Fall 12-20-2013

Utilizing Economic and Environmental Data from the Desalination Industry as a Progressive Approach to Ocean Thermal Energy Conversion (OTEC) Commercialization

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A Dissertation

Submitted to the Graduate Faculty of the
University of New Orleans
in partial fulfillment of the
requirements for the degree of

Doctor of Philosophy
in
Engineering and Applied Sciences
Engineering Management

by

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December 2013

Acknowledgement

I would first like to thank Professor Ioannis Georgiou for his guidance and continued support over the past 4 years. I would also like to thank the members of my PhD committee: Professor Paul Herrington, Professor Linda Sins, Professor Bhaskar Kura, and Professor Jay Hunt. Additionally, I would like to acknowledge the support from my colleagues at Lockheed Martin. Finally, I would like to thank my friends, my family, and Heather for their love and support.

Dedication

I would like to dedicate this work to my late uncle Dr. William Granado who was my inspiration for pursuing a PhD and following through to completion.

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Abstract

Ocean Thermal Energy Conversion (OTEC) is a renewable energy technology that has to overcome several key challenges before achieving its ultimate goal of producing baseload power on a commercial scale. The economic challenge of deploying an OTEC plant remains the biggest barrier to implementation. Although small OTEC demonstration plants and recent advances in subsystem technologies have proven OTEC's technical merits, the process still lacks the crucial operational data required to justify investments in large commercial OTEC plants on the order of 50-100 megawatts of net electrical power (MWe-net). A pre-commercial pilot plant on the order of 5-10 MWe-net is required for an OTEC market to evolve. In addition to the economic challenge,OTEC plants have potential for adverse environmental impacts from redistribution of nutrients and residual chemicals in the discharge plume.

Although long-term operational records are not available for commercial sizeOTEC plants, synergistic operational data can be leveraged from the desalination industry to improve the potential for OTEC commercialization. Large capacity desalination plants primarily use membranes or thermal evaporator tubes to transform enormous amounts of seawater into freshwater. Thermal desalination plants in particular possess many of the same technical, economic, and environmental traits as a commercial scale OTEC plant. Substantial long-term economic data and environmental impact results are now widely available since commercial desalination began in the 1950s. Analysis of this data indicates that the evolution of the desalination industry could be akin to the potential future advancement of OTEC. Furthermore, certain scenarios exist where a combined OTEC-desalination plant provides a new opportunity

for commercial plants. This paper seeks to utilize operational data from the desalination industry as a progressive approach towards OTEC commercialization.

Keywords: Renewable energy, desalination, scale-up cost, heat exchanger, cost estimation, aluminum, titanium, tubes, lifecycle cost analysis, mixed discharge, chlorination

Chapter 1

Introduction

Ocean Thermal Energy Conversion (OTEC) and desalination are technologies that are not particularly well known for most readers; therefore, an introduction to both technologies is detailed below. The objective of these introductions is to provide the reader with an independent background on both technologies before discussing key similarities and integration scenarios.

Introduction to OTEC

OTEC is a thermal energy conversion technology that is used to create electric power by exploiting solar energy stored in the oceans. AnOTEC system utilizes the temperature gradient between the cold deep seawater and warm surface seawater in tropical regions to produce work using a Rankine cycle. Using an appropriate working fluid such as ammonia can drive a turbine-generator to produce electric power. Typically, OTEC plants require a 20 degree Celsius (°C) difference between surface and deep seawater that is usually found in or near the tropics. AUnited States State Department-sponsored study performed by Dunbar (1981) determined that 98 nations and territories have access to the required OTEC resource within a 200 nautical mile exclusive economic zone (EEZ) (Vega, 1992).Since oceans cover more than 70 percent of the Earth's surface (Saha, 2008), they are the largest solar energy collector and storage system. A preliminary assessment of OTEC resources indicates the world's oceans could supply 3-5 terawatts (TW) of electric power using OTEC (Nihous, 2007). Since the total worldwide average energy consumption rate was 15 TW in 2008 (British Petroleum, 2009), OTEC could potentially meet 20-33% of the total worldwide energy demand, making it one of the largest sources of renewable energy in the world.

Although researchers have been investigating OTEC since the late 1800s, it was not until 1979 that proof of net power was demonstrated during operation. The demonstration plant, called Mini-OTEC, was deployed off of the Big Island of Hawaii by a small conglomerate led by Lockheed Missile & Space Company, the State of Hawaii, and the Dillingham Company. Mini-OTEC produced a gross power of 50 kilowatts (kW) with a net power production of only 10-15kW; however, the three-month experiment proved that OTEC could generate surplus electric power (Johnson, 1992). Mini-OTEC was an example of a closed-cycle OTEC (CC-OTEC) plant that is typically situated off shore. The CC-OTEC plants are somewhat limited by the size of the cold water pipe (CWP) required to upwell the deep seawater. The deployment of the CWP is one of the largest technical challenges for a commercial OTEC plant with a 100 MWe-net power, hereafter MW, plant requiring an approximate 10 m diameter pipe (Coastal Response Research Center, 2010). This size pipe would have to upwell deep seawater at a flow rate of approximately 320 cubic meters per second (m^3/s) to meet the heat sink requirement for a 100 MW plant (Grandelli & Rocheleau, 2011).

ACC-OTEC system is designed to pump 24-30°C surface seawater through a first array of heat exchangers (evaporators) to vaporize the working fluid. The vaporized working fluid is forced into a large turbine that drives a generator installed atop the offshore platform. Deep seawater with temperatures of 4-8°C is upwelled from ocean depths of 1000 m and cycled through the second array of heat exchangers (condensers) to convert the ammonia vapor back to liquid (Figure 1).

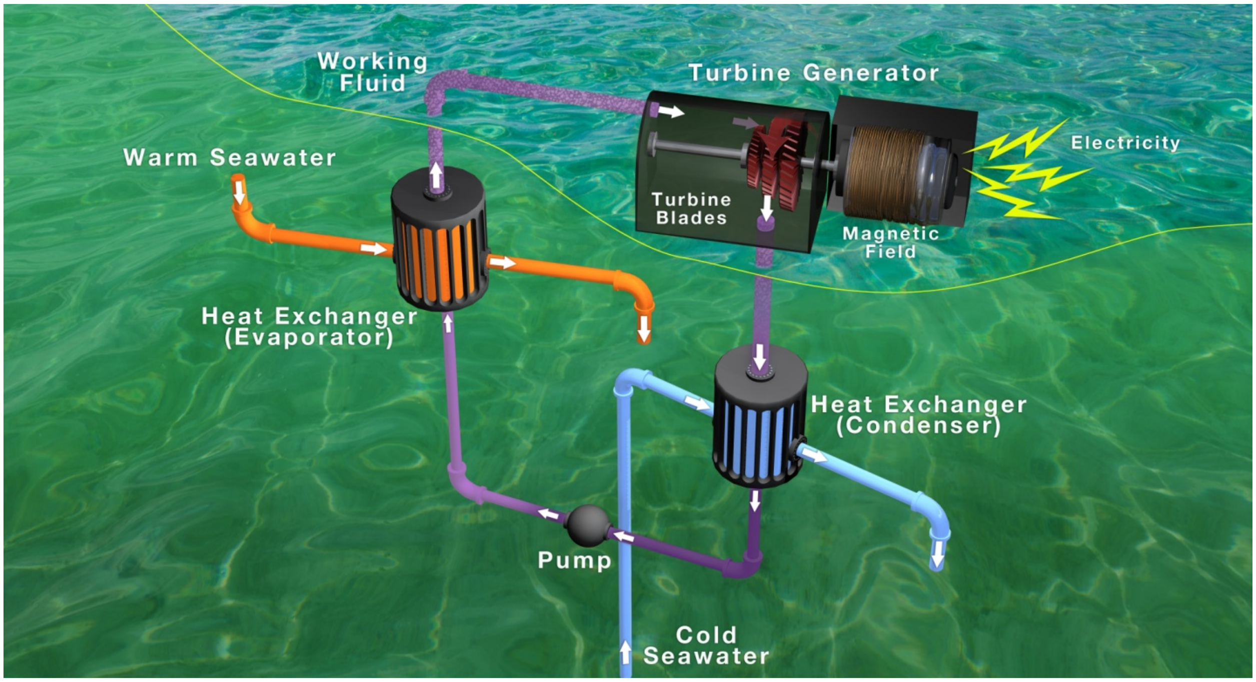

Figure 1: A CC-OTEC system diagram[1]

CC-OTEC power plants would need to have the capacity of at least 100 MW to be competitive with non-renewable power plants (Vega, 1992). This assessment assumes that the 100 MW plant be installed as a floating plant that supplies power to tropical island communities that rely heavily on expensive imported fuel. Since OTEC is capital intensive, the challenge with implementation of OTEC is more economic than technical.

The other primary type of OTEC scheme is an open-cycle (OC-OTEC) that uses a vacuum chamber to flash-evaporate surface seawater to drive the turbine-generator. Deep seawater is still required to condense the water vapor back to condensate, but a separate working fluid is no longer required in this type of system. Instead, a portion of the surface seawater is flash-

[1]Reproduced from Lockheed Martin Corporation. (n.d.). Ocean Thermal Energy Conversion. Retrieved September 27, 2013, from Lockheed Martin: http://www.lockheedmartin.com/us/products/otec.html

evaporated and the resulting steam drives the turbine. The OC-OTEC system has the benefit of producing fresh water as a byproduct that can be used for irrigation or other purposes; however, OC-OTEC systems are somewhat limited by the size of the vacuum chamber where the flash evaporation takes place. These systems have a practical maximum size of 1-10 MW with fresh water coproduction capacity of 1,700-35,000 cubic meters per day (m^3/day) (Vega, 1992). The smaller plant size requires a smaller CWP on the order of 3 m in diameter that can be deployed from the shore, allowing OC-OTEC plants to be installed on land.

Introduction to Desalination

Desalination is the process of converting salt water to fresh water that is suitable for human consumption or irrigation. The two primary methods of desalination are 1) phase change (thermal) desalination and 2) membrane desalination. Thermal desalination uses thermal energy to evaporate seawater and condense the resulting vapor into fresh water by processes such as Multistage Flash (MSF) distillation, Multiple Effect Distillation (MED), and Vapor Compression (VC) distillation. The typical non-thermal methods, Reverse Osmosis (RO) and Electrodialysis (ED), use membranes and pressure or electric fields as a method for separating the salt from seawater or brackish water. Desalination plants are sized based on the capacity of freshwater that is capable of being produced in a 24-hour day. Capacities are reported either in m^3/day or million gallons per day (MGD) where every one MGD is equivalent to a capacity of 3,785 m^3/day.

The 24th Worldwide Desalting Plant Inventory published by the Global Water Intelligence (GWI) and International Desalination Association (IDA) reported a total global capacity of 66.5 million m^3/day of fresh water produced at the 15,988 desalination plants in existence (Menon, 2011). The desalination industry has witnessed unprecedented growth as a result of the increasing global population driving higher demand for fresh water. According to the GWI/IDA, the global desalination industry experienced a 17% compound annual growth rate of new contracted capacity from 1990 to 2008. In 2000, thermal desalination was responsible for 75% of worldwide capacity; although at the time, more membrane desalination plants existed in the world (Economic and Social Commission for Western Asia, 2001). In 2008, membrane desalination plants overtook thermal desalination plants in total worldwide capacity in addition to totalnumber of worldwide installations (Bleninger & Jirka, 2010). Then again, thermal desalination plants are typically constructed with larger capacities than membrane desalination plants with some thermal plants having a capacityof 800,000 m^3/day or more.

Large-scale thermal desalination plants utilize either the MSF or MED process. The MSF process uses multiple stages of progressively lower pressures as the seawater boils at successively higher temperatures (see Figure 2). The feedwater is first heated with higher pressure to prohibit boiling until it reaches the first flash chamber where the pressure is released and sudden evaporation, called flashing, occurs. Only a portion of the feedwater is flashed in each successive stage, as the pressure is lowered. The water vapor rises past mist eliminator screens and condenses on the tubes in the upper section of the heat exchanger (Figure 2). Feedwater flowing through the tubes is at a lower temperature than the vapor that allows for condensation and collection of distillate product beneath the tubes. The distillate produced in each stage is sent to the next lower pressure stage until it exits the evaporator at the last stage where it is pumped to the post-treatment system (U.S. Bureau of Reclamation, 2003).

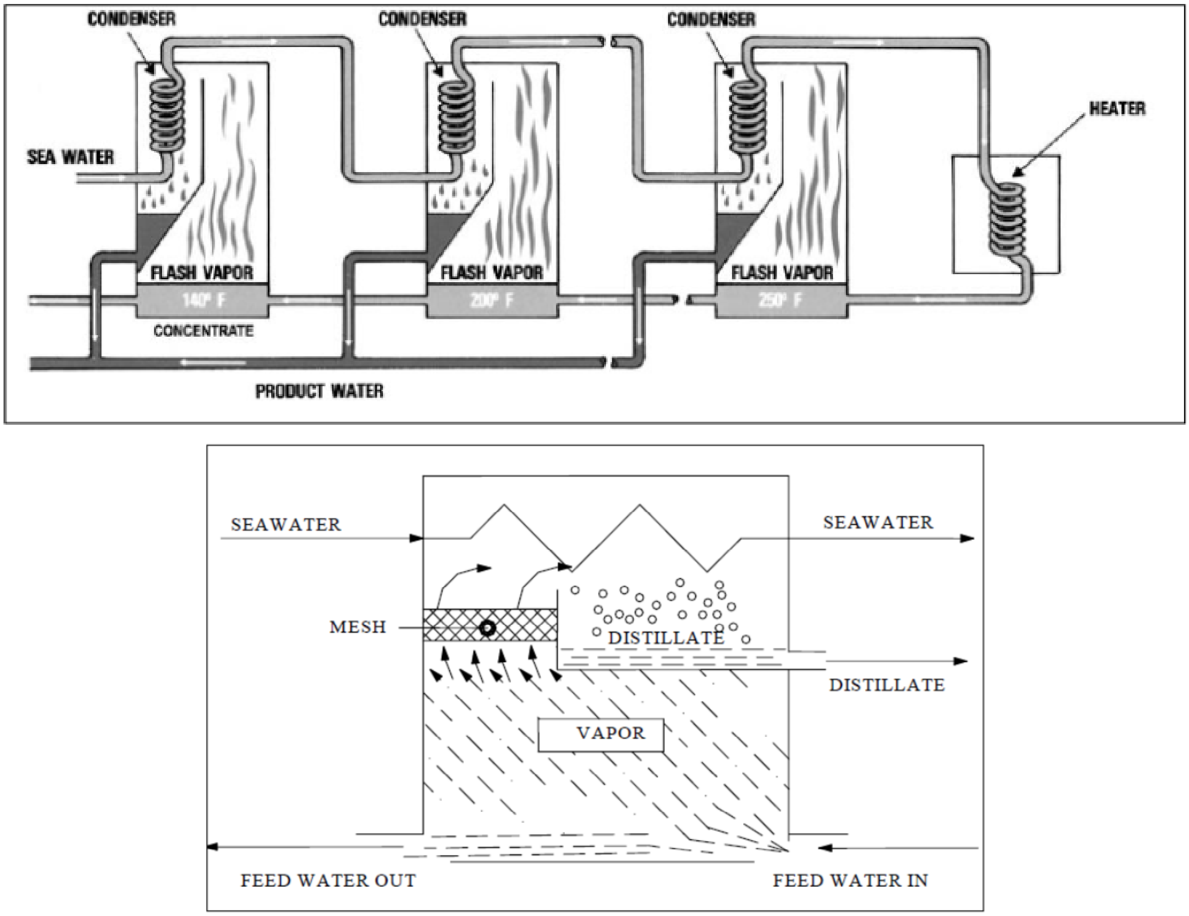

Figure 2: Diagram showing the MSF stages with successively less temperature and pressure (top) Diagram showing the feedwater condensing into distillate over a row of tubes (bottom)[2]

The MED process is very similar to the MSF process in that the feedwater is evaporated in multiple effects at progressively lower pressures. The MED process differs from MSF in the method of spraying the feedwater directly onto bundles of heating tubes to enable evaporation. A heat source, typically a steam supply, enters the first effect only to boil a portion of the water sprayed onto the tubes in the first effect. The water vapor is then transferred into the tube bundle of the next effect and condenses inside the tubes producing latent heat that assists with evaporation occurring on the outsides of the tubes in each successive stage (Figure 3). The process continues until the vapor in the last effect is condensed in a main condenser. The

