were specified. The results of a design study of an axial flow device previously performed in cooperation with Mitsubishi Heavy Industries, Ltd. (MHI). are summarized below[17].

In axial flow machines, the principal flow direction is parallel to the axis of rotation of the turbine. Axial flow steam turbines have been employed extensively in power generation systems for over a century and, hence, their design and fabrication may be considered a mature technology. Steam turbines used for generator drive in central power stations may have output capacities exceeding 1000 MW.

Flow capacities of the largest existing axial turbines were a primary consideration in identifying the generating capacity of the present OC-OTEC power system. Earlier calculations indicated that an L-0 low-pressure, nuclear power plant turbine stage utilizing 52-inch (1.32 m) rotor blades could produce the required 1.8 MW generator output at the specified steam conditions. Although some information on this class of turbine stage can be found in the literature, a detailed design study would require resources available only to a turbo-machine manufacturer.

Information previously provided by MHI that is applicable to the 1.8 MW OC-OTEC power system comprises a single stage, single flow, condensing, axial flow, reaction turbine coupled to a synchronous, 6-pole generator. The turbine is a horizontal axis device that operates at a rotor speed of 1200 rpm. Rotor blade height is 1.290 m (50.8 inches), and the tip-to-tip diameter of the rotor is 5.650 m.

[17] MHI is no longer manufacturing these turbines, but the information is currently useful in trying to identify potential suppliers that were contacted for the current study.

The turbine wheel is an adaptation of Mitsubishi's last stage rotor used in nuclear power stations where large volumetric flow rates of steam are encountered. Given the potential for corrosive conditions along the OC-OTEC steam path, material selection was guided by MHI's experience with geothermal turbines.

The baseline design steam flow rate is 93,870 kg/hr (26.08 kg/s). The corresponding turbine total-to-total efficiency is approximately 77.6% (this number is based on shaft power prior to subtracting turbine bearing and seal losses). A review of the MHI performance predictions (i.e., calculated aerodynamic and mechanical losses) concluded that values provided are credible and conservative.

The turbine rotor shaft drives the air-cooled generator via flexible coupling. The generator is rated at 2400 kVA, 1800 kW. The power factor is 0.8. At the rated kVA, efficiency is estimated to be 0.95.

Steam enters the turbine casing flowing vertically downward through the duct connected to the flash evaporator. Steam passes through a row of throttling vanes actuated by a programmable, electro-hydraulic speed control mechanism before being turned 90 degrees and expanding through the stator. The stator comprises 110 stainless steel twisted blades welded to the casing. After exiting the stator, the steam completes its expansion through the rotating blade row. The 130 twisted rotor blades are attached to a disk. Tip speed (at 1200 rpm) is 355 m/s corresponding to a Mach number of approximately 0.85. After exiting the rotor, flow decelerates in an annular diffuser having a pressure recovery coefficient of about 0.5, before exiting the turbine.

The 0.40 m diameter rotor shaft is supported by a pair of sleeve journal bearings. A single Kingsbury-type thrust bearing absorbs the small axial force that arises from the difference in pressures acting on the upstream and downstream faces of the disk and aerodynamic thrust generated by steam expanding through the rotor blade passages. A pressurized lubrication system circulates oil through the bearings.

A pair of mechanical seal glands on either side of the disk prevent contamination of the steam by in-leakage of air and oil mist. Sealing water is also employed. At 1200 rpm, Mitsubishi estimates that power dissipated in the seals and bearings totals 70.8 kW. The lubricating oil pump consumes an additional 26.3 kW.

The combined length of the turbine casing and annular diffuser is approximately 8 meters. Mass of the rotor assembly is estimated to be 25,600 kg. Total mass of the stage, diffuser, and casing is expected to be several times the rotor mass.

It should be noted that similar rotor components have been employed successfully in turbines operated at 1500 or 1800 rpm, at significantly higher steam mass flow rates. Since centrifugal stresses scale with the square of angular velocity and blade loading depends on mass flow rate, the present operating conditions are expected to present a more benign environment than exists in typical thermal power system applications.

Materials for the proposed turbine were selected to withstand corrosive attack. Possible carryover of seawater droplets in the flash-evaporated steam and evolution of dissolved oxygen from the warm seawater increase the potential for corrosive failure. In response to this challenge, Mitsubishi recommended rotor materials used in their geothermal turbines. Geothermal steam, unlike the steam in nuclear or combustion power plants, often contains high concentrations of impurities. Stationary components in the steam path, such as the casing and stator blades, are subject to lower stress levels than the rotating components and, hence, material requirements are less stringent. Additional corrosion protection options, such as coatings, are available if necessary.

Erosive moisture damage near the rotor blade tips may be forestalled by attaching stellite cladding onto the leading edges of the blades. It is not clear at this time, however, whether steam wetness, due to condensation or seawater carryover, will be a problem in the present application.

It should be mentioned that some advantages inherent to radial turbines were previously identified: their simple and rugged construction is less susceptible to erosive or stress-related failure, and their off-design performance is anticipated to be better than that of large axial turbines. The shaft power at the design point is theoretically identical for both axial design and radial device, with the slightly better aerodynamic performance of the latter being offset by larger estimated mechanical losses on a double shaft arrangement. The lack of manufacturing experience for the size of impellers proposed for the present OC-OTEC application, however, represents a clear and serious handicap for radial turbines. Moreover, they are expected to be more expensive than axial turbines.

Turbine and Generator Background

Interestingly, the choice of a turbine type has far-reaching consequences in the overall layout of the entire OC-OTEC plant. With the radial NPPE turbine, the vacuum structure was rather compact, with the evaporator and condenser radially symmetric and arranged in a concentric way; with an axial turbine, a so-called 'telephone' configuration imposes itself, where evaporator and condenser are well separated, and are only connected through the turbine.

While running the NPPE OC-OTEC plant synchronously connected to the electrical grid of the Big Island of Hawaii (HELCO), an unusual resonance problem arose, and power fluctuations as large as the mean gross power occurred at a rather low frequency (of the order of 0.3 Hz). In a stand-alone islanding mode, OC-OTEC power production was, however, very stable. The HELCO grid frequency control was recognized to be poor when compared to very large grids, since at the time the generating capacity on the Big Island was merely of the order of 100 MW, and that several generating units frequently experienced problems. This situation is representative of SIDS.

It was determined that the occurrence of the resonant frequency simply resulted from a basic fact unique to OC-OTEC technology: ***relatively very large turbines producing a small amount of electrical power***. The practical solution was to install a fluid coupler between the NPPE turbine and generator to stabilize synchronous OC- OTEC power generation. Power fluctuations were reduced to acceptable levels when a fluid coupler was inserted in the shaft of the NPPE turbogenerator.