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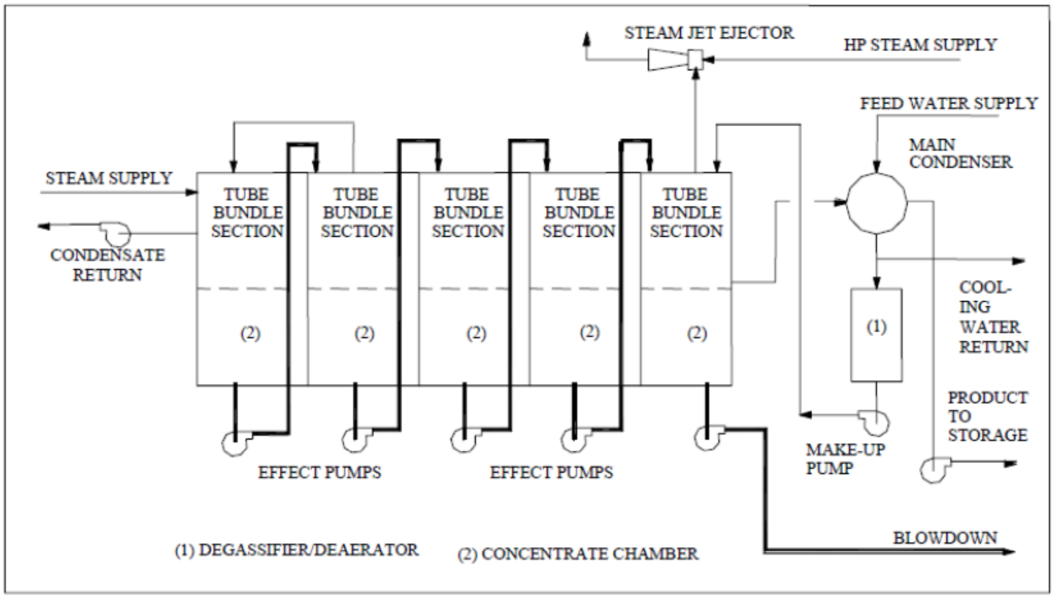
[2] Adapted from U. S. Bureau of Reclamation (2003). *Desalting Handbook for Planners*, 3rd edition. Retrieved September 4, 2011 from USBR.gov: http://www.usbr.gov/research/AWT/reportpdfs/report072.pdf

concentrated brine resulting in each effect can be transferred to the next effect or taken out at various points in the process. Distillate water product is collected as it condenses from each effect and is ultimately collected from the main condenser.



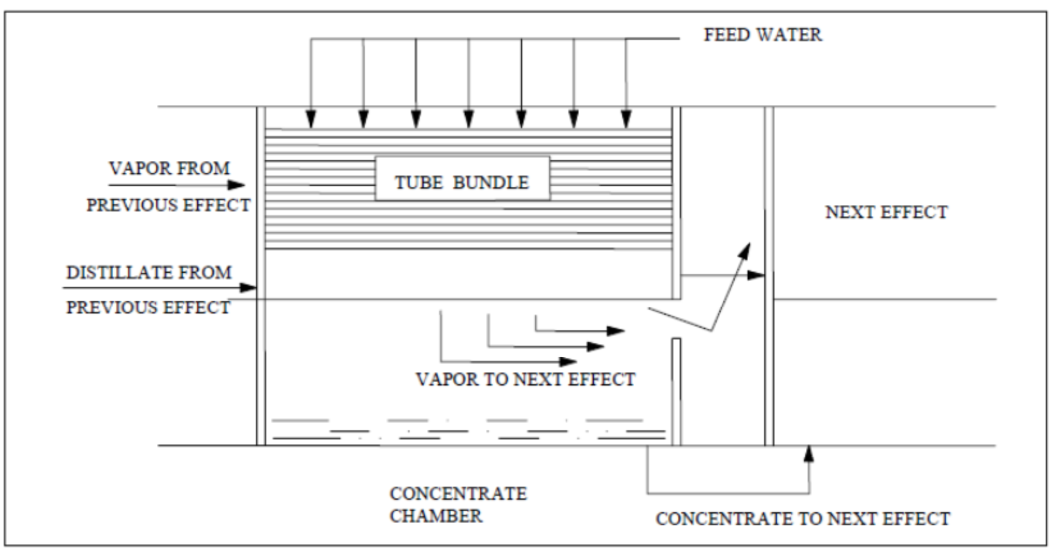


Figure 3: Diagram showing the successive stages of an MED with less temperature and less pressure (top) Diagram showing feedwater evaporating on the exterior of tubes of a first effect and condensing inside the tubes of the next effect (bottom)[3]

[3]Adapted from U. S. Bureau of Reclamation (2003). *Desalting Handbook for Planners*, 3rd edition. Retrieved September 4, 2011 from USBR.gov: http://www.usbr.gov/research/AWT/reportpdfs/report072.pdf

The most common MED configuration is the horizontal tube arrangement; however, vertical tube arrangements and vertically stacked tube bundle arrangements are also configurations that have been used. The horizontal tube arrangement is the most popular in the industry because it achieves good flow distribution across the entire tube bundle and it can be easier to construct large-scale horizontally orientated tube bundles versus vertically orientated tube bundles. MED plants can operate at a peak temperature of between 70-110°C depending on construction materials. The lower temperature of 70°C minimizes scaling effects and allows for the use of lower cost tube materials such as aluminum.

Lastly, RO is the leading membrane technology and most often can produce the lowest unit cost of water than any other desalination method. In the natural process known as osmosis, water has the tendency to pass through a semi permeable membrane from a solution with a low salt concentration into a solution with a high salt concentration. An osmotic pressure results from the difference in salt concentrations between the two solutions. When there is no net pressure of water through the membrane, the osmotic pressure is equal to the pressure head. When an external pressure greater than the osmotic pressure of the solution is applied to the concentrated solution, the osmosis is reversed and pure water passes through selectively permeable membrane leaving the salts in the concentrated solution. Spiral-wound elements are constructed from flat sheet membranes and spacers of various densities (Figure 4).

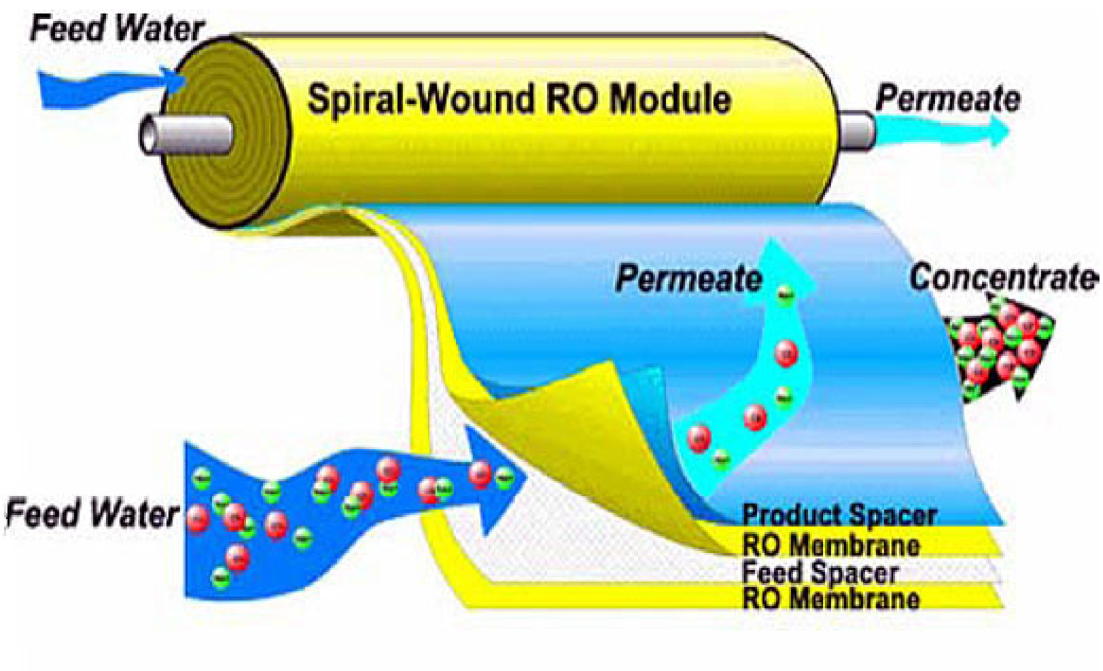


Figure 4: Diagram showing a spiral-wound RO module with typical process flow pressures[4]

The membrane and spacer elements form an envelope that is wrapped around a central collecting tube. An external pressure of 600-1200 pounds per square inch (psi) must be applied to the feedwater (for seawater feeds) to overcome the natural osmotic pressure of 390 psi. Because of the high pressure involved, the entire module is housed inside a thin fiberglass shell. Concentrated brine is discharged back to the sea or can be transferred to energy recovery devices to make use of its residual high pressure. Permeate is transferred to post processing and holding tanks for distribution. Since spiral-wound RO elements are susceptible to scaling and fouling from suspended solids and microorganisms, feedwater is typically pretreated with filtration devices and chemicals before entering the RO elements.

[4]Reproduced from Net Resources International (2012). *Perth Seawater Desalination Plant, Australia*. Retrieved October 4, 2013 from Water-Technology.net: http://www.water-technology.net/projects/perth/

OTEC Literature Review

SignificantOTEC literature started to become available in the late 1970s and early 1980s when oil prices were temporarily high, provoking investments in OTEC studies and demonstrations. In the modern OTEC era beginning in the late 2000s, new literature has become available as a result of restored domestic and foreign interest in renewable energy. Additionally, two key OTEC workshops where held in 2009 and 2010 by the National Oceanic and Atmospheric Administration (NOAA) and Coastal Response Research Center (CRRC). Workshop attendees included the many prominent OTEC researchers and developers that were assembled to assess both technical readiness and environmental impacts of OTEC in the modern era. The proceedings of these workshops will be discussed as well as contributions by other authors since the 1970s will be included in the review of OTEC economics and environmental impacts.

OTEC Economics

Hawaii's energy consumption will be considered first since it has historically been the top candidate for economical OTEC power plants in the United States (U.S.). The Hawaii Islands obtain approximately 90% of their energy from petroleum, 4.8% from coal, and the remainder from alternative and renewable energies (Figure 5).

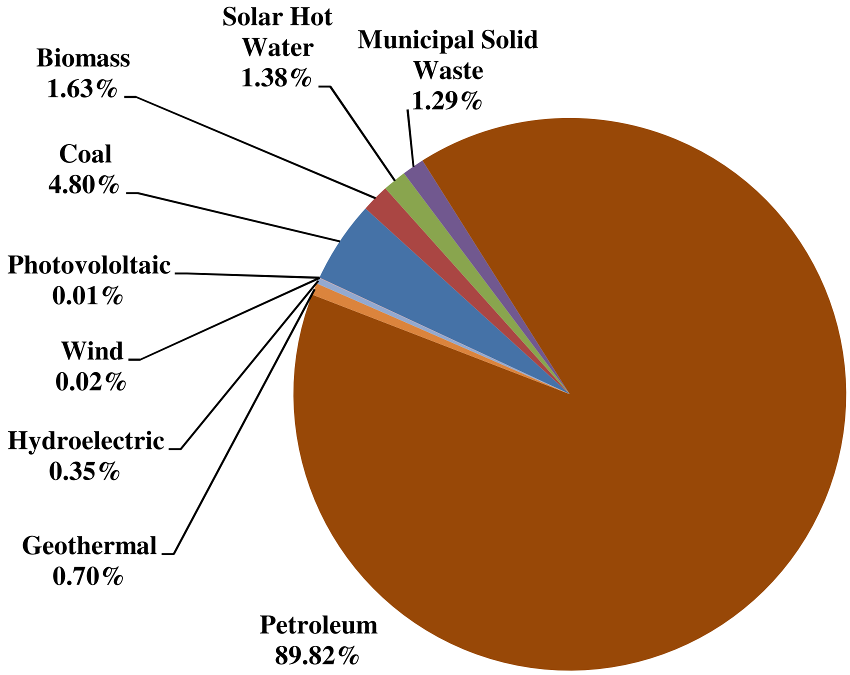


Figure 5: Diagram showing fossil fuels make up nearly 95% of Hawaii's energy supply[5]

The price of electricity depends heavily on the price of oil and the remoteness of the island where consumers are located. According to the Hawaiian Electric Company (HECO) homepage (www.heco.com), the average electricity rate paid by residents in 2011 is as follows: HECO electricity in Oahu had a rate of 32.04 cents per kilowatt hour (¢/kWh), Maui Electric Company (MECO) electricity in Maui had a rate of 35.77¢/kWh, Hawaii Electric Light Company (HELCO) in the Big Island had a rate of41.92¢/kWh, MECO electricity in Molokai had a rate of 43.02¢/kWh, and Maui Electric Company (MECO) electricity in Lanai had a rate of 44.05¢/kWh (average rates paid for 2012 will be available at an undisclosed date in 2013). It is understood that these prices represent electricity supplied primarily by fossil fuels and a small supplement of

[5]Reproduced from "The Potential of Renewable Energy to Reduce Dependence of the State of Hawaii on Oil" by Arent, Doug; Barnett, John; Mosey, Gail; Wise, Alison, 2009, Proceedings, 2009, 42nd Annual Hawaii International Conference on System Sciences.

renewable energy technologies. The renewable and nonrenewable costs cannot be accurately extrapolated from these electricity prices; however, representative renewable energy costs from other regions are detailed in Table 1.

Table 1: Representative renewable energy prices of various renewable energy technologies[6]

Renewable Energy	Cost of Electricity	Notes
Wind	5-8 ¢/kWh	On shore sitting, 1-3 MW, 60-100 m blade diameter
Solar	20-40 ¢/kWh	Low latitude locations, assuming solar insolation of 2,500 kWh/m^2/yr
Concentrated Solar Thermal	12-18 ¢/kWh	50-500 MW parabolic trough and 10-20 MW tower designs
Biomass	4.5-17 ¢/kWh	Technologies include a 25 MW fluidized bed, 25 MW stoker, 25 MW integrated gasification combined cycle, and 1 MW wastewater treatment plant
Municipal Solid Waste/Landfill Gas	3-12 ¢/kWh	12 MW system
Geothermal	4-7 ¢/kWh	1-100 MW binary, single and double flash natural stream systems
Hydroelectric	4-7 ¢/kWh	

[6]Adaptation from "The Potential of Renewable Energy to Reduce Dependence of the State of Hawaii on Oil" by Arent, Doug; Barnett, John; Mosey, Gail; Wise, Alison, 2009, Proceedings, 2009, 42nd Annual Hawaii International Conference on System Sciences.

Although the costs of the renewable energy technologies in Table 1 could be higher in Hawaii because of its remote location, the cost of electricity is still favorable given the current high prices paid for electricity in the Hawaiian Islands (Arent, Barnett, Mosey, & Wise, 2009).

Vega (2010), hereafter Vega, predicts the cost of electricity for various OTEC plant sizes are shown in Table 2. Vega produced two different scenarios for the cost of electricity under an 8%

15-year commercial loan versus a 4.2% 20-year government bond. It is clear that Vega's cost of electricity estimates for 50-100 MW OTEC plants are competitive with other forms of renewable energy for Hawaii; however, the underlying difference is that these OTEC costs are unproven while the other forms of renewable energy are based on actual installation costs. Although Vega's cost estimation uses a valid basis of estimation (i.e. budgetary quotes for equipment purchased in the U. S., Europe, or Japan including deployment and installation by a U. S. based company), many costs are unknown because no OTEC plants larger than 0.25 MW have ever been successfully implemented anywhere in the world. Currently, Vega (1999) holds the world record of producing net power of 103 kW from an OC-OTEC experiment performed at the Natural Energy Laboratory of Hawaii (NELHA) from 1993-1998. Even though 103 kW was a great achievement for the OTEC community, the true costs for a 5-10 MW commercially viable demonstrator plant are still unknown and difficult to predict by the systems engineering approach. Even with the best systems engineering estimation methods in the world, the predicted cost for large OTEC plants is just a rough order of magnitude with a high margin of error.