5.0 EVAPORATORS

During the testing phase of the NPPE it was confirmed that the inverted vertical spout is the optimum configuration for an OC-OTEC flash evaporator. It offers a desirable combination of good thermal performance, limited pressure drop and simplicity of construction. To flash some of the 6 m^3/s of warm surface seawater pumped into the evaporator vacuum chamber, vertical PVC spouts, 0.25 m in diameter, are selected for the 1.8 MW-gross plant, since they provided satisfactory experimental performance.

Spouts should extend below the baffle plate to leave an adequate space for the release, accumulation, and removal of non-condensables. In addition, the section above the baffle plate must be higher than the pool water level. The vertical clearance between spout edge and pool free surface is called the active spout height, as discussed below. Accounting for all these factors resulted in the selection of a spout length equal to 1.3 m, including 0.8 m above the baffle plate.

Spout velocity is the velocity of water passing through the spout. All experimental data available at present have demonstrated that higher spout velocities result in a decrease in evaporator performance. For multiple-spout configurations, this effect is more pronounced. Higher velocity also incurs greater spout hydraulic losses, which is a salient parasitic loss of the evaporator system. Moreover, more droplets will eventually settle down for a given chamber height, with lower spout velocities; this would result in a better steam quality. A spout velocity of 1 m/s is recommended for the evaporator. Accordingly, 122 spouts are required to supply 6 m^3 /s of warm water into the evaporator. As determined with the NPPE, these spouts must include an exit flare to double their cross sectional area.

It was observed during the operational phase of the NPPE that the presence of steam bubbles and seawater outgassing at the spout exit created an approximately 50% void such that the liquid velocity was essentially twice the design value. Adding an exit flare (diameter increased by $\sqrt{2}$ in the upper portion of the spout) yielded the desire performance.

The distance separating spouts should evidently be as small as possible, if flashing performance remains high, so that the evaporation vacuum chamber would not become excessively large.

For both power-cycle (first-stage) and water-cycle (second-stage) evaporator, a center-to-center distance of 1.03 m is proposed, with an original baseline thermal effectiveness of more than 80%. However, the experimental data obtained with the NPPE shows that values above 90% will be obtained with this design. An evaporator vessel 13.4 m in diameter is then required, which also allows a 0.5 m wide annular trough around the spout plate for warm water discharge.

Mist eliminators improve the quality of steam, for better turbine performance, and reduced dissolved salt content in freshwater by-products. Since the steam velocity in both evaporators reaches 26 m/sec, obliquely mounted mist eliminators are provided to keep the salinity of the freshwater condensate within acceptable standards, desirable levels for total dissolved solids and chlorides are, respectively, 200 mg/l and 25 mg/l. The desalinated water produced with the NPPE met these requirements although it had to be treated for human consumption because environmental microbes, which entered the system after production, were essentially impossible to avoid.

Total heights from foundation to top are 15.75 m and 14.6 m for the first and second evaporators, respectively. Figure 5.1 shows the breakdown of height for the first stage evaporator: A 2.15 m high space is provided for warm water residence upstream of the spouts. This space acts as a passive predeaeration chamber where a significant fraction of non-condensables will be released. Steam follows a vertical flow path approximately 4.7 m long from the spout exit to the evaporator outlet. This straight path will help moisture droplets to settle down, thus increasing steam quality before the mist eliminator and evaporator outlet bend. The diameter of this outlet is taken as 7.6 m to sustain a steam velocity of the order of 30 m/s. The second stage evaporator is similar, except for a 6.6 m diameter outlet corresponding to a 50 m/s steam velocity since pressure drop is less critical.

Warm surface seawater is fed to a supply sump below the first stage evaporator assembly. After flashing, warm water is discharged to the second stage evaporator through a common sump open to atmosphere. The diameter of the warm water intake nozzle and the inner diameter of the supply pipe from the sump to the evaporator is 2.26 m, for a warm water velocity of 1.5 m/s in both cases. For the warm water discharge system, a 0.5 m wide and 1 m deep annular trough is provided around the spout plate, with four 1.15 m diameter discharge nozzles symmetrically located around the evaporator assembly. The corresponding exit velocity is 1.5 m/sec.

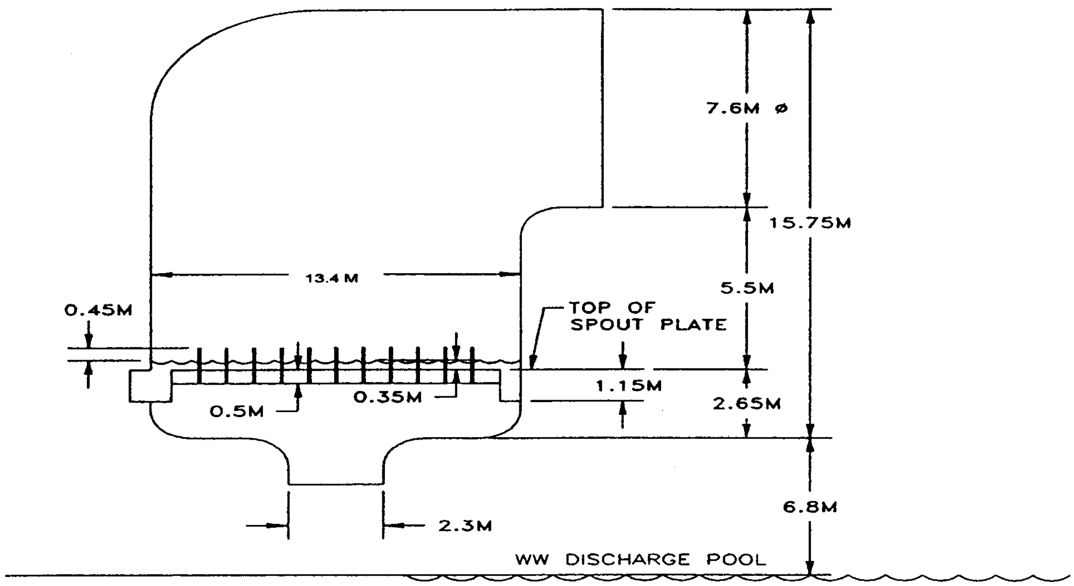


Figure 5.1 - First Stage Evaporator Sketch

Warm Seawater Predeaeration

Non-condensable gases dissolved in seawater are released in the low-pressure processes' characteristic of Open-Cycle OTEC. This phenomenon requires OC-OTEC plants to be equipped with vacuum compression systems, to prevent the accumulation of non-condensables in the vacuum chamber(s). Such an accumulation would rapidly shut down the plant, as soon as the overall pressure exceeded the evaporation threshold (~ 2.6 kPa). The vacuum compression system (or non-condensables exhaust system) imposes significant capital and power penalties on the overall OC- OTEC plant.

Predeaeration is an elegant way to sharply reduce the vacuum compressor load, and therefore the size of the required hardware. It exploits the fact that a large fraction of the gases dissolved in seawater can be released at pressures far above the evaporation threshold, or, if a Direct Contact Condenser (DCC) is selected, above the very low condensation pressure. In what follows, and without loss of generality, focus will be on warm seawater predeaeration since the design presented here opted for a Surface Condenser (SC).

The concept of predeaeration in its simplest form requires that seawater be exposed for some time to a low enough pressure in a chamber where a large free surface permits exchanges between liquid and gas phases. If the exposure time were theoretically infinite, the incoming seawater would reach thermodynamic equilibrium, corresponding to the predeaeration pressure P, before flowing toward the evaporator. Because such equilibrium represents a limit, it is useful to establish the corresponding composition of the gas phase flowing out of the predeaeration chamber (toward a compressor).

All experimental results gathered at the NPPE when producing OC-OTEC power show that the outgassing of non-condensable gases within the evaporator chamber is virtually complete. Moreover, all non-condensable species dissolved in the seawater entering the evaporator are outgassed. The non-condensables are removed from the process via vacuum pumps (Section 7.0) and reinjected into the return water piping without atmospheric release.

6.0 CONDENSERS

From the outset, the design of the 1.8 MWOC-OTEC plant focused on electricity production as well as on the by-products of this technology. For example, the low- pressure steam driving the turbogenerator is essentially pure H_2O, although it is produced from the boiling of surface seawater. Downstream of the turbogenerator, the steam must continually be condensed, and the deep cold seawater provides the necessary heat sink for this purpose. Inasmuch as the condenser design does not place the steam and cold seawater in direct contact but keeps them always separated by a heat-conducting metal surface, desalination can effectively be achieved in an OC-OTEC plant.

The NPPE provided a test bed for several ideas pertaining to OC-OTEC condensers. While the condenser of the NPPE was a DCC, and therefore did not allow for desalination, since the steam condenses directly on a spray of seawater droplets, a couple of initiatives were taken to investigate innovative desalination concepts. We were able to test and validate the compact channel Aluminum SC proposed by ANL based on CHART technology. We designed the test unit to process 0.35 kg/s of steam diverted from the evaporator, and therefore it was large enough to yield valuable performance data, and information about costs and manufacturing.

Because of the recognized importance of desalinated water in SIDS, we selected a surface condenser (SC) for the 1.8 MW-gross plant instead of a direct-contact condenser (DCC). To maximize desalinated water production, a Second Stage is included (Fig 2.3) to take advantage of the residual temperature difference of about 10°C between the seawater effluents of the OC-OTEC plant. While this leftover thermal resource would be insufficient to produce more OC-OTEC electricity, it can be used for the purpose of desalination, however, since no significant pressure drop is necessary from the Second Stage evaporator to the Second Stage condenser in the absence of a turbine. Because there essentially is no difference between the condensers of either stage, except for a reduced amount of non-condensable gases in the Second Stage.

OC-OTEC condensers operate under very unusual and critical conditions. For example, the volumetric flow rate of steam is relatively large which implies substantial dimensions for the condenser assembly, and a corresponding need for compactness. On the other hand, pressures as low as 1.3 kPa (≈ 1.3 % of atmospheric pressure) render any steam-side pressure drop extremely undesirable for efficient condensation to take place. The water-side pressure drop should be minimized as well from a net power viewpoint, even though high cold seawater velocities may result in higher heat transfer coefficients. Finally, the potentially negative effects of non-condensable gases upon the steam condensation process complicate the analysis and design task.

The input parameters for the 1.8 MW system are the steam flow rate out of the turbine (98% quality), 25.6 kg/s, the inlet steam pressure, 1.3 kPa, and the cold seawater temperature, 4°C (se Figure 2.3 for baseline conditions). This corresponds to a heat load of 60 MWth.

The preferred condenser should be the compact channel configuration tested with the NPPE. We should be able to have this design manufactured by either CHART (USA) or Fives Cryo (France). As an alternative tube and shell condensers are also considered.

The schematic layout of the compact channel configuration is shown on Figure 6.1 (steam ducting is not included). It is a cross-flow arrangement, with cold seawater flowing through horizontal channels in two passes, while steam follows a downward vertical path. An overall heat transfer coefficient of 2.2 kW/m^2-K and a moderate parasitic power consumption of 27 kWe were estimated for this surface condenser. These values were confirmed with the unit tested at the NPPE.

The main characteristics of plain tube-and-shell cross-flow arrangement are listed in Table 6.1. The parameters given are for a steam mass flow rate of 27.4 kg/s at the inlet (7% higher than the baseline value). The overall heat transfer coefficient is lower (1.44 kW/m^2-K), than the value for the compact channel, but this design is available "off-the-shelf". Data was supplied by Toshiba.

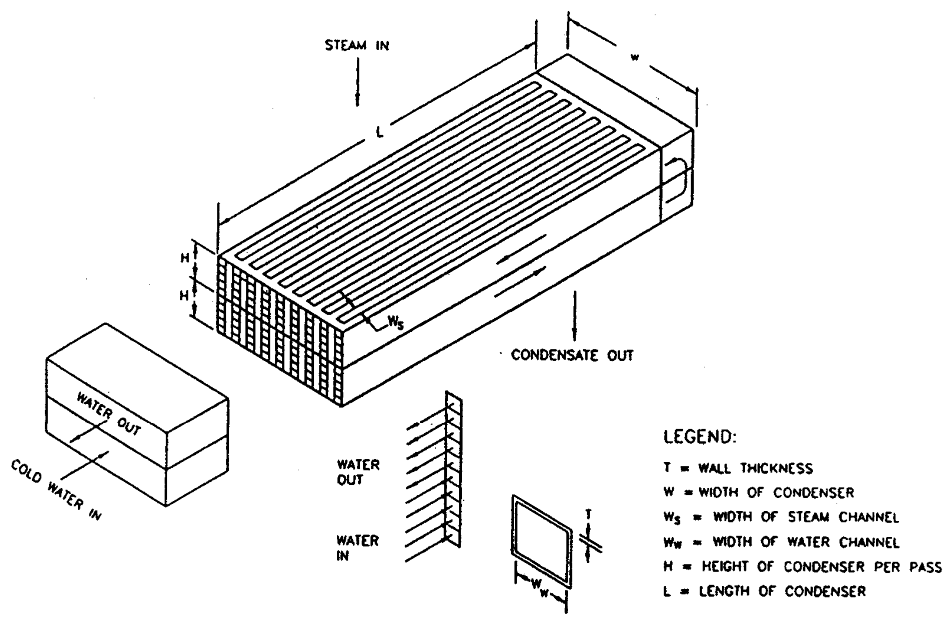


Figure 6.1- Compact Channel Surface Condenser for OC-OTEC Application (excluding the steam ducting)