Table 2: Cost of electricity for various OTEC plant sizes under different financing scenarios[7]

Nominal Plant Size (MW)	Cost of Electricity {8%/15 year commercial loan}	Cost of Electricity {4.2%/20 year government bond}
1.35	94 ¢/kWh	75 ¢/kWh
5	50 ¢/kWh	40 ¢/kWh
10	44 ¢/kWh	35 ¢/kWh
53.5	19 ¢/kWh	15 ¢/kWh
100	18 ¢/kWh	14 ¢/kWh

[7]Adaptation from "Economics of Ocean Thermal Energy Conversion (OTEC): An Update" by Vega, Luis, 2010, Proceedings, 2010 Offshore Technology Conference.

OTEC plants are capital intensive because of the low theoretical efficiency of converting heat stored in warm seawater into mechanical work. The maximum net efficiency of an OTEC plant converting thermal energy to net electrical energy is approximately 2.5 and 3% (Avery & Wu, 1994). Because of the low efficiency, OTEC requires a large amount of heat exchanger surface area to make up for low efficiency. Heat exchangers have the greatest impact on performance and must be designed as large as possible to maximize thermal efficiency. Consequently, enormous volumes of seawater flowing through these heat exchangers rely on large process equipment including pumps and a CWP. Most economical OTEC schemes are situated on an offshore platform with turbine-generators installed topside and an undersea cable transmitting electricity back to the shore. An example of the capital cost breakdown for the major components in a conceptual 100 MW plant are shown in Table 3.

Table 3: Example of capital cost breakdown for major components of a conceptual 100 MW OTEC plant[8]

Component	Percentage of Total Capital Cost
Moored Platform	30%
Heat Exchangers	25%
CWP	20%
Other Components • Turbine-generators • Controls • Working fluid system • Seawater pumps • Onshore electricity facility • Mooring/Anchoring • Submarine power cable • Others	25%

[8]Adaptation from "Ocean Thermal Energy Conversion (OTEC): Technical Viability, Cost Projections, and Development Strategies" by Plocek, T. J., Laboy, & Martí, 2009, Proceedings, 2009 Offshore Technology Conference.

Capital costs for major OTEC components vary depending on the plant size and some of these costs are proportionally less expensive with larger plants. Vega presented an analytical model for assessing the economics of OTEC in his 1992 publication "Economics of OTEC". He also established specific economic scenarios that could make OTEC competitive with conventional power cost at the time. To gather appropriate cost estimates, Vega used technical specifications to solicit current budgetary quotes for various components. In 2010, he presented an update to his OTEC economics publication that updated his assessments to present-day costs using the U.S. 20-year average for equipment price index inflation. In his 1992 and 2010 papers, Vega held a conviction that OTEC plants of the 50-100 MW size could produce cost-effective electricity in tropical island states such as Hawaii; however, he cited that the lack of operational data made it difficult to convince the financial community to invest in OTEC plants.Thus, implementing a pre-commercial pilot plant of a 5-10 MW size is necessary to obtain the critical operational record. Since a pre-commercial plant is not expected to produce cost-effective electricity, Vega believes that the pilot plant should be government funded or financed.

The global market for OTEC is considered to include two distinct entities 1) industrialized nations and 2) small island developing states (SIDS) with modest needs for power and freshwater (Vega, 2010). The CC-OTEC offshore plants with capacities of 50-100 MW are geared more towards the industrialized nations that require large baseload power while the land-based OC-OTEC plants of the 1 MW to 10 MW size with fresh water production capacities of 1,700-35,000 m^3/day address the SIDS market. A summary of first-generation OTEC plant capital costs is reproduced in Table 4.

Table 4: First generation OTEC plant capital cost estimates by capacity in $2010[9]

Nominal Plant Size, (MWe-net)	Installed Capital Cost ($/kW)	Land/Floater	Source
1.4	41,562	L	Vega, 1992
5	22,812	L	Jim Wenzel, 1995
5.3	35,237	F	Vega et al, 1994
10	24,071	L	Vega, 1992
10	18,600	F	Vega, 2010
35	12,000	F	Vega, 2010
50	11,072	F	Vega, 1992
53.5	8,430	F	Vega, 2010
100	7,900	F	Vega, 2010

[9]Adaptation from "Economics of Ocean Thermal Energy Conversion (OTEC): An Update"by Vega, Luis, 2010, Proceedings, 2010 Offshore Technology Conference.

The 1.4 MW, 5 MW, 5.3 MW, 10 MW (Land), and 50 MW plant size costs were extrapolated by Vega from archival estimates, whereas the 10 MW (Floater), 35 MW, 53.5 MW, and 100 MW plant size costs were compiled using 2010 estimates. Vega reported that these costs included deployment as well as purchasing equipment from USA, Japanese, or European firms with installation by USA firms. Intuitively, later generation plants are expected to decrease in costs and become increasingly more cost competitive. When the data in Table 4are plotted, a power law curve is exhibited that can be used to estimate the capital cost in dollars per kilowatt ($/kW) as a function of plant size in MW (Figure 6).

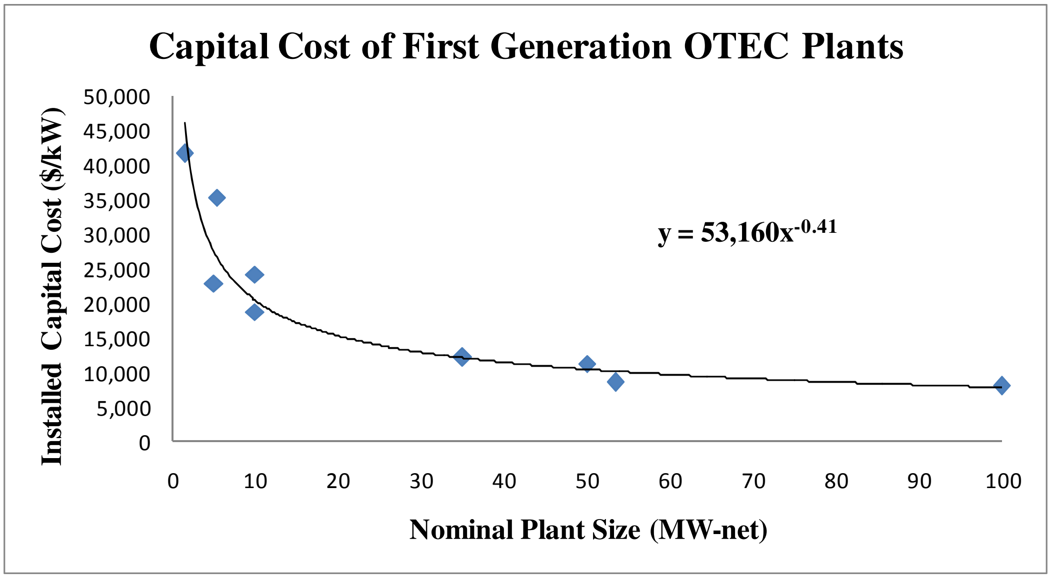


Figure 6: First generation OTEC plant capital cost estimates for increasing plant capacity[10]

It is important to note that Vega developed seven of these eight cost estimates. As shown in Table 4, only one of these eight cost estimates was presumably generated by an independent source, Wenzel (1995); therefore, the data is largely biased towards Vega's own experience with OTEC cost estimation methods. Since these costs only reflect the capital costs for the first generation of OTEC plants, Vega had previously presented cost scenarios for the 10th generation OTEC plants at the NOAA *Technical Readiness of OTEC* workshop. The 10th generation OTEC plants represent a great deal of technology maturity and a much-improved economy of scale (Figure 7).

[10]Reproduced from "Economics of Ocean Thermal Energy Conversion (OTEC): An Update" by Vega, Luis, 2010, Proceedings, 2010 Offshore Technology Conference.

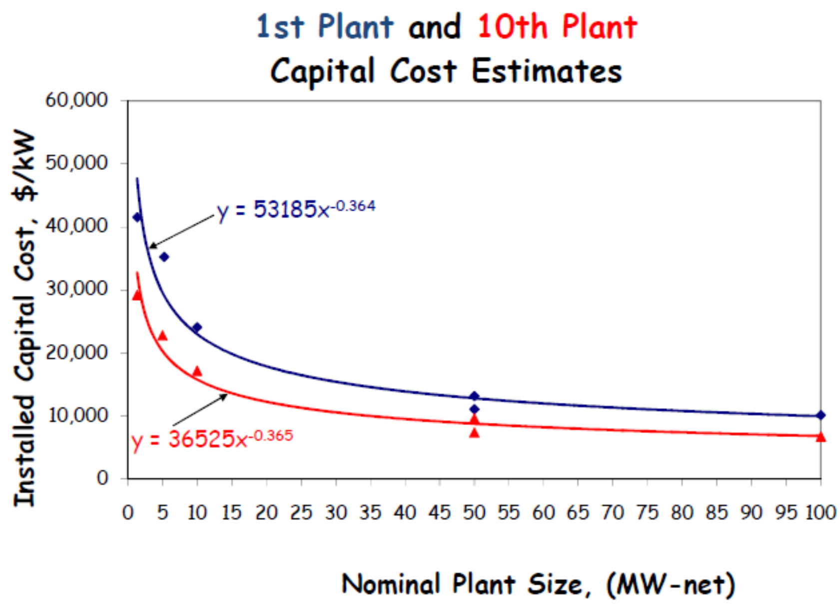


Figure 7: Vega's first and tenth generation OTEC plant capital cost estimates for increasing plant capacity[11]

The 10th generation capital costs are compared with that of the first generation capital costs and are presumed to be calculated in $2006 since other cost estimates in his presentation refer to 2006 dollars. Interpolating the coefficient from the first generation plant curve in Vega's economic update in Figure 6 above ($53,160), it can be assumed that the 10th generation cost coefficient will be approximately $36,549 (in $2010). Since the power-law exponent increased to a magnitude of 0.41 for the first generation plants in Figure 6, it is fair to assume that 10th generation plants will also retain the same exponent given the near identical curve exponents shown in Figure 7. It is important to note that the power law exponent is essentially the same value for the first generation plants and the 10th generation plants. Although initial outlay for capital costs are expected to decrease for the 10th generation plants, the scaling factor for increasing net power output is expected to remain the same.

[11] Adaptation from "Technical Readiness of Ocean Thermal Energy Conversion" by Coastal Response Research Center, University of New Hampshire, and NOAA, 2010. Reproduced by permission of the author.

A different economy of scale perspective reported by Van Ryzin J. (2010) demonstrated the cost in dollars per megawatt ($/MW) between a 10 MW and a 100 MW OTEC plant. Furthermore, the analysis reveals the relative cost factors for the major system components of the 10 MW and 100 MW plants (Figure 8). It is assumed that these cost assumptions are derived from the top-down systems engineering approach that typically includes component cost estimates from industry suppliers.

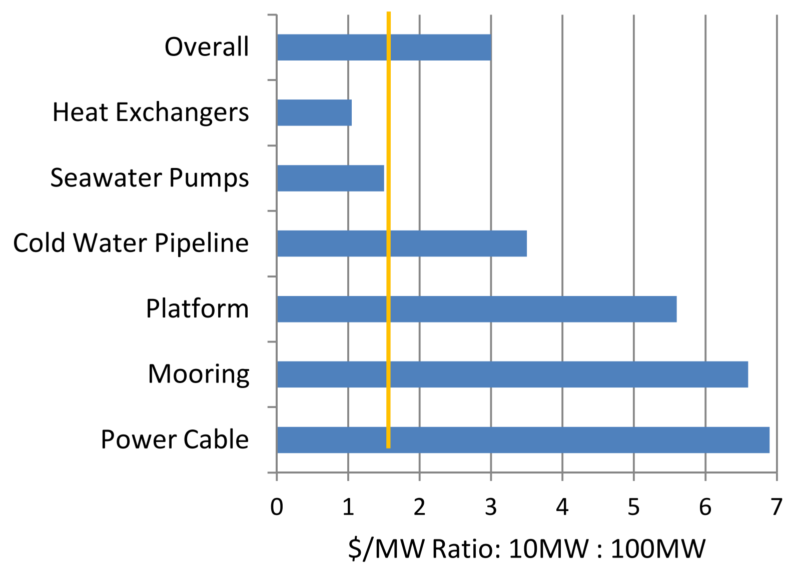


Figure 8: Chart showing OTEC economy of scale for 10 MW and 100 MW plants[12]

The chart in Figure 8 indicates that the cost of a 10 MW OTEC plant, on a $/MW basis, will be three times more than the cost of a 100 MW OTEC plant. This is somewhat consistent with Vega's estimates in Table 4 where the cost of an offshore 10 MW plant will cost 2.35 times more

[12]Reproduced from "OTEC Ongoing Engineering Effort in Hawaii" by Van Ryzin, Joseph, 2010, Proceedings, 2010. Asia Pacific Clean Energy Summit and Expo.

than the cost of an offshore 100 MW plant on a $/kW or $/MW basis. The interesting aspect of the economy of scale for OTEC is that the heat exchangers scale at an approximate one to one ratio indicating that the same investment per MW is required for heat exchangers whether the plant is 10 MW or 100 MW in capacity.

OTEC Heat Exchangers

Heat exchangers are the most critical item influencing OTEC economics because they are selected on a cost-performance tradeoff. Heat exchanger designs such as plate-frame, shell and tube, brazed aluminum fin, and others have all been considered as candidates for OTEC plants. Regardless of the design, the two most researched heat exchanger materials of construction have been titanium and aluminum. Titanium is the obvious choice with excellent corrosion resistance and proven service life of 30 years or more in seawater applications such as surface condensers for coastal power plants. Aluminum is less costly than titanium, but it does not have the high corrosion resistance in seawater or the longstanding service life record that titanium does. Both options have strongly been considered for OTEC heat exchangers and will be discussed in further detail.

Heat exchanger corrosion resistance over the lifetime of an OTEC plant is an enormously important factor for selecting either aluminum or titanium as construction materials. Heat exchanger construction materials must possess the physical and chemical characteristics for seawater corrosion resistance as well as a dependable service record to reduce the risk of premature heat exchanger failures. Titanium's excellent corrosion resistance is attributed to the formation of a very stable, continuous, highly adherent, and protective oxide film that forms spontaneously when surfaces are exposed to air and/or moisture (Donachie, 2000). Because of titanium's resistance to liquids containing chlorides, hypochlorides, sulfates, and sulfides it demonstrates excellent performance in seawater applications. Original equipment manufacturers (OEMs) such as Valtimet have reported a 40-year lifetime for grade 2 titanium seawater condenser tubes without one corrosion incident (Richaud-Minier & Gerad, 2009). Although titanium is relatively immune to most types of corrosion, the most susceptible form of corrosion is crevice corrosion resulting when the corroding media is virtually stagnant (Donachie, 2000). Since OTEC plants are designed to utilize continuously flowing seawater at an anticipated 85-90% operating factor, the risk of crevice corrosion is substantially reduced.

Aluminum has a higher electronegative potential than titanium and will oxidize easier; however, aluminum can be very stable in oxidizing media such as air and/or water because aluminum is a passive metal that is covered with a continuous and uniform natural oxide film will also form spontaneously in oxidizing media (Vargel, 2004). Aluminum is more susceptible to localized corrosion when this oxide film is ruptured because it is a passive metal whereas titanium is a reactive metal and is able to instantaneously regenerate its oxide film. A depleted oxide film can lead to pitting corrosion that will ultimately be the biggest risk for a long-lasting aluminum OTEC heat exchanger (Eldred, Van Rizyn, Rizea, Chen, Loudon, Nagurny, Maurer, Jansen, Plumb, Brown, & Eller, 2011). Vargel (2004) believes it is possible to determine the maximum pitting depth and expected corrosion resistance for heat exchangers comprising X thousand aluminum tubes at 10, 20, 30, and 40 years of service only if pitting tests are performed according to a rigorous measurement protocol using a representative environment. Eldred et al. (2011) reported that pits might be acceptable if they passivate, but this is difficult to determine using only post-removal analysis methods such as those proposed by Vargel. When pits stop growing, usually after a few days, the pits will re-passivate and will not be reinitiated again in that area. Measuring tubes or tube specimens after removal can interrupt and alter the re-passivation; therefore, in-situ measurement methods should be explored to determine pitting susceptibility and growth rates (Eldred, et al., 2011).

Furthermore, OTEC researchers have understood that deep seawater has a much different affect on aluminum corrosion than surface seawater. In the Pacific Ocean, the dissolved oxygen (DO), pH, and temperature all have lower values at 1000 m depth than at the surface. It was determined by (Dexter, 1977) that increased corrosion rates of 5000 series aluminum alloys was attributed to a combination of decreasing pH and temperature with depth rather than lower concentrations of DO. The low pH encourages initiation of pitting and crevice corrosion and the lower temperature has a tendency for initiation because it shifts the corrosion potential in the noble direction, but decreases the growth rate; a decreased DO concentration suppresses initiation and decreases the growth rate (Dexter, 1977). Thus, Dexter concluded that a decreasing DO concentration could not be responsible for an increased rate of corrosion in the depths of the Pacific Ocean. The role of DO was later confirmed by (Vargel, 2004) where he reports that long term tests in circuits such as seawater desalination demonstrated that the corrosion resistance of aluminum is the same in aerated seawater (with an approximate concentration of 8 ppm oxygen) or deaerated seawater (with an approximate concentration of 0.1 ppm oxygen) when all other parameters such as temperature, salinity, flow rate, etc. are kept at the same values.

Although titanium has a more favorable corrosion resistance than aluminum, its cost and availability can prohibit its use for OTEC. A dramatic increase in titanium metal prices between 2003 and 2006 was primarily triggered by the combination of supply shortage and skyrocketing orders for commercial and military aircraft from companies such as Boeing, Airbus, and Lockheed Martin (Seong, Younossi, Goldsmith, Lang, & Neumann, 2009). It is important to note that titanium is expensive because of its difficulty to refine, process, and fabricate; not because of its rarity. Titanium is actually the fourth-most abundant metal in the earth's crust and ninth-most abundant element; however, aluminum is the most abundant metal and third-most abundant element in the earth's crust. Aluminum is much easier to refine, process, and fabricate which is why its price is much lower when compared to titanium. When evaluating the cost of titanium and aluminum in heat exchangers, it is critical to evaluate the prices of the final mill product forms rather than the raw ingot or sponge prices.

OTEC investigators at the John Hopkins University Applied Physics Laboratory and The Trane Company have suggested it may be more cost-effective to use aluminum for heat exchangers with replacement at regularly scheduled intervals than to use titanium (Charlier & Justus, 1993). Similarly, Westinghouse Electric Corporation made the underlying assumption in their 1978 report *OTEC Power System Development: Phase 1: Preliminary Design, Final Report* that aluminum would not last as long as titanium and would have to be replaced at specific intervals over the 30-year lifetime of the plant. Many metallurgists debated the actual life expectancy of aluminum tubes at the time because very little data existed on aluminum in non-coastal seawater. The optimistic proponents of aluminum believed a life of 20 years or more was possible while the pessimistic proponents assumed aluminum bundles would last as little as two years and should be considered an annual expense instead of a depreciable asset (Westinghouse Electric Corporation, 1978). Although a wide range of opinions was expressed, a life of seven years was agreed upon as the most probable life (Table 5).

Table 5: Tube life in years for titanium versus aluminum as estimated by metallurgists in 1977[13]

	Titanium	Aluminum
Shortest Probable Life	20 years	2 years
Most Probable Life	30 years	7 years
Longest Probable Life	40 years	20 years

[13]Adaptation from "Ocean Thermal Energy Conversion Power System Development: Phase 1 Final Report"byWestinghouse Electric Corporation, 1978.

It should be noted that the tube life expectancies in Table 5 were assumed to be identical for the condensers and evaporators. Westinghouse (1978), hereafter Westinghouse, assumed no difference in corrosion performance whether the tubes were exposed to surface seawater or deep seawater. This may have been fair to assume in 1977 because of the stated lack of corrosion data on aluminum in seawater; however, current available data suggests that this assumption is no longer valid. As described earlier, the combination of lower pH and lower temperature of deep seawater can increase the pitting corrosion potential; therefore, the expected lifetime for aluminum tubes will be different when used in surface seawater versus deep seawater.

Nevertheless, the tube life expectancies were further expanded using randomly selected values from the split-Gaussian life distribution to calculate the probability of lifecycle costs for aluminum versus titanium (Figure 9).

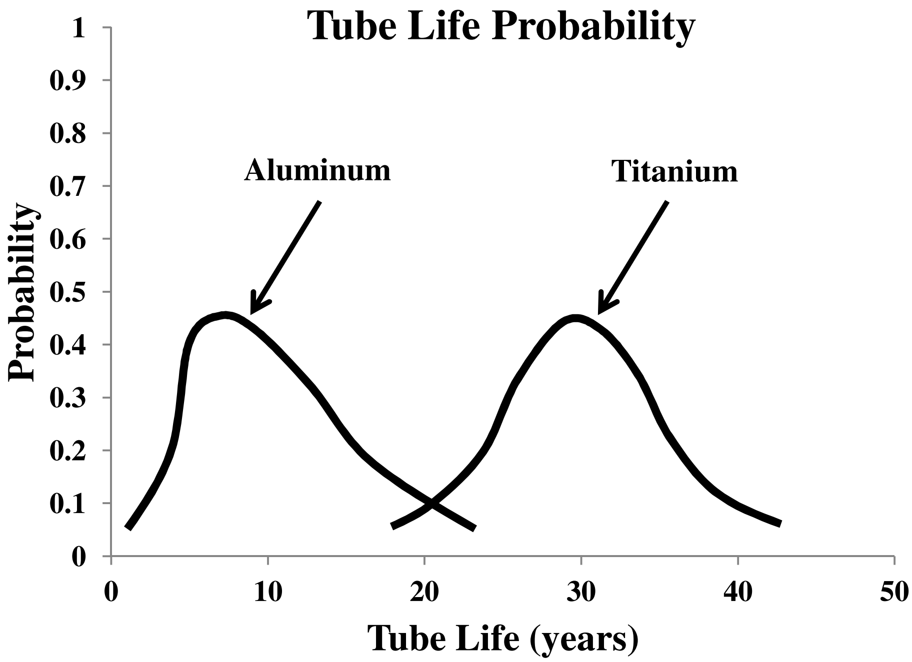


Figure 9: Probability distribution for aluminum and titanium tube life expectancies[14]

Westinghouse performed a discounted and undiscounted cash flow analysis on titanium versus aluminum tubing for OTEC heat exchangers to determine the total expected lifecycle costs. The unknown lifecycle of aluminum resulted in a poor lifecycle cost estimate when compared against the known 30-year lifecycle of titanium and the modest increase in cost of material. The break-even life for aluminum would occur if the aluminum tubes could last for 17 years, but this lifetime was unprecedented at the time of this report. To achieve better lifecycle costs for aluminum, Westinghouse stressed the importance of trying to find material substitutions to standard aluminum tubes that would improve cost scenarios. Westinghouse believed it would be reasonable to assume that when OTEC became a commercially viable option, advances in

[14]Reproduced from "Ocean Thermal Energy Conversion Power System Development: Phase 1 Final Report" by Westinghouse Electric Corporation, 1978.

research and development will have led to an aluminum solution capable of surviving in seawater for the 30-year life of a plant. They predicted future aluminum tube unit costs with the upper bound being the expected replacement with current technology, and the lower bound being an aluminum tube unit with tubing costs as simple strip costs with no corrosion allowance and negligible manufacturing costs for making the welded tubing from the aluminum strip (Figure 10).

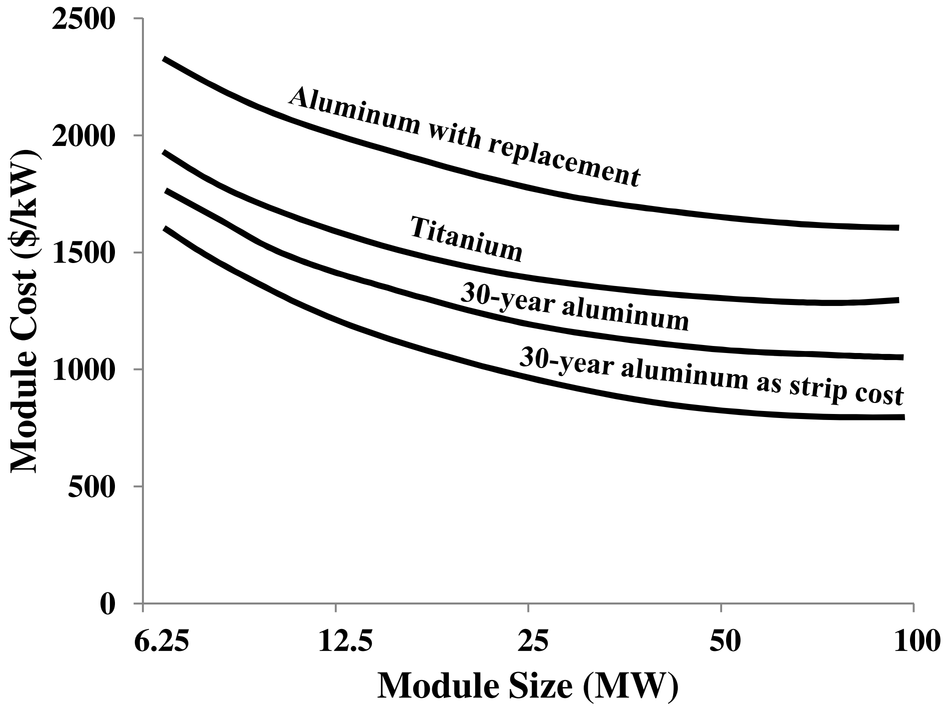


Figure 10: Predicted ultimate power module costs for aluminum and titanium tubing alternatives[15]

Westinghouse eventually selected titanium over aluminum as their baseline tube material based on the above economic reasons; however, material prices and heat exchanger design practice have drastically changed since 1977. Furthermore, data is available on aluminum lifecycles in

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[15]Reproduced from "Ocean Thermal Energy Conversion Power System Development: Phase 1 Final Report" by Westinghouse Electric Corporation, 1978.

non-coastal seawater that will change the lifecycle cost analysis. The cash flow analysis will also be updated using modern lifecycle data, material prices, and interest rates. This cash flow analysis will be presented in the discussion section of this paper.

Heat Exchanger Cost Estimation Methods

The cost of heat exchangers can vary greatly for the same application depending on design requirements, operating factors, fabricator, material prices, and other economic indicators. Large heat exchangers for an application like OTEC would certainly be custom-fabricated because of the size and specific end-use application. It would be insurmountable for fabricators and suppliers to carry an inventory of large Commercial Off-The-Shelf (COTS) heat exchangers that are suitable for specific applications like OTEC. The custom nature of fabrication and lack of standard pricing data makes it difficult to estimate the cost of heat exchangers; however, some heat exchanger cost estimation tools exist that provide reasonable or marginal accuracy.

One estimation tool that is available publically on the Internet is the McGraw Hill "Equipment Costs" cost estimating tool from *Plant Design and Economics for Chemical Engineers* (http://www.mhhe.com/engcs/chemical/peters/data/) that can be used to estimate costs for numerous types of equipment including shell and tube heat exchangers. The tool can calculate costs for fixed tube, floating head, and finned tube-floating head; all of which are all heat exchanger types of interest for OTEC. For the fixed tube and floating head heat exchangers, the tool assumes ¾" outside diameter (OD) tubes on a 1" square pitch and 16 foot (ft) or 20 ft length tube bundles. The option is given to select design pressures of 100 pounds per square inch absolute (psia), 150 psia, 300 psia, 450 psia, or 1000 psia, but it does not allow the user to select specific tube side and shell side pressures. Furthermore, only two shell material options are given (carbon steel and stainless steel) while a few additional options are available for the tube material in the floating head case (copper, nickel alloy, stainless steel, and titanium). The user has the option to size the heat exchanger by inputting a surface area in terms of square meters (m^2), but the maximum allowed size for any heat exchanger is 1,000 m^2 of surface area. Despite the limited design factors and material choices, the maximum size input is the biggest limitation of using this tool for OTEC heat exchanger cost estimation.

Another estimation tool publically available from Matches, a small licensed chemical engineering firm, provides cost correlations for over 270 individual pieces of equipment including heat exchangers at http://matche.com/EquipCost/Exchanger.htm. The firm describes the estimates as order of magnitude costs that should be used with caution because the actual costs will depend on many factors not accounted for by the tool. The costs are assumed to be in $2007 with free on board (FOB) origin being a gulf coast fabricator in the U. S. The tool allows the user to select shell and tube heat exchangers of either the fixed head or floating head type. The internal pressure rating can be chosen as full vacuum, 150 pounds per square inch gauge (psig), 300 psig, 450 psig, 600 psig, and 900 psig. The tool will only allow a maximum surface area of 6,000 square feet (ft^2) [557 m^2] for the fixed heat type and 10,000 ft^2 (929 m^2) for the floating head type, with no mention of tube sizes, pitch, or length. The usefulness for estimating the costs of OTEC-sized heat exchangers is again significantly limited. The one advantage of Matches' estimation tool over the McGraw Hill tool is the ability to select materials independently for the shell and the tubes; therefore, it allows the user to keep all other variables constant and determine the specific cost for selecting one material over another.

A comprehensive estimation method was developed by Purohit (1983), Purohit hereafter, in his article “Estimating the costs of shell-and-tube heat exchangers” that was originally published in the August 1983 edition of the *Chemical Engineering* journal. In his article, Purohit defined a shell and tube heat exchanger baseline constructed from a typical set of parameters that was priced using an evaluation of bids by U. S. manufacturers. He then developed a series of equations and tables that are used to correct and correlate costs for heat exchangers of virtually any design parameters and material selection. A flow chart for this calculation process is shown in Figure 11.

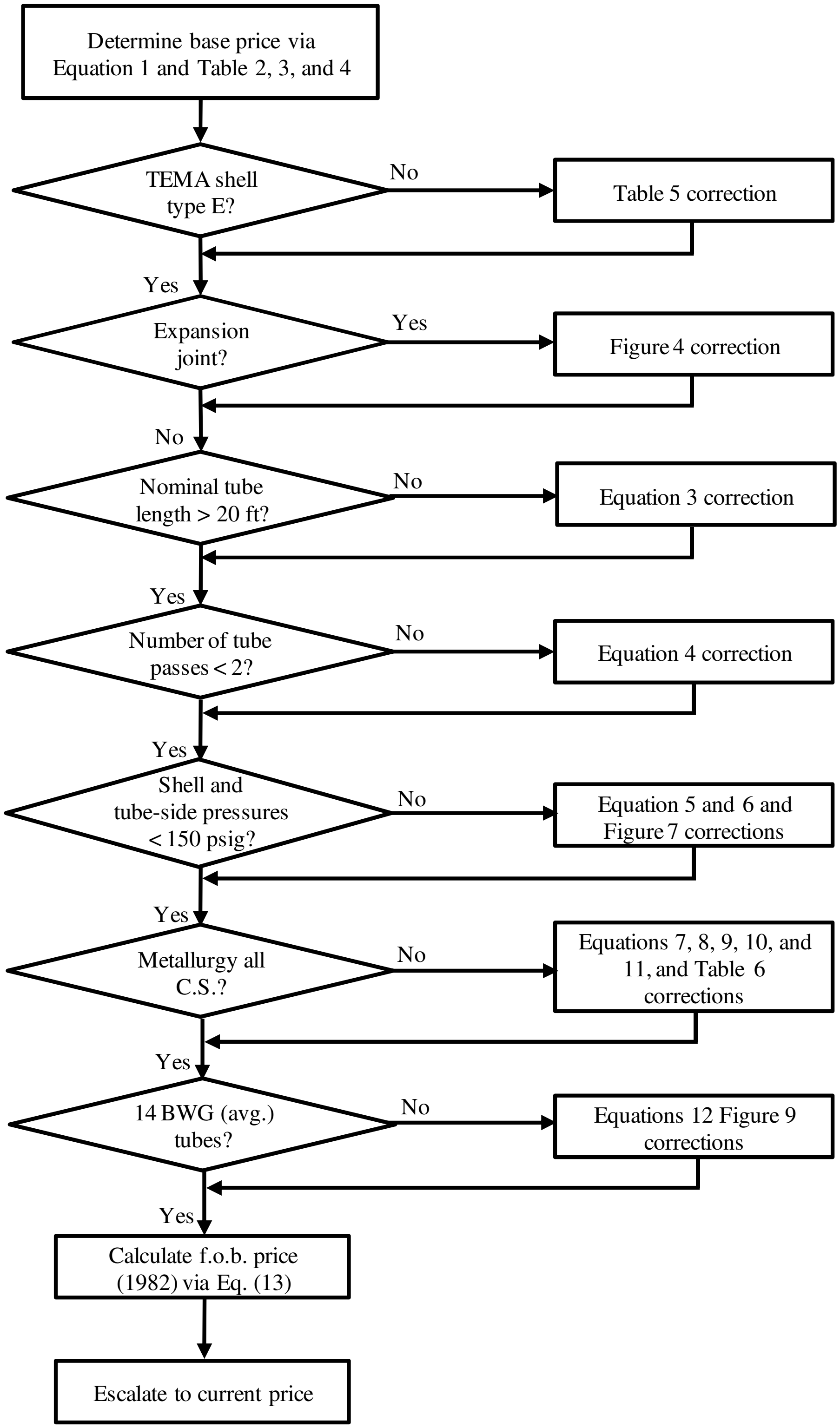


Figure 11: Flow chart of shell and tube heat exchanger cost estimation model[16]

[16]Reproduced from "Estimating costs of shell-and-tube heat exchangers" in *Chemical Engineering* by Purohit, G., 1983.