Inlet Steam, kg/s	**27.4**
Number of shells	**1**
Overall length, m	**18.9 (including steam ducts)**
Overall height, m	**12.7**
Overall width, m	**21.0**
Total number of tubes	**16,000**
Nominal tube diameter, mm	**25.4**
Tube wall thickness, mm	**1.2**
Tube length, m	**12.0**
Tube material	**Al**
Heat transfer area, m^2	**15,321**
Overall heat transfer coeff. kW/m^2-K	**1.44**
Tube side pressure drop, kPa	**11.9**
Shell side (steam) pressure drop, Pa	**5.92**

Table 6.1 Toshiba's Tube and Shell Surface Condenser (Main: Power Cycle)

The configuration of the Toshiba main condenser is depicted in Figure 6.2.

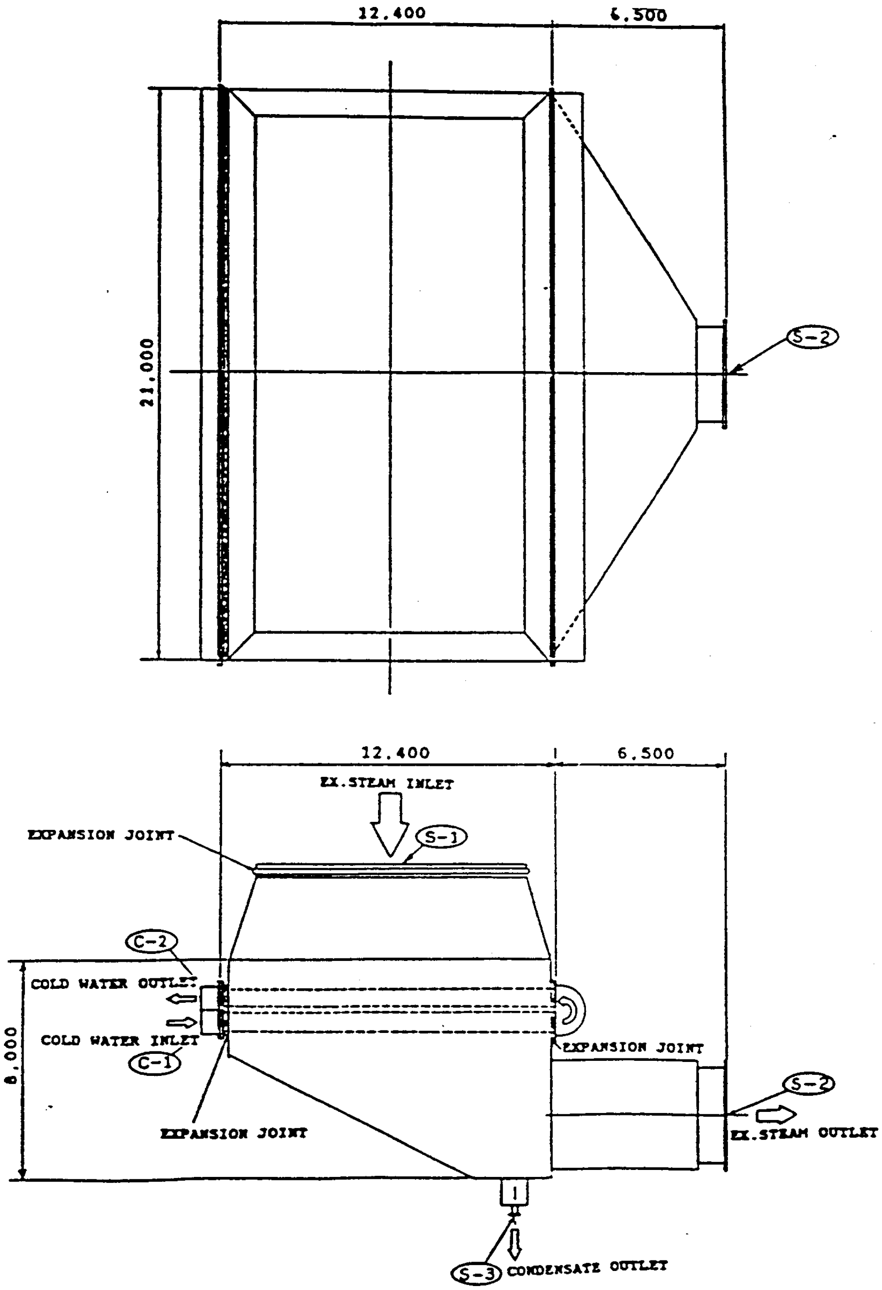


Figure 6.2 - Tube and Shell Condenser by Toshiba (Main unit with dimensions in mm)

7.0 NON-CONDENSABLE GAS REMOVAL SYSTEM

Water from the ocean contains dissolved gases which are released when it is exposed to the low pressures prevalent in an OC-OTEC system. The operational phase of the NPPE revealed that 19.36 mg of "air" (61.2% N_2, 36.4% O_2 and 2.4% $C0_2$) per kg of warm seawater are released under OC-OTEC process pressures. These released gases cause an accumulation of non-condensables which have to be continuously removed to maintain the low operating turbine back pressure. Unlike steam, these non-condensables (NC) cannot be liquefied. The presence of NC in a surface condenser and their accumulation on the heat-transfer surface results in a reduction of the heat transfer coefficient.

Warm seawater, which is closer to the ocean surface than the deep cold seawater, has NC contents almost at the saturation level for its temperature. Cold seawater contains much less oxygen than the equilibrium amount defined for its temperature. [The NPPE database reveals that 18.18 mg of "air" (85% N_2, 8% 0_2 and 7% $C0_2$) are released per kg of deep cold seawater in a DCC chamber]. In an OC-OTEC system, with a surface condenser, cold seawater is not exposed to low pressures. For the 1.8 MW design, we therefore only consider NC liberated in the warm water stream. For the baseline warm water flow of 6196 kg/s, a total of 0.119 kg/s should be released. The 1.8 MW plant is designed to release 50% of the NC in the predeaeration chamber (17 kPa) and the rest in the flash evaporator. The NC released in the predearation chamber are diverted away from the OC-OTEC process into the inlet of the last stage of the train of vacuum compressors. In this fashion the overall power required to operate the vacuum compressors is decreased and the crucial first and second stages of compression have their loading reduced such that vacuum pumps are available off-the-shelf.