Many of the correction factors account for the basic mantra that larger heat exchangers are more economical on a dollars per square foot ($\$/ft^2$) basis than small diameter heat exchangers, and long, skinny heat exchangers are more cost effective than short, fat ones (Purohit, 1983). Furthermore, higher-pressure vessels cost more than lower-pressure vessels because flanges can be simpler, and expensive expansion joints are typically not required on low-pressure vessel shells with small temperature differences between exchanging fluids. Other cost factors consider the number of tube passes, tube size, and tube packing efficiency since they all influence the amount of heat transfer surface area available. The materials selection cost corrections factors have the largest impact on cost with respect to the baseline carbon steel material. Changes in material for the tubes, shell, channels, and tubesheets are all corrected using material price ratios.

The various material alternatives are assigned a cost ratio, M_1, for the tubing cost relative to carbon steel and a cost ratio, M_2, for the shell, channel, and tubesheet cost relative to carbon steel plate. Although no dollar values are given, the factors are based on material pricing from January, 1982. Tubing prices are heavily dependent on current economic conditions and factors such as order quantity, cut length, and whether the tubes are of welded or seamless construction. Purohit is the only heat exchanger estimation model discovered that accounts for the significant cost premium for selecting seamless tubing over welded tubing. He lists almost 80 different metal types including aluminum and titanium thatare of great interest for OTEC. The M_1 and M_2 cost ratios for aluminum and titanium relative to carbon steel are shown in Table 6.

Table 6: Price ratios for aluminum and titanium materials relative to carbon steel in $1982[17]

	M_1, Tubing Price Ratio Relative to Welded Carbon Steel Tubes		**M_2, Price Ratio for Shell, Channel, and TubesheetRelative to Carbon Steel**
Material	Welded	Seamless	
Carbon Steel	1.0 (base)	2.50	1.0 (base)
Aluminum	Not Standard	1.60	1.60
Titanium (grade 2)	11.00	22.00	11.00

17 Adaptation from "Estimating costs of shell-and-tube heat exchangers" in *Chemical Engineering* by Purohit, G., 1983.

The stated accuracy for the price ratios, M_1 and M_2 is expected to be within plus or minus (+/-) 20%, but the Purohit suggested that these ratios should be updated periodically to reflect current market prices. Moreover, the final cost of the shell and tube heat exchanger, using all the equations stated in the flow chart in Figure 6, must be updated to current prices using an escalation index such asthe *Chemical Engineering* plant cost index or the Marshall & Swift (M&S) equipment cost index. Correlating costs for longer periods results in more unreliable estimates (Towler & Sinnott, 2012). It is necessary to use these indexes with caution because of other economic and technological factors that could contribute to price fluctuations.

Because OTEC researchers are primarily interested in the cost of large diameter heat exchangers, it is critical to confirm that these equations can be applied to them. Although some of Purohit's supplied graphs have curves only extending to shell diameters of 60", he claims that the curves are valid beyond 60" in diameter. This claim is substantiated by a quick analysis of his database of 104 heat exchanger purchase prices where it is clear that his equations yielded very close estimations of the actual purchase prices of some very large diameter heat exchangers (Table 7).

Table 7: Three of the largest diameter heat exchangers estimated with reasonable accuracy[18]

Shell ID (in.) x Nominal Tube Length (in.)	Tube OD (in.) x Pitch (in.) x Layout Angle (degrees)	Design Pressures (psig) Shell/tube	Metallurgy Tube/Shell/ Channel or Bonnet/ Tubesheet	Purchase ($1982)	Estimated ($1982)	Accuracy (%)
122 X 432	$3/4 \times 15/16 \times 30$	100/140	Ti (Gr2)/CS→	1,300,000	1,489,000	14.5
128 X 336	$1\,1/2 \times 1\,57/64 \times 30$	100/100	All 1 Cr-½Mo	669,000	600,000	-10.3
148 X 360	$2 \times 2\,1/2 \times 30$	100/100	70-30 Cu-Ni/CS/70-30 Cu-Ni→	1,214,000	1,070,000	-11.9

18Adaptation from "Estimating costs of shell-and-tube heat exchangers" in *Chemical Engineering* by Purohit, G., 1983.

One of the most valuable aspects of Purohit's approach was that he derived estimates using this model and compared them against actual prices of 108 heat exchangers purchased during 1982. He published the design factors for all 108 heat exchangers that are used to generate an estimated cost on a $/ft^2 basis, and compared that against the actual purchase prices for all heat exchangers. Interestingly, the estimates of all individual heat exchangers fall within +/- 15%, and 60% fall within +/- 10% of actual purchase prices; furthermore, the total purchase price amount of all 108 heat exchangers was $10.615 million (M) and the total estimated price was $10.469M, giving an overall accuracy of -1.4% (Purohit, 1983). A newer list of heat exchanger purchases (purchased in the 2000s or later) would be greatly effective for reconfirming the accuracy of Purhoit's model; however, a publically available list of heat exchanger purchases is difficult to acquire. Because of the ultra-competitive nature of heat exchanger manufacturing in our current global economy, it is unlikely that suppliers or end users would willingly publish a detailed list of heat exchanger designs along with corresponding purchase prices. Consequently, the estimation method will have to be updated to current year's currency using an alternative method. This method will be discussed in detail in Chapter 3 of this report.

OTEC Environmental Impact

The magnitude and severity of the environmental impacts from OTEC plants have been debated since OTEC experimentation began decades ago. A statute of OTEC environmental regulation was created under the OTEC Act of 1980 whereby the NOAA Office of Ocean and Coastal Resource Management (OCRM) was declared the lead licensing agency for commercial OTEC facilities. Any attempt at deploying a commercial OTEC plant will require a license from the OCRM; however, under this act, the Secretary of Energy was given the authority to exempt *demonstration* plants from NOAA's licensing requirements. A demonstration plant is defined as a test platform that will not operate as an OTEC plant after conclusion of the testing period (NOAA, 1981). Although a demonstration plant is not required to obtain a full license, the Department of Energy (DoE) will likely require an Environmental Impact Statement (EIS) before issuing a permit for testing.

The *Final EIS for Commercial OTEC Licensing* issued by NOAA in 1981 identifies regulatory alternatives for mitigating adverse environmental impacts associated with construction, deployment, and operation of commercial OTEC plants (NOAA, 1981). The information presented was intended to help identify research needs required by the OTEC Act of 1980 and to develop a technical support document that provides guidance to NOAA regarding the environmental information submitted with an OTEC application by developers. The overall sentiment of the EIS is that environmental impact from commercial OTEC plants is expected to be minimal when compared to fossil fuel or nuclear power plants; however, many uncertainties associated with the withdrawal and redistribution of large volumes of ocean water need to be better understood. NOAA divided the marine environmental effects into two categories 1) Major:

those potentially causing significant environmental impacts 2) Minor: those causing insignificant environmental disturbances, and 3) Potential: those occurring only during accidents. A summary of these effects is shown in Table 8.

Table 8: Major, minor, and potential environmental effects from OTEC plants as defined by NOAA[19]

Major Effects	
Activity	**Effect**
Platform presence	Biota attraction
Withdrawal of surface and deep ocean waters	Organism entrainment and impingement
Discharge of waters	Nutrient redistribution resulting in increased productivity
Biocide release	Organism toxic response
Minor Effects	
Activity	**Effect**
Protective hull-coating release	Concentration of trace metals in organism tissues
Power cycle erosion and corrosion	Effect of trace constituent release
Implantation of CWP and transmission cable	Habitat destruction and turbidity during dredging
Low frequency sound production	Interference with marine life
Discharge of surfactants	Organism toxic response
Open-cycle plant operation	Alteration of oxygen and salt concentrations in downstream waters
Potential Effects from Accidents	
Activity	**Effect**
Potential working fluid release from spills and leaks	Organism toxic response
Potential oil releases	Organism toxic response

[19]Adaptation from "Final EIS for Commercial OTEC Licensing" by NOAA, 1981.

NOAA developed a set of mitigating measures for the major effects listed in Table 8. The corresponding mitigation measures, also published in the *Final EIS for Commercial OTEC Licensing,* are shown in Table 9.

Table 9: Mitigating measures for major issues for commercial OTEC plants[20]

Issue	Mitigating Measures (Ranked by Effectiveness)
Biota Attraction and Avoidance	• Site away from breeding and nursery grounds • Reduce lights and noise to minimum needed for safe operation • Reduce attraction surfaces
Organism Entrainment	• Site intakes away from ecologically sensitive areas • Site intake depths that will entrain the least number of organisms • Reduction in through-plant shear forces
Organism Impingement	• Use velocity caps to achieve horizontal flow fields • Use fish return system • Site intakes at depths that will impinge the least number of organisms • Reduce intake velocities
Biocide Release	• Discharge below photic zone • Use alternate methods of biofouling control • Rapid dilution through use of diffusers • Site specific biocide release schedule and concentration • Site discharges away from ecologically sensitive areas
Nutrient Redistribution	• Discharge into photic zone • Discharge below photic zone
Sea-Surface Temperature Alterations	• Discharge below the thermocline

[20]Adaptation from "Final EIS for Commercial OTEC Licensing" by NOAA, 1981.

Since the platform is an essential variable of offshore commercial OTEC, some level of biota attraction is unavoidable; however, many impacts resulting from the physical presence of the platform should be very similar to those observed near offshore oil rigs (Coastal Response Research Center, 2010). Biocide release is another major issue detailed in Table 8 that garners attention from environmentalists because of the inherent toxicity to organisms in the receiving waters. The major biocides for offshore OTEC plants that can cause toxicity to organisms in the receiving waters are chemicals for biofouling resistance and working fluids for turbine operations. Trace metal from heat exchangers, although not a biocide can cause adverse toxicity effects on organisms. The toxicity effects of these constituents will be discussed in further detail below.

Although working fluid releases and accidental spills are considered minor environmental effects in Table 8, it is worth reviewing the selection criteria and potential impacts of OTEC's candidate working fluid, ammonia. Ammonia is a popular choice as a working fluid because it has four-to-six times greater heat transfer characteristics compared to halocarbon refrigerants (Stoecker, 1998). Additionally, the threat of ozone depletion and global warming has made ammonia more attractive than fluorocarbon alternatives, especially since the U. S. Environmental Protection Agency (EPA) has been leading the phase-out of chlorofluorocarbons (CFCs) and hydro chlorofluorocarbons (HCFCs) through Clean Air Act Regulations. Although ammonia is much more environmentally safe, its toxicity has been a disadvantage that has impeded its wider use as a working fluid (Khan, Khan, Chyu, Ayub, & Chatta, 2009).

Normal leaking of ammonia is expected to be approximately 2.4 micrograms per liter (μg/L), but upon reaction with seawater only 5% would remain as unionized ammonia resulting in an unionized ammonia concentration of 0.66 μg/L. This concentration is 0.12 μg/L greater than the ambient concentration of unionized ammonia, but much less than the EPA minimum risk level of 10 μg/L. Although normal ammonia leakage has a minimal risk to the environment, it will pose the greatest threat to the environment in the event of an accidental spill. The total volume of ammonia required for a 10 MW plant ranges between 50 cubic meters (m^3) and 250 m^3;

however, the total volume of ammonia for a 100 MW plant can be as large as 2,500 m^3. These types of ammonia volumes have potential for inhibiting photosynthesis in unspecified marine phytoplankton if the concentration of ammonia reaches 55 milligrams per liter (mg/L) to 71.1 mg/L (NOAA, 1981).

Biofouling is a great concern for heat exchanger performance since seawater flows through its channels to create a heat source and heat sink necessary for evaporating and condensing the working fluid, respectively. Biofoulingis described as the undesired deposition of cells and the subsequent formation of a cell layer or biofilm. Biofouling can be classified by its two main subgroups: macro-fouling and micro-fouling. Macro-fouling is known as the macro-organisms (such as clams, barnacles, cockies, and mussels) that while in their early life stages can pass through water intake strainers and begin to grow on heat exchanger surfaces. Micro-fouling is known as the micro-organisms (such as algae, fungi, and bacteria) produce a slime that adheres to heat exchanger surfaces, Micro-organism adherence to heat exchangers adds to the thermal resistance and pressure drop and also entrap silt or other suspended solids, giving rise to deposit differential corrosion. OTEC researchers have long known about the threat of biofouling on the overall performance OTEC plants. In a 1977 issue of the *OTEC Liaison* [Volume 1 Number 3] (a monthly newsletter that was initiated to grow a community of OTEC researchers and developers) went as far as suggesting that biofouling could be “OTEC’s Public Enemy Number One”.

The biocide cleaning method of chlorination will be discussed first since it widely practiced for treating biologically fouled seawater and is a leading biofouling control solution for OTEC heat exchangers. Chlorination is described as the application of chlorine compounds to water or wastewater, generally for the purpose of disinfection. Manual addition of chlorine to water can require bulk storage of chlorine gas that can take up excessive space and also present significant safety hazards. The more practical solution for supplying chlorine could potentially betheelectrochlorination process that uses an electrolytic generator to produce an in situ solution of sodium hypochlorite. The process utilizes the following reaction: NaOCl (sodium hypochlorite) + H_20 (water) → HOCl (hypochlorous acid) + NaOH (sodium hydroxide). The electrolyte flow is forced between anode and cathode surfaces and electrodes pass current through the seawater where part of the salt is converted to sodium hypochlorite. Siemens Water Technologies produces a commercial electro-chlorination system called Chloropac® that can produce up to 500 kilograms per hour (kg/hr) equivalent chlorine per generator for marine systems such as power plants, desalination plants, oil and gas offshore platforms, and naval vessels (Siemens, 2009).

The Mini-OTEC experiment of 1978 was a foundation for operational data because it logged four months of operating data including the use of continuous chlorination at a rate of 0.1 mg/L that was effective in preventing biofouling in the evaporators and condensers (Cohen, 1982). Following the OTEC-1 experiment of 1981, Cohen (1982) reported that chlorination testing conducted over the course of several months included injecting the evaporators and condensers with a chlorine dosage of 0.4 mg/L for one hour per day according to (Castellano, 1981). It was later reported by (Avery & Wu, 1994) that the OTEC-1 chlorination dosage was 0.06 mg/L for one hour per day according to (Gavin &Kuzay, 1981). Since chlorination studies were conducted for several months during the OTEC-1 experiment, it will be assumed that a range of chlorination dosages were tested and both dosages were used during testing. Following the

OTEC-1 experiment, a variety of heat exchanger biofouling control studies were conducted at the present-day NELHA by various researchers from 1983 through 2011. A summary of OTEC chlorination studies is summarized in Table 10.

Table 10: Chlorination dosages reported to control heat exchanger biofouling in various OTEC experiments

Chlorination dosage (mg/L) reported to effectively control biofouling	**Test Location**	**Source**
0.1 (continuous)	Offshore Hawaii: Mini-OTEC	Cohen, 1982
0.06 (1 hr/day)	Offshore Hawaii: OTEC-1	Avery & Chu, 1994 (Castellano, 1981)
0.4 (1 hr/day)	Offshore Hawaii: OTEC-1	Cohen, 1982 (Gavin &Kuzay, 1981)
0.05-0.07 (1 hr/day)	Onshore Hawaii: NELHA	Avery & Chu, 1994 (Larsen-Basse, 1983)
0.1 (1 hr/day)	Onshore Hawaii: NELHA	Berger and Berger, 1986
0.07-0.10 (1 hr/day)	Onshore Hawaii: NELHA	Panchal et. al 1990
0.07 (continuous)	Onshore Hawaii: NELHA	Eldred et al, 2011

Although Cohen reported that chlorine was applied to both the evaporators and condensers in Mini-OTEC and OTEC-1, later researchers demonstrated that chlorination would be required only in the warm water evaporators and not the cold water condensers. Chlorine injections at a concentration of 0.07-0.1mg/L for one hour a day were adequate in prohibiting biofouling in the warm seawater specimens while no chlorination was required for the cold seawater specimens (Panchal, Stevens, Genens, Thomas, Clark, Sasscer, Yaggee, Darby, Larsen-Basse, Liebert, Berger, Bhargava, & Lee, 1990). These studies also determined that aluminum alloy heat exchanger test samples required about a 30% higher level of chlorination than stainless steel and titanium to achieve a comparable value of biofouling resistance. No significant difference in the rate of biofouling for the aforementioned metals is expected in tropical seawater on a long-term basis (Panchal, et al., 1990).

Trace constituent releases are expected in the OTEC discharge because of normal corrosion and erosion of major components such as the heat exchangers and metallic piping. Heat exchangers represent the largest source for trace metal release because of the enormous amount of surface area in contact with seawater. Aluminum and titanium both have low toxicity to humans from oral ingestion and also have low bioaccumulation tendencies in marine fish muscle and shellfish or crustaceans (NOAA, 1981).

The expected 30-year trace metal loss for aluminum heat exchangers resulting from uniform corrosion range from 56 micrometers (μm) to 84 μm for warm water exposure and 108-198μmfor cold water exposure (Panchal, et al., 1990). Panchal later noted that this amount is substantially less than the acceptable level of 380 μm for 15-plus year heat exchanger service life; although, it was also concluded that if good practices are employed, these aluminum alloys can be considered for a potential heat exchanger life expectancy of 30 years with acceptable wall-thickness loss as shown in Figure 12.

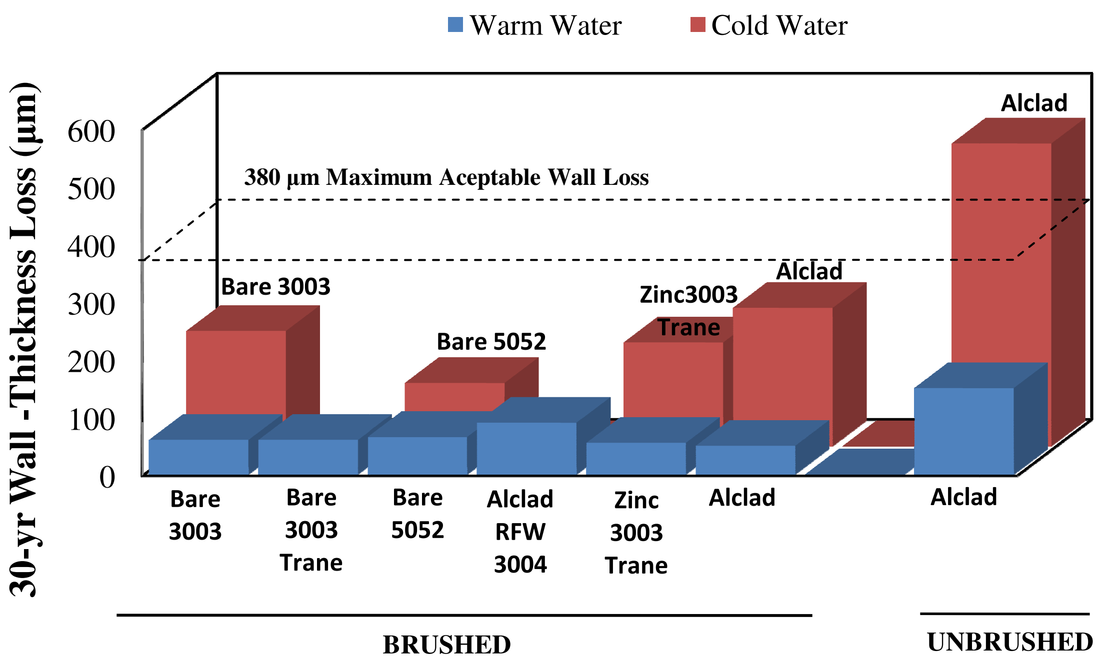


Figure 12: Wall-thickness losses for candidate OTEC heat exchanger aluminum alloys[21]

The last major issues detailed in Table 8 are organism entrainment, organism impingement, nutrient redistribution, and sea-surface temperature alterations, all of which are strongly influenced by the intake and discharge design of an OTEC plant. The warm seawater and cold seawater intake design and location will have significant impact on the organism entrainment and impingement while the discharge plume will include biocide release, nutrient redistribution, sea-surface alterations, and trace metal release (Figure 13).

[21]Reproduced from "OTEC Biofouling and Corrosion Study at the Natural Energy Laboratory of Hawaii 1983-1987" by Panchal, C. ; Stevens, H. ; Genens, L. ; Thomas, A. ; Clark, C. ; Sasscer, D. ; Yaggee, J. ; Darby, J. ; Larsen-Basse, J. ; Liebert, B. ; Berger, L. ; Bhargava, A. ; Lee, B., 1990.

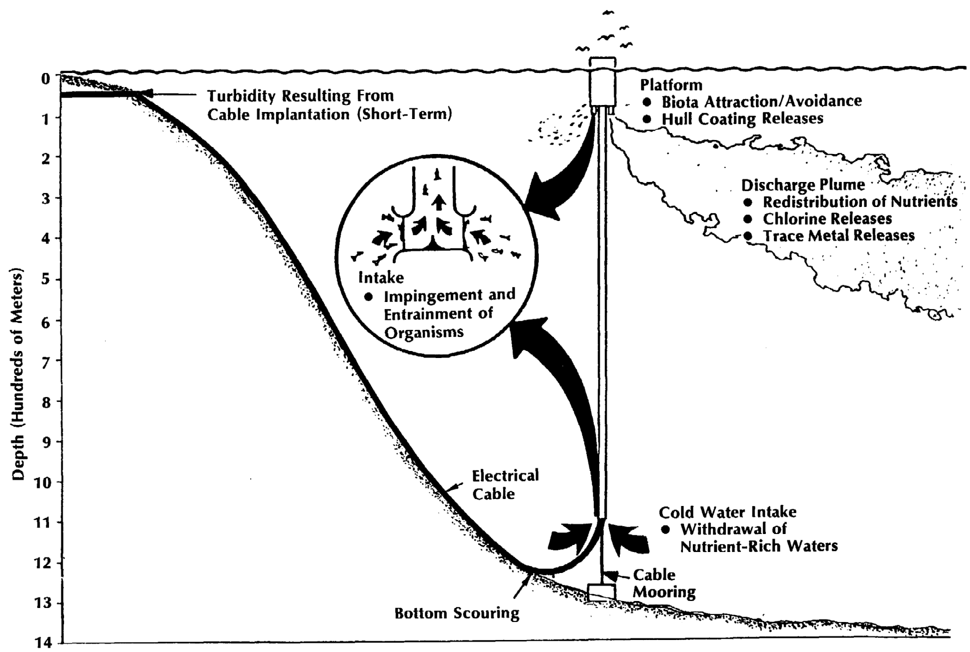
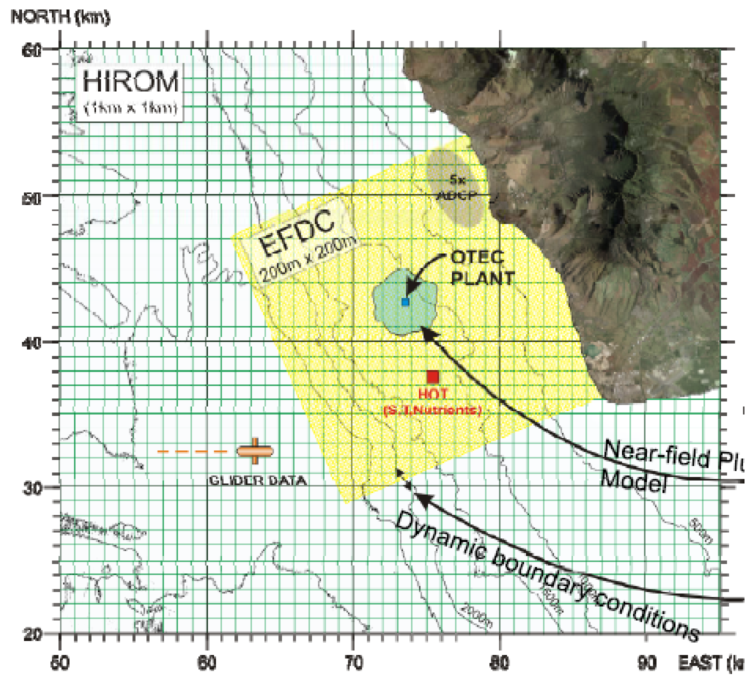


Figure 13: Diagram showing major and minor environmental effects of OTEC operations[22]

In recent years, more modern hydrodynamic modeling techniques have been utilized to define the intake and discharge effects shown in Figure 13. Namely, OTEC plume modeling developed by Pat Grandelli and Greg Rocheleau of Makai Ocean Engineering. Their near-field OTEC plume model was coupled with an Environmental Fluid Dynamics Code (EFDC) domain and nested within the University of Hawaii Regional Ocean Model (HiROM). The EFDC is an EPA-certified three-dimensional, time-dependent model with a coupled lagrangian plume model for thermal discharges that has been used in numerous studies involving coastal and estuarine systems. The HiROM model is nested within the Regional Ocean Model System (ROMS) that provides nowcasts and hindcasts from the state of Hawaii (Coastal Response Research Center, 2010) (Figure 14).

[22] Adaptation from "Final EIS for Commercial OTEC Licensing" by NOAA, 1981. Retrieved October 4, 2013 from NOAA.gov: http://coastalmanagement.noaa.gov/otec/docs/otec_feis1981.pdf



Makai Ocean Engineering, Inc. Otec Plume

Figure 14: Hydrodynamic model with OTEC plant located within a near-field EFDC grid nested within a far-field HiROM grid[23]

In a previous study prepared for the 2010 NOAA Environmental Workshop, Grandelli and Rocheleau determined that discharging OTEC flows downward at depths below 70 m would allow for adequate dilution and small enough nutrient enrichment that 100 MW OTEC plants can be operated in sustainable manner. They defined sustainability as an intake/discharge design that has no thermal resource degradation and no adverse nutrient redistribution. Because of higher nitrate and nitrite levels in deep seawater, one of their major concerns was that OTEC discharges would promote a biological response and an increase in primary productivity of certain species (Grandelli & Rocheleau, 2011). Their OTEC plume model assumed a surface seawater intake at 20 min depth having a temperature of 25.7°C, a density of 1023.39 kilograms per cubic meter (kg/m^3), and a flow rate of 420 m^3/s while their deep seawater intake at a depth of 1,000 mhaving

[23]Adaptation from "OTEC: Assessing Potential Physical, Chemical, and Biological Impacts and Risks" by Coastal Response Research Center, University of New Hampshire, and NOAA, 2010. Reproduced by permission of the author.

a temperature of 4.1°C, a density of 1027.36 kg/m^3, and a flow rate of 320 m^3/s. The combined warm and cold seawater discharge plume with a total flow of 720 m^3/s will lose vertical momentum and exhibit some weak upward velocity as it entrains almost 9,000 m^3/s of the ambient receiving waters (Figure 15).

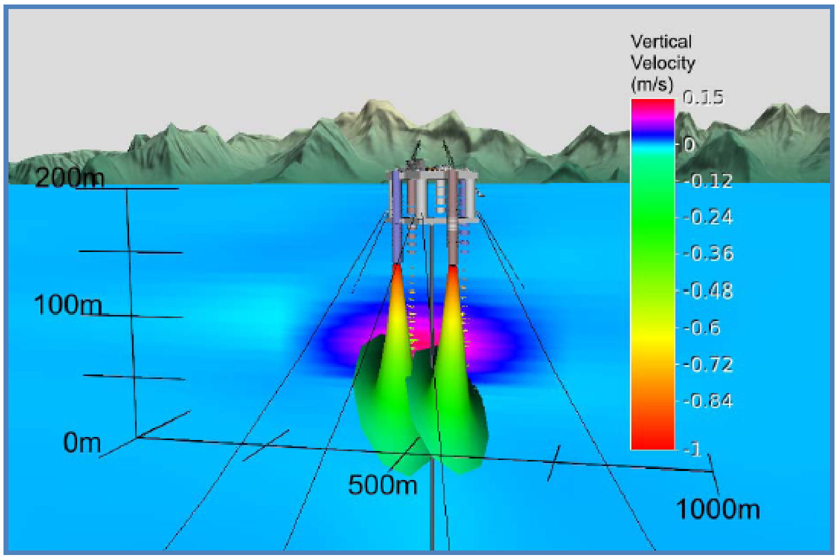


Figure 15: Map showing OTEC discharge plume with strong downward velocity and some weak upward velocity[24]

The authors determined that strong current flows increased entrainment and dilution in near-field plumes resulting in shallower equilibrium depths, but less concentrated plumes. Stratification and background temperatures were stated to have a secondary effect when compared to current forces. The far-field plume advection and dilution was also dominated by background currents, and when analyzed in a cluster of three 100 MW OTEC plants spaced 1.3 kilometers (km) apart, the plumes did have interaction in the far-field, but did not create a discernible increase in nitrate concentration (Grandelli & Rocheleau, 2011). The authors found it unlikely that a discharge at a

[24]Adaptation from Physical and biological modeling of a 100 megawatt ocean thermal energy conversion discharge plume by Grandelli, P. ; Rocheleau, G. J., Proceedings, Oceans 2011.

70-100 m depth and 1 meter per second (m/s) velocity would stimulate phytoplankton blooms because of the rapid dilution that limits the horizontal extent of nutrient redistribution in addition to the lack of light at the far-field plume depth.

OTEC-Desalination

The first production of potable water by OTEC was achieved by a team of researchers from Argonne National Laboratory (ANL) and Solar Energy Research Institute (SERI) who produced 5.8 gallons per minute (GPM) of fresh water at NELHA in 1987 (Thomas A. H., 1988). In addition to the 103 kW of net power produced during the 1993-1998 OC-OTEC experiment at NELHA, desalinated water was also produced at a rate of 0.41 liter per second (l/s) or 6.5 GPM (Vega, 2003). In 2007, researchers at India's National Institute of Ocean Technology (NIOT) commissioned a 1 million liter per day (MLD) barge mounted desalination plant off the coast of Chennai that utilized the Low Temperature Thermal Desalination (LTTD) process to flash evaporate warm seawater in a vacuum chamber and liquefy the vapor in a condenser to produce fresh water. The LTTD process uses the same principles as OC-OTEC, but produces only fresh water and no net power. Nevertheless, NIOT was the first to use the ocean's thermal gradient to produce desalinated water offshore and transmit back to shore through the use of geo bags (Everest Transmission, 2007). As of 2013, a *de facto* offshore OTEC plant has still never produced desalinated water.

It was previously discussed that OC-OTEC uses a large flash chamber to evaporate seawater and later condense with cold seawater. The single chamber is inherently less efficient than multi-stage flash chambers, but the overall cost is seen as potentially competitive because the distillate product is produced using only a small portion of the electricity generated by the OTEC process. Researchers developing OC-OTEC desalination water production designs stated that product water would cost \$1.21/m^3 assuming a 30-year payback period at an inflation rate of 5% and a discount rate of 9.5% (Syed, Nihous, & Vega, 1991). The authors noted that their design at the time was 15% more cost-effective than an equivalent RO plant that could produce product water at a cost of \$1.40/m^3 in 1991.With modern RO plants such as the recently-opened Tampa Bay RO facility producing desalinated water for as low as \$0.50/m^3, the case for OC-OTEC desalinated water has certainly become more challenging.

Fortunately, OTEC researchers have suggested the possibility of coupling RO with CC-OTEC systems given the sharp decrease in the cost of RO witnessed in the past decade. The CC-OTEC process can have a second stage of MSF, RO, or a combination of both (see Figure 16 below). If the OTEC plant is located offshore, the real estate available for desalination equipment comes at a much higher premium than onshore. Most commercial CC-OTEC schemes are thought to be most cost effective in an offshore scheme; therefore, the options for offshore desalination methods will be discussed later in further detail.