Infiltration is also a potential source of NC in the OC-OTEC system. On the basis of the NPPE experience, however, leakage should be at least one order of magnitude smaller than outgassing from warm seawater.

Predeaeration

Warm water predeaeration can be either passive or active. With passive predeaeration, warm water flows through a low pressure predeaeration chamber where NCs are released. In active predeaeration schemes, water is forced through a packed column under low pressure. The packed column enhances NC release, but it also results in additional hydraulic losses. Thus passive predeaeration was selected for this design.

The factors which determine the fraction of NC release include: predeaeration pressure, residence time, bubble formation enhancement, such as seeding and wall roughness.
Passive predeaeration is accomplished by adding a predeaeration chamber upstream of the evaporator. The scheme adopted here consists in using the space below the evaporator baffle plate (Figure 5.1). For a given evaporator configuration, the predeaeration pressure, below the baffle plate, depends on the pressure in the evaporator. A value of 17 to 15 kPa is appropriate given the evaporator spout length.

Figure 7.1 shows the schematic of warm water predeaeration. As stated above a baseline gas flow rate of 0.06 kg/s is evacuated from below the baffle plate through a vertical nozzle and diverted to the train of vacuum compressors. The flashing of warm seawater in the evaporator liberates additional 0.06 kg/s of non-condensables, which associate with the

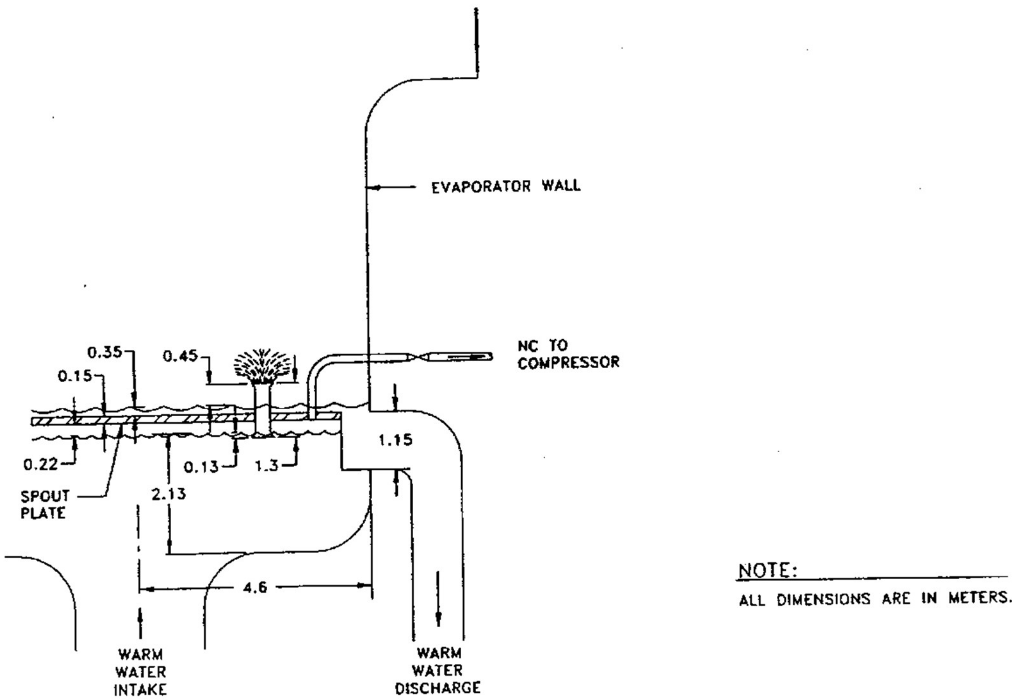


Figure 7.1 - Removal of Non-Condensables and Water Discharge from the First Stage Evaporator

Steam flows up to the vent condenser and enters the first stage of the Compressor train.

The warm water entering the second stage unit (water production, see Fig 2.3) should have already been 100% deaerated in the first stage evaporator. As a result, no additional release of NC is anticipated in the second stage unit. Moreover the air leakage rate in the second stage should be even more negligible, as no rotating machinery (turbine) is involved. For initial air evacuation (plant startup), however, a connection is provided to the vacuum compressor through a small additional vent condenser.

Vacuum Compressor Train

Experienced acquired during the design and testing phases of the OC-OTEC Experimental Apparatus (NPPE) indicates that compared to commercially available positive displacement pumps, centrifugal compressors can be cost-competitive while consuming less power due to their higher efficiencies at high volumetric flow rates.

The baseline design parameters (Figure 2.3) indicate that 60 g/s of NC and 240 g/s of steam exit the condenser system at 1190 Pa. The mixture of water vapor and NC is continuously removed from the OC-OTEC plant with a compressor train. The train consists of several stages of compressors (vacuum pumps) with a pre-cooler at the inlet and coolers between the stages. A DCC pre-cooler cools the mixture to 6 °C while condensing a portion of the water vapor. The pressure drop across the DCC should be less than 70 Pa. The compressor train taken as the baseline for Figure 2.3 consists of high speed centrifugal vacuum pumps similar to those used for the NPPE but modified to incorporate appropriate bearing systems. These pumps would consume 80 kW to remove the NC and re-inject them into the seawater effluent at 30 kPa. Alternatively commercially available positive displacement vacuum pumps can be used.

Table 7.1 provides the conditions for a four stage train using positive displacement pumps and plate type coolers with cold seawater as the coolant (pressure drop across these coolers is taken as 2% of inlet pressure). The NC released in the predeaeration chamber at injected at the inlet of the fourth stage and its outlet gas stream is re- injected into the seawater discharge system to be hydraulically compressed.

	Stage 1	Stage 2	Stage 3	Stage 4
NC, g/s	60	60	60	120
H2O, g/s	181	16	5	4
Ncmw, g/mol	29	29	29	29
H2Omw, g/mol	18	18	18	18
dm/dt total, g/s	241	76	65	124
MW mix, g/mol	19.88	25.69	27.70	28.44
Tin, °C	6	7	7	7
Tin, K	279.15	280.15	280.15	280.15
Pin, Pa	1120	3300	8100	16350
Ro, J/mol-K	8.314	8.314	8.314	8.314
V, m3/s	25.12	2.09	0.67	0.62
V, ACFM	53233	4423	1430	1316
Pout, Pa	3370	8260	16680	30000

Table 7.1 - Four Stage Vacuum Compressor Train with Positive Displacement Pumps

The selection of either compressor train system has to be based on operation, maintenance and repair (life cycle) considerations because the capital cost of the plant, expressed in $/kWnet, is expected to be the same for both systems.

8.0 AUXILIARY SYSTEMS

The balance of the OC-OTEC system consists of: (i) the energy transfer system to deliver power to the end user's grid as well as to all the auxiliary loads in the plant; (ii) desalinated water storage and delivery to the user's potable water piping system; (iii) the emergency diesel generator, sized to provide a minimum of 1 MW base load to the grid, and to meet the power demand for seawater pumps and compressor during the startup; (iv) a water-based fire suppression system is used to protect the main power conversion building as well as other auxiliary buildings and the fuel oil storage tank area; and, (v) a compressed air system.

9.0 COSTS (*Original values updated with USA Manufacturing Price Index to 2022*)

To assess the relative cost competitiveness of OTEC the levelized cost-of-electricity (LCOE), without profit or environmental credits for avoidance of Greenhouse Gas Emissions, is estimated over an appropriate plant life for realistic interest and inflation rates. Credit is taken for desalinated water production and for the air conditioning load. Operational costs are based on the experience gathered operating the NPPE as well as the installation of several bottom-mounted seawater pipes at NELHA.

Capital Costs *(2022 Estimates)*

The seawater systems, which include warm-water and cold-water supply pipes, as well as the mixed-effluent return pipe, represent the largest expenditure, with an estimated cost of $15M. The cost of seawater pumps is estimated at $1.3M. The cost of the land structure and piping is estimated at $8.4M, the main evaporator at $1.7M and first stage surface condenser at $4.6M. The turbine-generator system at $5.9M and the high speed centrifugal pumps, non-condensables (NC) removal, system at $3.4M (or the positive displacement vacuum pumps system at $1M with lower net power output). The auxiliary diesel generator should cost $0.8M and the balance-of-the-system $1.7M. These include costs associated with conditioning and transmission of electricity and desalinated water up to the connection to national or provincial "grids".

In summary, the total capital cost of the single stage system, with positive displacement vacuum pumps, is estimated at $40.4M, with a baseline net power output of 1300 kW ($31,080/kW); or $42.8M with centrifugal vacuum pumps and a net power of 1360 kW ($31,470/kW).

The addition of the second stage increases the capital cost by $7M (structure, evaporator, condenser, and balance-of-system), decrease of net power ≈100 kW, and increases desalinated water production resulting in a cost of ≈ $39,524/kW for either compressor train. The addition of a 300 ton air conditioning system using 90 kg/s of cold seawater as the chiller fluid, would decrease the net power output by ≈ 10 kW (additional seawater pumping) and increase the capital cost by $1.7M. However, it would save the additional 240 kW that would be required to meet the 300 ton AC load. Therefore, when applicable, an electricity production credit is taken in the estimation of the "equivalent" cost-of-electricity.

Levelized Production Cost-Of-Electricity *(2022 Estimates)*

The following algorithm is used to calculate the levelized cost-of-electricity (LCOE) over the life of the system:

COE($/kWh)=(CRF.CC + OMRR.G.CRF - WP.WV.G.CRF)/ (NP.CF.8760)

CRF: Capital Recovery Factor, a function of Loan Interest rate (%) and term (years). Herein we consider only two cases: Commercial Loan @ 8%/15 years; and. Concessionary ;loan @ 2.5%/20 years.

CC: Capital cost, in $.

OMR&R: Operation, maintenance, repairs, & replacements covering the first year in $.

G: Present worth factor as a function of I, N, and escalation rate (inflation). Inflation taken as 2.65% derived from the USA Manufacturing Price Index Inflation average over the last 20 years.

WP: Annual water production, m^3

WV: Water value in $/$m^3$ taken as constant value of 1.5 $/$m^3$ corresponding to the current average rate for RO system sized between 2,000 to 6,000 m^3/day. Note that the largest RO systems at 900,000 m^3/day yield rates of 0.5 $/$m^3$.

NP: Net power production (kW) with credit for air conditioning (240 kW for 300 Ton AC).

CF: Production capacity factor, 337 days out of 365 (28 days for Maintenance & Repair)

8760 : hours in one year.

The following Table provides a summary of capital costs and production levels for different configurations. These are used to determine the LCOE. Although the values are for systems using centrifugal vacuum pumps, the LCOE is the same using positive displacement pumps (i.e., ratio of capital cost to net power is the same). It must be emphasized that the LCOE gives the cost of production and <u>does not include profit or return on investment.</u>

	Single Stage no AC	Single Stage with AC	2nd Stage no AC	2nd Stage with AC	Single Stage no Water/AC
Net Power, kW	1360	"1590"	1260	"1490"	1360
Water, m^3/day	2450	2450	5670	5670	0
AC, Ton	0	300	0	300	0
CC, $M	42.8	44.5	49.8	51.5	39.2
OMR&R 1st Year	2.29	2.40	2.76	2.87	2.05
	LCOE, $/kWh	**LCOE, $/kWh**	**LCOE, $/kWh**	**LCOE, $/kWh**	**LCOE, $/kWh**
Int. 8%/15 yrs	**0.58**	**0.52**	**0.59**	**0.53**	**0.64**
Int. 2.5%/20 yrs	**0.40**	**0.36**	**0.36**	**0.33**	**0.47**

United Nation guidelines for developing countries indicate that 200 liters/day of fresh water should be available per person. In developed countries the consumption is 3 to 4 times more and in agricultural communities 7 to 10 times more. The UN guidelines appear to be low, therefore, if 400 liters/day is a more reasonable number, the single stage system would meet the water demand of 6,100 people and the system with an additional second stage 14,000 people. The electricity production rates could meet the electricity demands of a similar range of people.

10.0 CONCLUSIONS AND RECOMMENDATIONS

The design philosophy originally adopted reflected an emphasis on feasibility: a 1.6 m OD HDPE conduit was selected as the design starting point, rather than a prescribed net power output. Consistent with this choice, some critical hardware components were preferred over alternative configurations because at the time they were available off-the-shelf.

The analysis and design work performed indicates that future design efforts must concentrate on developing cost effective turbines, and reliable bearing systems for the centrifugal pumps used in vacuum compression systems.

The major conclusion continues to be that cost effective electricity and fresh water could be supplied to SIDS communities if financing via Concessionary Loans is available (e.g. 2.5%/20 years). Two global design options were identified, depending on the importance of desalinated water for these communities, in addition a 300-room air conditioning system can be included for resort development:

- an OC-OTEC power plant proper, with a net power production capability of about 1,360 kW and freshwater production of 2,450 m^3/day;
- an OC-OTEC power plant fitted with a second-stage water flashing unit, with a net power production capability of about 1,260 kW and freshwater production of 5,670 m^3/day.

These designs are cost competitive with conventional power plants if investment loans with interest rates of < 3% are available and if credits for fresh water and air-conditioning by-products are included.