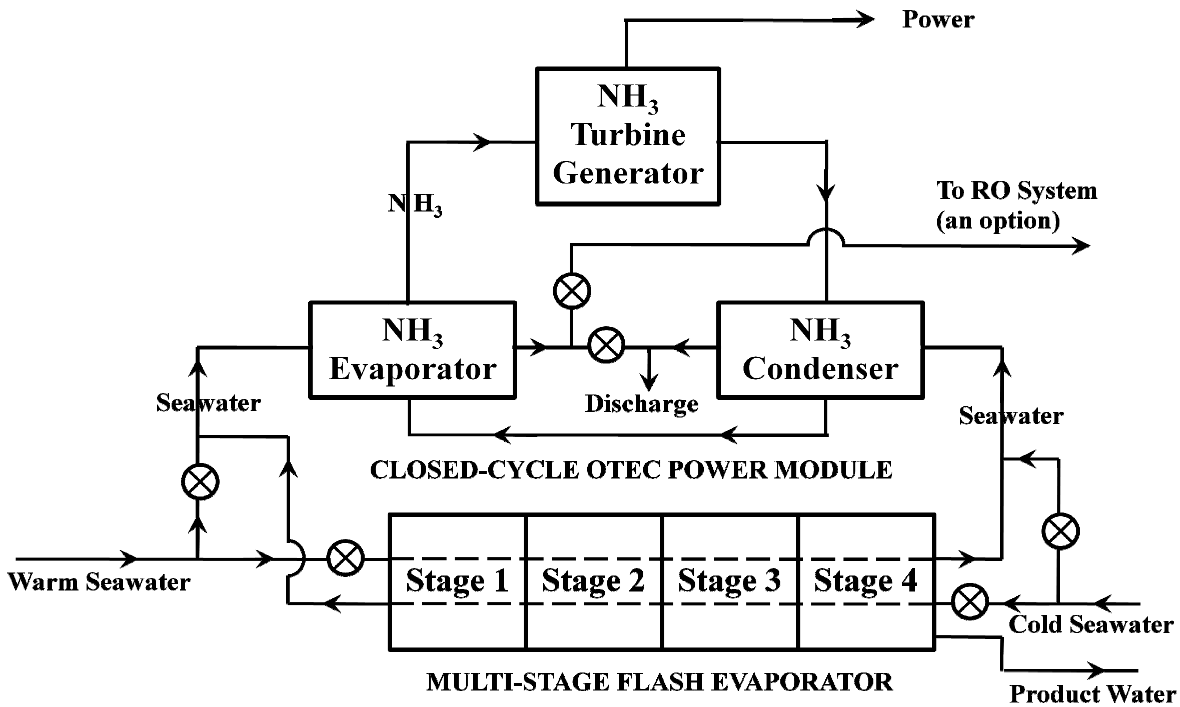


Figure 16: A CC-OTEC scheme with second stage production of desalination water using MSF with an option for an RO system[25]

Desalinated water produced by CC-OTEC uses the electricity generated in situ and does not require extensive electricity transmission since the RO equipment is onboard the OTEC platform or vessel. An OTEC-desalination plant would be permanently moored offshore and would be designed to withstand 100-year storm conditions. The feedwater flow comes from tapping a small portion of the water exiting the OTEC heat exchangers and the concentrate discharge is mixed back with the primary OTEC discharge. Vega presented various costs for OTEC plants with second stage desalination schemes throughout the years (Table 11). The cost of desalinated water reported in the Table 11 were not described in further detail, but it can be assumed that these values were the best case scenario.

[25]Reproduced from "Production of Desalination Water Using Ocean Thermal Energy" by Rabas, T. and Panchal, C. B. 1991.

It is noticeable that the cost of water decreases as the plant capacity increases and because of the switch to a CC-OTEC process with RO as the desalination method.

Table 11: Costs of OTEC desalinated water for different plant sizes, sitting factors, cycle types, and desalination processes[26]

Plant Size and Sitting Factor	Cost of Desalinated Water (per m^3)
1 MW land-based OC-OTEC with second stage flash evaporation	$1.60
10 MW land-based OC-OTEC with second stage flash evaporation	$0.90
50 MW land-based CC-OTEC with second stage RO	$0.80

[26]Adaptation from "Ocean Thermal Energy Conversion (OTEC): Electricity and Desalinated Water Production" by Luis A. Vega, 2005.

Since electricity typically represents about 50% of the operating costs of an RO system, the water unit cost is largely influenced by the cost of electricity, which is primarily influenced by the cost of fossil fuels. The majority of desalination systems use conventional sources of energy (i.e. fossil fuels), but some systems can be powered by renewable energy course such as wind, solar, and geothermal (Karagiannis & Soldatos, 2007). Although better for system independence and reduced gas emissions, desalination using renewable energy sources can be substantially more expensive than using conventional sources of energy (Table 12). Researchers investigating renewable energy-supplied desalination have stated that the one of the key barriers to "renewable desalination" is the variable nature of renewable energy sources.

Table 12: Costs of renewable energy desalination methods for different feedwater types[27]

Type of Energy	Cost of Desalinated Water (per m^3)	Feedwater Type
Conventional	$0.44 - $3.38	Seawater
Wind	$1.25 - $6.25	Seawater
Photovoltaic	$3.93 - $11.25	Seawater
Solar Collectors	$4.38 - $10.00	Seawater
Geothermal	$2.50	Brackish

[27]Adaptation from "Water desalination and cost literature: review and assessment" by Karagiannis, Ioannis C.; Soldatos, Petros G. , 2007, Desalination and the Environment.

Comparative renewable energy costs and capabilities were later presented in a report by (Isaka, 2012) where the economics in Table 13 show improvement from the data reported in Table 12. The water cost assumes only desalination of seawater (cost scenarios for brackish water are omitted from this table). Although many factors can contribute to the final cost of desalinated water shown in these tables, it is noticeable that the lower unit water costs are attributed to the larger capacity plants, while the higher costs are more representative of the smaller capacity plants.

Table 13: Costs and capabilities of renewable energy desalination methods[28]

Renewable Energy	Technical Capacity	Water Cost ($/m^3)	Development Stage
Solar Stills	< 0.1 m^3/day	1.3 - 6.5	Application
Solar-Multiple Effect Humidification	1-100 m^3/day	2.6 - 6.5	R&D Application
Solar-Membrane Distillation	0.15-10 m^3/day	10.4 - 19.5	R&D
Solar/CSP-MED	> 5,000 m^3/day	2.3 - 2.9 (possible cost)	R&D
Photovoltaic-RO	< 100 m^3/day	11.7 - 15.6	R&D Application
Wind-RO	50-2,000 m^3/day	< 100 m^3/day unit 6.5 – 9.1 < 1,000 m^3/day unit 2 - 5.2	R&D Application
Wind-MVC	< 100 m^3/day	5.2 - 7.8	Basic Research
Geothermal-MED	-	3.8 - 5.7	-

[28]Adaptation from "Water desalination Using Renewable Energy" by Isaka, M., 2012.

Since the unit cost of desalinated water ranges from \$0.44-\$3.38/m^3 using conventional energy, the lower end of the range, namely \$0.44/m^3, represents a benchmark that desalination developers must strive to attain if they are to remain competitive in the conventional energy-supplied desalination market. In contrast, the \$1.25/m^3 cost of desalinated water using wind energy is a benchmark for renewable energy-supplied desalination. A quick comparison reveals that the estimated unit cost of OTEC-desalinated water by Vega is competitive with this benchmark even at the 1 MW plant size. Improved economy of scale with larger OTEC plants at the 10 MW and 50 MW capacities firmly surpass the current renewable desalination benchmark; however, the best case scenario unit water costs of \$0.80-\$0.90/m^3 are still two times more expensive than conventional energy-supplied desalination. Although OTEC desalination is likely to be produced at a premium cost, conventional energy is burdened with fluctuating oil prices that frequently change desalination economics, whereas OTEC energy prices will remain stable over time. Further economic analysis of the OTEC-desalination scenarios will be analyzed in the discussion section.

Desalination Literature Review

The literature available for desalination dates back to the 1950s and 1960s when desalination plants began commercial implementation in the Middle East and other arid regions. The literature available for desalination differs significantly from the literature available for OTEC because the desalination industry has achieved a significant degree of maturity over the past 60 years and has undergone unprecedented growth in the past decade. The literature review will focus primarily on research in the last decade since much of data and assumptions included in publications before 2000 are becoming obsolete given the rapidly changing desalination environment. A review of desalination economics and environmental impacts will follow the review of OTEC literature.

Desalination Economics

Cost is the primary factor when considering whether or not to implement a desalination plant in a water-stressed region. The cost of the desalination option is almost always compared against the cost of transporting water from a water-rich region to the water-stressed region. Transporting water can be cheaper and more effective, but does not establish a long-term capability to meet the growing water demands of the region. Thus, the decision to implement desalination plants is readily becoming an important decision for many regions. The cost of a desalination plant varies greatly depending on many factors with perhaps the most influential factor being the type of desalination method employed (i.e. RO, MSF, MED, etc.). The other high-level factors affecting desalination cost are: quality of feedwater, plant capacity, site characteristics, and regulatory requirements (Younos, 2005).

The implementation costs are categorized as construction (startup) costs and operating and maintenance (O&M) costs. Construction costs include land, production wells, surface water intake structure, process equipment, auxiliary equipment, buildings, concrete disposal, freight and insurance, and construction overhead (Younos, 2005). Younos indicated that following cost models are available for estimating desalination costs: WTCost© Model {developed by the Bureau of Reclamation with the assistance of I. Moch& Associates and Boulder Research Enterprises}, Desalination Economic Evaluation Program (DEEP) {developed by the International Atomic Energy Agency (IAEA)}, and WRA RO Desalination Cost Planning Model {developed by Water Resource Associates (WRA)}. The DEEP program, in particular, provides capital and O&M cost estimates for various desalination methods and feedwater types as well as values for the levelized cost of power in dollar per kilowatt hour ($/kWh) required to produce desalinated water at a final levelized cost of water in dollars per cubic meter ($\$/m^3$). Alternatively, other researchers are using a desalination plant cost database that can be used as a tool for estimating the cost of desalination.

Zhou & Tol (2005) performed an evaluation of 442 worldwide desalination plants using the MSF process from 1957 to 2001 determined that average unit cost of desalinated water has decreased significantly from $\$9.00/m^3$ in 1960 to about $\$1.00/m^3$ in 2001; this represents an annual reduction rate of 5.3% in the unit cost of desalinated water by MSF over the past 40 years. A cost database of over 300 desalination plants was compiled by (Wittholz, O'Neil, Colby, & Lewis, 2008) to evaluate the capital cost correlations as a function of plant capacity for large-scale thermal and membrane desalination plants. The authors indicate the usefulness of using existing data from current desalination plants to plan for future plants using the power law equation where the exponent m will vary depending on the type of desalination plant (Equation 1).

$$\frac{(Capital\ Cost_{plant\ 1})}{(Capital\ Cost_{plant\ 2})} = \frac{(Plant\ Capacity_{plant\ 1})^{m}}{(Plant\ Capacity_{plant\ 2})} \qquad (1)$$

The desalination cost data was collected from surveys, reports, and published journals spanning from 1970 to 2005; however, the data was adjusted to 2008 value in U. S. Dollars (USD) using chemical engineering plant cost index (CEPCI) and using U. S. Federal Reserve Bank exchange rates for data published using foreign currency (Wittholz et. al, 2008). Capital costs vary significantly based on the desalination method, but thermal desalination plants typically require more capital investment than membrane plants (Figure 17).

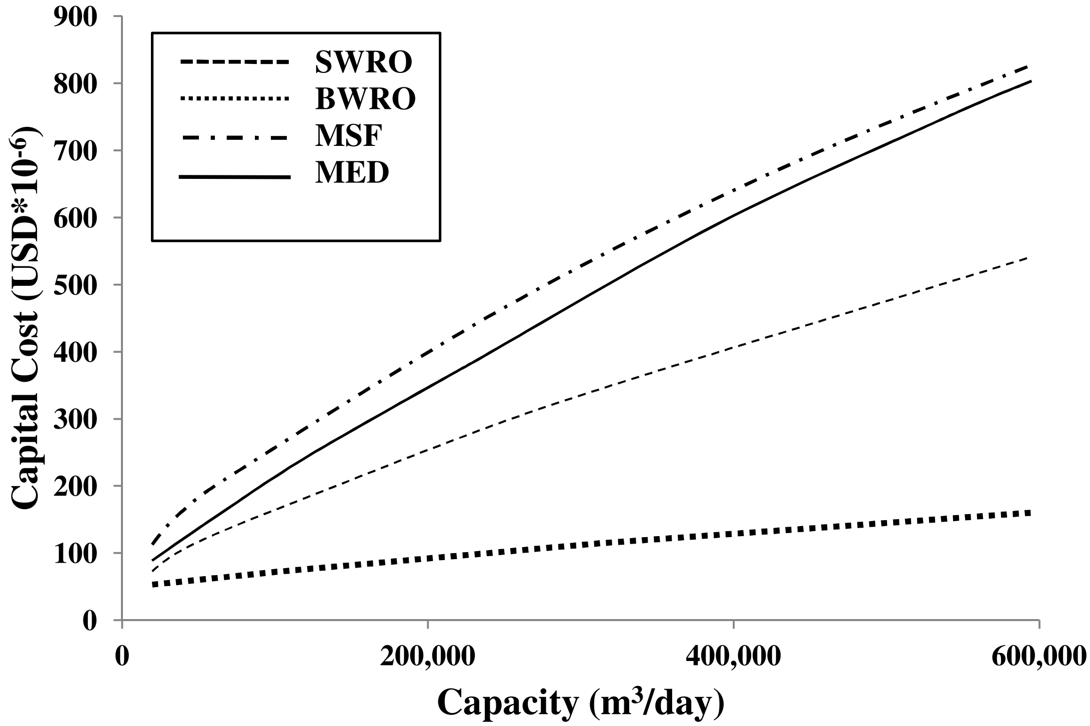


Figure 17: Graph showing the capital cost versus capacity for various desalination types using power law scale up model[29]

The capital costs of BWRO are by far the lowest, but are also significantly lower for SWRO when compared to the thermal processes MED and MSF. Although the capital costs are higher for thermal desalination plants, these types of plants often utilize waste heat from a co-located power plant or industrial plant (Tonner, 2008). Utilizing waste heat reduces the energy requirement for thermal plants whereas membrane plants are exclusively dependent on electricity. The electrical and thermal energy requirements for various methods of water supply are shown in Table 14.

[29]Reproduced from “Estimating the cost of desalination plants using a cost database” by Wittholz, Michelle K.; O'Neil, Brian K.; Colby, Chris B.; Lewis, David, 2007.

Table 14: Electrical energy costs for various methods of desalination[30]

Type of Energy	Electrical Energy (kWh/m^3)	Thermal Energy (MJ/m^3)
BWRO	0.5 – 3.0	N/A
SWRO	2.5 – 7.0	N/A
MSF	3.0 – 5.0	250-330
MED TVC	1.5 – 2.5	145-390
Surface Water Treatment	0.2 – 0.4	N/A
Waste Water Reclamation	0.5 – 1.0	N/A
Transport (Aqueducts)	1.6 – 2.8	N/A
Transport (Pipeline)	12.0	N/A

[30]Adaptation from "Development of an Environmental Impact Assessment and Decision Support System for Seawater Desalination Plants" by Lattemann, Sabine, 2010.

It can be seen from Table 14 above that SWRO has a higher average electrical requirement than the MSF and MED thermal desalination processes; however, the thermal processes also have a thermal energy requirement that is supplied at a cost. Moreover, advances in membrane technology and pre-filtration of feedwater are increasing membrane life and further reducing energy requirements of RO.

Desalination Heat Exchangers

The use of large-scale thermal desalination technologies began in the 1950s primarily to provide fresh water supplies to the arid Middle Eastern states (Economic and Social Commission For Western Asia, 2001). The thermal desalination plants' heat exchangers, or evaporators as many researchers denote them, play a very important role for all large-scale thermal desalination technologies. Material selection is a very important consideration for these heat exchangers because of how the material affects cost, performance, and reliability. In general, the capital cost for large metallic tube evaporators are responsible for 40-50% of the total cost of water (U.S. Bureau of Reclamation, 2009). Heat exchange tubes represent 25-35% of the overall cost for evaporators in desalination plants (Sommariva, Hogg, & Callister, 2003). Early MSF evaporators used tubing materials such as copper-nickel alloys while more modern MSF are moving towards thin-walled stainless steels and titanium alloys. The MED evaporators can use either aluminum brass or aluminum alloys since the operating temperature of 70°C is lower than MSF. Aluminum brass is more frequently used for MED evaporator tubing over aluminum alloys because aluminum has had varying results during its history of use in desalination.