However, the transfer of OTEC to SIDS should not be exclusively assessed from the perspective of present-day cost effectiveness since it offers these isolated communities some degree of energy independence while preserving their environment. In this regard the most important finding is not related to technical matters but rather to financial considerations: *is a concessionary loan available from Development Banks?*

Recommendations Pertaining to the Present Conceptual Design

Among the various items that deserve further study to refine the technical and financial issues, the most critical are:

- requirements for SIDS to qualify for Concessionary Loans;

- technical feasibility of turbines specifically designed for OC- OTEC application and using non-metallic components should be assessed.

- companies that already manufacture positive displacement vacuum pumps and the more efficient centrifugal pumps (with proven bearing systems) should be identified and quotes should be solicited.

- companies that already manufacture surface condensers like the ones discussed above must be identified and quotes should be solicited.

Appendix 7: Potential OTEC Plantships

Plantship Capital-Cost estimates: Information Requested

OTEC Plantship Identifier	LBP (m)	Beam (m)	Height (m)	Ops Draught (m)	Displacement * (tonnes) Cb ≈ 0.95	Station Keeping Thrusters (kW)	Shipyard Name & Location	FOB Shipyard (US $M)
10 MW CC	90	32	16	9	26,000	4 x 1,000		
10 MW OC	80	74	16	9	53,400	4 x 1,000		
50 MW CC	198	39	24	16	120,600	4 x 2,200		
50 MW OC	176	90	24	16	247,400	4 x 2,200		

* *Given that shape of the OTEC Plantships the* ***DWT is 73% of the Displacement***

The OTEC vessels are either moored at 1,100 m depth or slowly drifting (grazing) such that the rotational thrusters are primarily required for dynamic positioning and maneuverability once at station or slowly moving at about ½ knot (0.25 m/s). The moored vessels can use their thrusters to transit to station between 10 km and 100 km offshore. The grazing vessels transit on their own propulsion to their area of operation. In either case the 1000 m long vertical pipe (cold-water pipe: CWP) is towed horizontally to station, upended, and attached to the plantship.

The thrust from each thruster is required to overcome the drag force (N) on the CWP moving with the vessel at ½ knot. Four thrusters instead of one are installed for additional maneuverability and emergency situations.

A 160 N/kW thrust (**N**ewtons) to power (kW) ratio is assumed to size each thruster.

For example: Calculations for our “100 MW“ H2-OTEC Plantship”

- Thruster required to overcome drag forces on a 10m CWP and two 12.5m MDPs of the slowly (0.5 knots) drifting Plantship:

  Pipes Cross sectional area: 10 m x 1000 m + 2x(12.5 m x 60m) = 11,500 m^2
  Drag Force (F_D): $1/2 \varrho C_D A U^2 = 404{,}009$ N
  Cd for the 10 m CWP estimated at 1.1 from the “1/3 scale CWP at-sea test”
  T= $F_D/160 \approx 2{,}500$ kW

- Four 2,500 kW rotational thrusters are included for emergencies and drifting at ≈ 1 knot
  (Actual conversion 1 knot = 0.514 m/s)

Potential OTEC Plantships

Only Conceptual and Preliminary Designs Available

OTEC Plantships	**LBP x Beam x Draught meters**	**"Displacement"** tonnes**	**Design Date**	**Vessel Conceptual Cost (design year) excludes OTEC Equipment US $M**
5 MW Hybrid 1st Stage: CC-OTEC 2nd: Flash Evaporator/ Surface Cond.	122 x 30.5 x 10 (Height: 16 m) (Lightship: 2.67 m)	**36,300** (Cb : 0.95) Deadwgth: 26,600 Lightwgth: 9,700 (27%) Hull Steel: 4,920 Machinery: 600 Hull Outfit:1,210 OTEC Equipment: 2,950	**Aug 1994** **Preliminary** Design Vega et al Design Phases: • Conceptual • Preliminary • Final (ready for Shipyard)	**40** New Ship: 35 Thrusters: 5 {Used Tanker: $20 M) **CC ($M)/(LBPxBxD)=** **1075 $/m³** **CC ($M)/DWT=** **1504 $/t**
10 MW CC-OTEC	90 x 32 x 9 (Height:16)	**26,000** DWT: 18,980 26000 x 0.73=18,980	**October 2009** **Conceptual** Design Vega	**41** New Double Hull Ship: 33 Thrusters: 8 **CC ($M)/(LBPxBxD)=** **1582 $/m³** **CC ($M)/DWT=** **2160 $/t**
50 MW CC-OTEC	198 x 39 x 16 (Height:24) Similar to Ever Orient Evergreen O-Class 2634 TEUs (**2021**) 195 x 32 x 11.4 DWT: 32,926	**120,600** DWT: 88,038 120,600 x 0.73 = 88,038	**Feb 2009 Conceptual** Design Vega	**100** **CC ($M)/(LBPxBxD)=** **809 $/m³** **CC ($M)/DWT=** **1136 $/t**
50 MW OC-OTEC	176 x 90 x 16 (Height:24)	**247,400** DWT: 180,602 247,400 x 0.73 = 180,602	**Feb 2009** Conceptual Design Vega	**200** **CC ($M)/(LBPxBxD)=** **789 $/m³** **CC ($M)/DWT=** **1107 $/t**
100 MW H2 CC-OTEC	250 x 60 x 20 (Height:28)	**285,000** DWT: 208,050 285,000 x 0.73 = 208,050	**1993** Conceptual Design Nihous & Vega	**NA**
Existing Container Ships	**LBP x Beam x Draught meters**	**"Displacement"** tonnes**	**Date & Shipyard**	**All included Cost US $M**
Indonesia 2011 Study 2004 Data	NA	**DWT: 23,200** **1644 TEU** **14.1 t/TEU**	**2004** **South Korea or Japan**	**11.5 ± 0.8** **CC ($M)/DWT=** **496 ± 35 $/t** **CC ($M)/TEU=** **7,000 ± 500 $/TEU** 30% less in China
Ever Orient (Evergreen O-Class)	195 x 32 x 11.4	Deadwght: 32,500 Displacement: 43,749 (Cb:0.6) **2634 TEU** **12.3 t/TEU**	**2021** Cost taken from similar order by Namsung Shipping to Hyundai for 2500 TEU ships	**41 (2021)** **43 (2022)** **CC ($M)/(LBPxBxD)=** **576 $/m³** **CC ($M)/DWT=** **1262 $/t** **CC ($M)/TEU=** **15566 $/TEU**

Emma Maersk Single Diesel Engine: 81 MW **2,300 t** 150 m long shaft \$25M (309 \$/kW) 15% of CC Also 4 bow & stern Thrusters Wartsila Sulzer Finland	397x 56 x 16 Height: 30	**15,000 TEU** Derived Displacement: 218,991 t **DWT: 164,243 t** **11 t/TEU** Reported: 156,907 N.B. Maersk defines Containers as 14 t each DWT≈14 x 11,000 others by volume (15,000) as used here	**2006** Odense Steel Shipyard Denmark	**170** **CC (\$M)/(LBPxBxD)=** **493 \$/m³** **CC (\$M)/DWT=** **1035 \$/t** **CC (\$M)/TEU=** **11,333 \$/TEU**
20 new Container Ships Evergreen Marine Corp (Taiwan)	NA	**15,000 TEU** each	2024-2025 **Samsung** Heavy Industries South Korea	**115** to **130** each **CC (\$M)/TEU=** **8167 ± 500 \$/TEU**
Maersk Triple E 2 20 Container Ships 1st Generation 2 x 30 MW Engines	400 x 59 x 16 (Height: 73 m)	DWT: **196,000** **18,000 TEU** each Lightwgth: **55,000** Displacement≈250,000 **10.9 t/TEU**	Other placed in **2011** delivered 2013-2015 **Daewoo** **(South Korea)**	**185 each** **CC (\$M)/(LBPxBxD)=** **490 \$/m³** **CC (\$M)/DWT=** **944 \$/t** **CC (\$M)/TEU=** **10277 \$/TEU**
Ever Given *(Evergreen G-Class)* Container Ship 1 of 13 ships **"Imabari 20000 Design"**	399.94 x 58.8 x 14.5 (Height: 32.9 m) Single Engine: 59 MW Two Bow Thrusters: 2.5 MW each	**265,876** (Cb : 0.76) Deadwgth: 199,629 Lightwgth: 66,247 (25%) **20,124 TEU** 9.9 t/TEU	**Sep 2018** **Imabari** Shipbldg Japan	**150** **CC (\$M)/(LBPxBxD)=** **440 \$/m³** **CC (\$M)/DWT=** **751 \$/t** **CC (\$M)/TEU=** **7454 \$/TEU**
Maersk Triple E 2 11 Container Ships 2nd Generation	400 x 59 x 17 (Height: 73 m)	DWT: **210,019** **20,568 TEU** each 10.9 t/TEU	Other placed in 2015 delivered 2017-2019 **Daewoo** **(South Korea)**	**185** each **CC (\$M)/(LBPxBxD)=** **461 \$/m³** **CC (\$M)/DWT=** **881\$/t** **CC (\$M)/TEU=** **8995 \$/TEU**
Evergreen A-Class 13 Ships	400 x 61.5 x 16.5	Ever Ace (July 2021) Deadwgth: 241,960 **23,992 TEU** 10.1 t/TEU	**2021 to 2022** **6** (Samsung) **7** (China State Shipbuilding Co.)	**150 ± 10** **CC (\$M)/(LBPxBxD)=** **370 ± 25 \$/m³** **CC (\$M)/DWT=** **619 ± 41 \$/t** **CC (\$M)/TEU=** **6252 ± 417 \$/TEU**

Other Ships	**LBP x Beam x Draught meters**	**"Displacement"** tonnes**	**Date & Shipyard**	**All included Cost US \$M**
MS Ore Brasil Ore Carrier	350 x 65 x 23 (Height: 30.4 m)	Deadwght: 402,347	**2011** **Daewoo** Shipbldg South Korea	NA
Typical Double Hull Tanker	180 x 32.2 x 11.2 (Height: 19.2 m)	**57,000** (Cb : 0.86)	NA	NA
Old Panamax Limit (1914)	294.1 32.3 x 12 (Height: 57.91 m)	DWT: 52,500 Capacity ≤ 4,500 TEU		NA

New Panamax Limit (2016)	366 x 51.25 x 15.2 (Height: 57.91 m)	DWT: 120,000 Capacity ≤ 13,000 TEU		NA
World Navigator (Atlas Cruise)	129 x 18.9 x 4.7	**10,000** (Cb : 0.85)	June **2021** Portugal	**80** Luxury Passenger Cruise Ship
Knock Nevis Crude Carrier Longest ship ever built	440 x 69 x 24.6 (Height: 29.8 m)	**657,019** (Cb : 0.86) Deadwgth: 573,826 Lightwgth: 83,193 (25%)	Life: 1981 to 2010 Built in Japan by **Sumitomo** Heavy Industries 1986 missile sunk it off Iran. Refloated and repaired 1988. 2004 converted to FSO	NA

** Loaded Seawater Displacement (tonnes) = Weight of Ship (Light Displacement tonnage)
+ Weight of Cargo (Deadweight tonnage, DWT)

** Displacement (tonnes) = LBP x B x D x ϱ x Cb ; ϱ = 1022 kg/m^3
Ever Given = 399.94 x 58.8 x 14.5 x 1.022 x Cb = 265,876 t (therefore Cb= 0.76)
TEU: refers to **T**wenty-Foot **E**quivalent container **U**nits

Typical Block Coefficient (Cb)
Container Ship: 0.6 to 0.72
Oil Tanker/Bulk Carrier: 0.8 to 0.86
LNG: 0.75

Circa 2007 Typical Container Ship Values per HYAUNDI

TEU	6,000	8,000	12,000	18,000
DWT (tonnes)	70,000 t	93,000 t	137,000 t	200,000 t
DWT/TEU	**11.7**	**11.6**	**11.4**	**11.1**
LOA/LBP (m)	305/290	365/340	400/380	470/450
B (m)	42	43	52.5	60
Draught (m)	12.5	13.5	14.5	15.7
Cb	0.59	0.61	0.62	0.62
Derived Displacement 1.025 t/m^3	92,073 t	123,406 t	183,834 t	269,388 t
DWT/Displacement	**0.76**	**0.75**	**0.75**	**0.74**

Container Ships Manufacturers	Location
HYUNDAI Heavy Industries Korea Shipbuilding & Offshore Engineering Company (**KSOE**)	South Korea
DAEWOO Shipbuilding & Marine Eng. Company (DSME)	" N.B. Hyundai/Daewoo Merger blocked by EU
SAMSUNG Heavy Industries	"
K Shipbuilding	"
IMABARI Shipbuilding	Japan
MITSUBISHI Heavy Industries	"
MITSUI	"
SUMITOMO	"

ROM Current Cost Estimates Based on Container Ships Published Data per new Algorithm (05/24/23)

OTEC Plantship: Nominal Size	DWT	Estimated Cost
10 MW CC-OTEC	18,980	$28.3M
50 MW CC-OTEC	88,038	$84.5M
50 MW OC-OTEC	180,602	$141M
100 MW H2 Plantship	208,050	$156M