A general cost breakdown for thermal desalination evaporators can be considered when the tubes employed are a combination of copper-nickel, aluminum-brass, and/or titanium (Figure 18). This chart excludes the use of aluminum as heat exchange tubing since it is not as widespread as the other alloys noted; however, this chart is useful to determine the relative cost contribution of each component with respect to the overall cost of the evaporator.

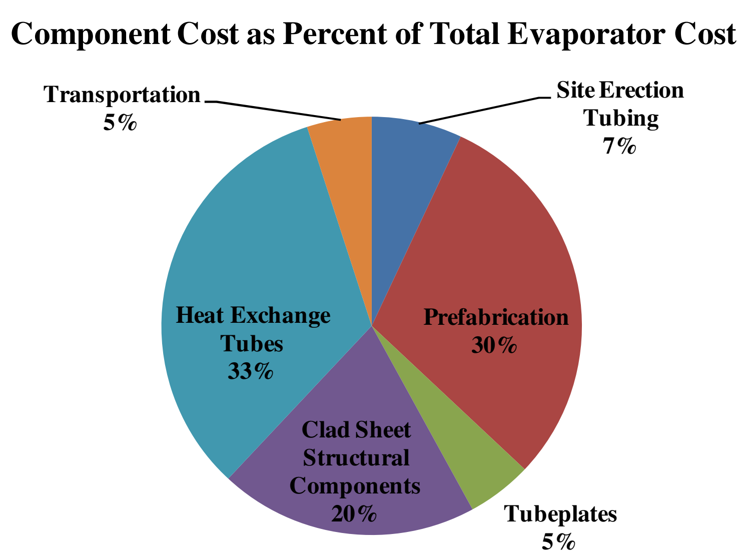


Figure 18: Chart showing cost breakdown of thermal desalination evaporators[31]

[31]Reproduced from "Cost reduction and design lifetime increase in thermal desalination plants: thermodynamic and corrosion resistance combined analysis for heat exchange tubes material selection" by Sommariva, Corrado; Hogg, Harry; Callister, Keith, 2003.

The cost breakdown for desalination evaporators is very similar to the cost breakdown for OTEC heat exchangers and will befurther analyzed in later sections. Since the use of aluminum tubing could have a significant impact on the cost contribution of heat exchanger tubes relative to the total cost, it is worthwhile to investigate the history of aluminum tubes in desalination. Furthermore, since aluminum tubing is of interest for OTEC heat exchangers, the remainder of this section will focus primarily on the operational track record of aluminum tubes in desalination.

As far back as 1966 researchers recommended the use of aluminum alloy 5052 in desalination after pitting studies on aluminum alloys 1100, 3003, 5052, 5054, and 6061 in 80°C oxygen-saturated water revealed that 5052 had the highest pitting resistance (Zaki, 2006). Additional studies performed by researchers in 1973 demonstrated that aluminum alloys 3003, 5052, and 6063 had excellent resistance to pitting and could be successfully used in marine service with careful consideration for water chemistry, oxygen, and pH levels (Zaki, 2006). In 1976, a study was performed by a conglomerate of Japanese researchers to determine the aluminum alloys that have suitable properties as heat transfer tubes for large-scale desalination plants of the MSF type. They discovered 3003 and 3004 performed the best followed by 5052 and 6063. All alloys experienced some problems with local corrosion from contact with other metals in the system; however, the biggest concern was that the growth of pitting could prohibit long-term use (Watanabe, Nagata, Nakamura, & Onimura, 1976). The authors concluded that aluminum alloy tubes could not be used for MSF type plants available in 1976, but cited possible use in future large-scale desalination plants if proper designs were developed.

The best documented example of aluminum tubing lifecycle in seawater service is the 1.25 MGD MED plant on the Virgin Islands installed by IDE Technologies Ltd. in 1980. At the time, this plant was one of the few examples of desalination plants using aluminum tubing and was likely a significant risk given the large plant capacity and investment. After 13 years of continuous use, operating at an average efficiency of 95%, only four tubes had to be replaced out of 36,000 tubes (Global Water Intelligence, 1994). The tubes had a diameter of 38 mm (1.5") and are used in lengths of 4-5 m. At the IDA World Congress 2007, representatives from IDE Technologies Ltd. reported that aluminum tubes continued to be successful after 25 years of operation in the Virgin Island MED plant installed in the early 1980s (Ophir & Gendel, 2007).

In 2011, the Virgin Islands Water and Power Authority (WAPA) board initiated the gradual transfer from the MED units to RO systems to supply the island's future water needs. Regarding the overall performance of the MED units installed in 1980, the WAPA Executive Director, Hugo V. Hodge Jr., stated that the MED units "served the Authority well over the last 30 years, (but) there comes a time when you have to evaluate your current technology and see how you can provide the service in a more beneficial and economical manner" (Virgin Islands Water and Power Authority, 2011). It should be understood that Hodge made a testament to the 30 year life of the aluminum tubing from the end-user prospective instead of the developer's prospective. It is very significant that both the developer (IDE Technologies) and the end-user (WAPA) both acknowledged the 30-year lifetime of the aluminum tubes in this seawater service application.

In 1984, IDE installed a 20,000 m^3/day MED plant in Ashdod, Israel that was considered to be one of the largest installations in the world at the time. Aluminum tubes of 5052 alloy were used as the primary heat transfer surface with a seawater evaporation temperature of 74°C in the first effect. Scale prevention was conducted using polyphosphate dosing and on-line cleaning was reported to occur after six months to two years of operation (Khalid 1990). In 1988, IDE installed two MED units in Guantanamo Bay, Cuba using aluminum tubes and epoxy-painted carbon steel shells. The maximum allowable brine temperature in these units was 165°F (74°C) because of the aluminum tubes. The units operated successfully for 10 years; however, because of corrosion and scaling, these units were decommissioned in 2000 (Ko, Lohman, & King, 2006).

In a 1990 study on the service life of aluminum heat exchangers in seawater, it was reported that aluminum tubing of the 5052 alloy used in MED plants had a uniform corrosion rate of 12.7 μm per year with no signs of crevice corrosion or stress corrosion cracking, even while the tubes were exposed to significant amounts of hydrogen sulfide (H_2S) (International Atomic Energy Agency, 1990). In a 2002 study by the International Atomic Energy Association, the authors stated that desalination plants are typically designed for a life time of approximately 25 years, although some MSF plants have operated for up to 30 years. Furthermore, they reported that MED vessels and piping are similar to those of MSF; however, when MED systems with aluminum tubes must be retubed at an approximate 15-year interval (International Atomic Energy Agency, 2002).

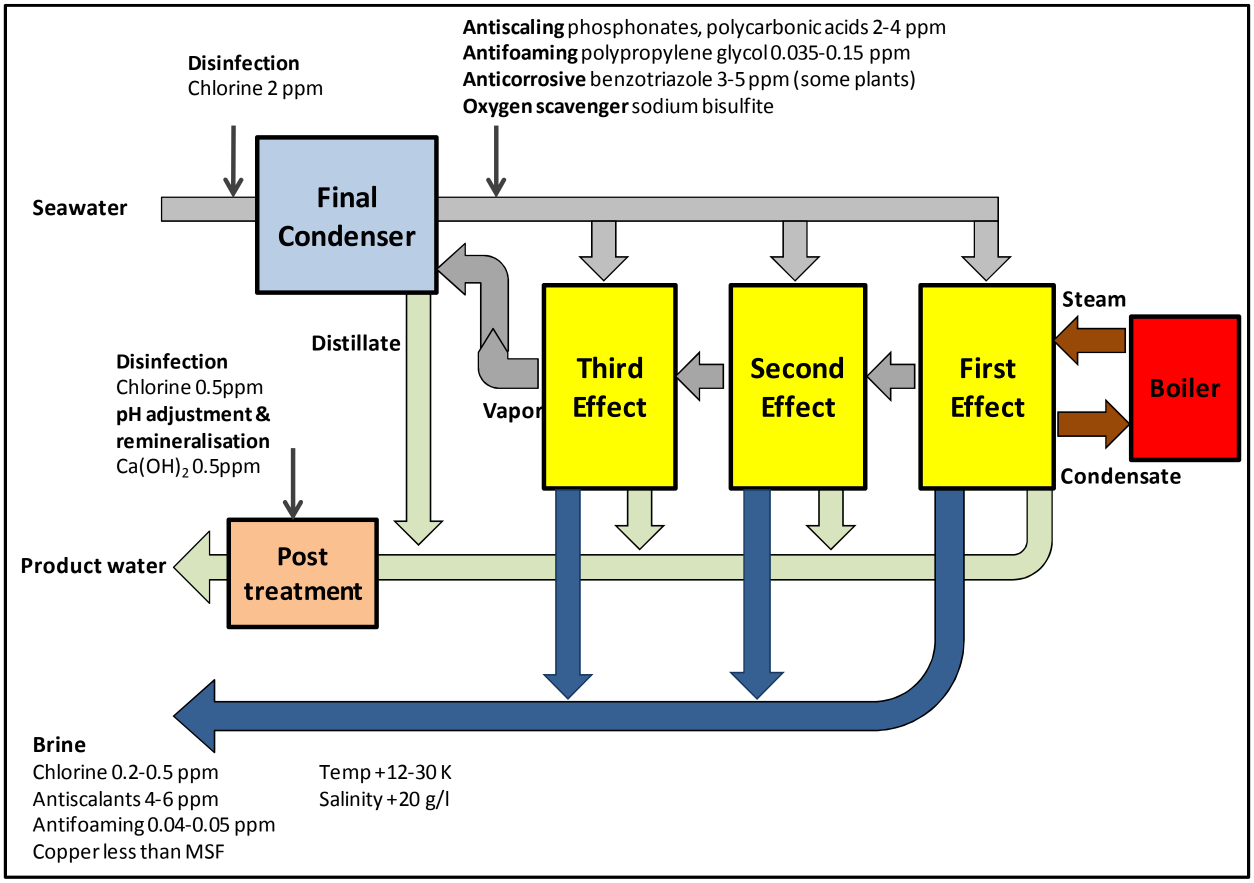
Westinghouse was the first to consider aluminum tube lifecycle data from desalination operations in their analysis of aluminum heat exchangers for OTEC. Since their OTEC power system development research was published in 1978, they did not have the benefit of the confirmed 30-year track records reported above. Westinghouse formulated their conclusions on aluminum tubing in seawater service using one of IDE's first publications on the subject as well as personal communications with Abraham Ophir of IDE in 1977. They confirmed that 5052 tubes had apparently good results in the desalination application, but they were not able to confirm that the tubes were ever inspected for pitting failures since there was not much concern for small leaks. The MED process has steam condensing inside the tubes at a higher pressure than the seawater film evaporating on the outside of the tubes; therefore, small leaks via pits, pinholes, or cracks would only result in an insignificant loss of distillate as vapor and/or condensate that would not result in contamination of the distillate (Westinghouse Electric Corporation, 1978).

Furthermore, Westinghouse stated that aluminum was not used for flowing seawater service in the MED desalination plants because of the concern for erosion effects. Flowing seawater in MED plants comes from a surface where particles such as sand can pass through intake screens and cause adverse erosion effects. For OTEC plants located offshore, erosion of aluminum heat exchanger tubing from particulates is not a substantial issue, but could be a problem for land-based OTEC plants with insufficient intake screen protection. The normal offshore operating flow rates of seawater could be erosive to aluminum over a 30-year lifetime, so it is necessary to choose an appropriate wall thickness to have allowance for erosion as well as pitting effects. The aluminum tubes used in IDE's MED plants typically have ODs of 1" to 1.5" and corresponding wall thicknesses of 0.069" and 0.098" (Tramer, 2012). If aluminum tube failure is seen as a significant risk for OTEC developers, then it may be valid to opt for a thicker tubing wall to mitigate the risk of pitting and erosion.

Desalination Environmental Impact

The environmental impact from desalination processes can be quite substantial. Large-scale desalination has grown at such a rapid rate in the last decade that only now are the environmental issues starting to gain attention. It is sometimes difficult to imagine that seawater desalination can cause impacts to the sea since the amount of water being desalted is minute compared to the water flow rates passing through a sea region; however, the largest capacity of desalination in the world is concentrated in the Middle East and North Africa (MENA) region that is primarily consists of closed basin seawater systems. Because closed basin systems have poor transport and mixing characteristics when compared with coastal systems, desalination discharges concentrations will be higher in these systems. Biocides such as chlorine are necessary at almost all thermal desalination plants in order to control biofouling growth and fresh water contamination. Consequently, chlorine and other biocide toxicity to marine life is one of the primary environmental concerns with desalination.

Chlorination dosing occurs at the surface water intake and enters the heat exchanger sections of the desalination plant. The effluent discharged back to the sea contains a residual chlorine content that is typically 10%-25% of dosing concentration (Lattemann & Höpner, 2008). Similarly, the RO process also has significant chemical injections for treating seawater and controlling biofouling; however, the RO process employs a dechlorination process that removes oxidants from the water using hydrogen sulfide and sodium bisulfite (Figure 19). Chlorine can contribute to the deterioration of membranes, so RO systems are typically designed with a dechlorination step that also reduces residual chlorine in the discharge.



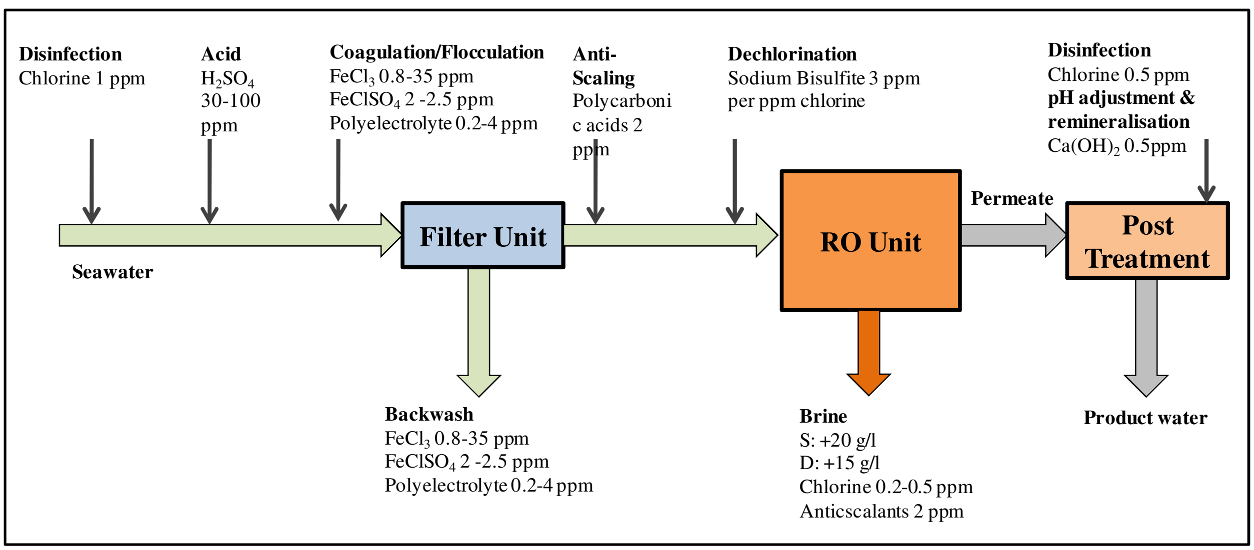


Figure 19: Diagram showing input/output concentrations of constituents and brine characteristics for an MED system (top) and a RO system (bottom)[32]

[32]Reproduced from "Concentrating Solar Power for Seawater Desalination" by Trieb, F., 2007.

Thermal desalination plants and coastal power plants use somewhat similar chlorination dosages to control biofouling. Coastal power plants use low-level chlorine concentration doses of 0.5-1.0 mg/L, and thermal desalination plants use doses of 0.4-4.0 mg/L with levels of 0.02 mg/L observed near the outlet of coastal power plants and 0.03-0.5 mg/L observed near the outlet of thermal desalination plants (Lattemann S., 2010). Various environmental regulatory entities around the world have published references values for acceptable chlorine discharge concentration into receiving waters (Table 15).

Table 15: Summary of reference values for chlorination concentration discharge[33]

	Short-term	**Long-term**
European Union (EU) Best Available Techniques (BAT)	≤ 0.5 mg/L (24-hr average) {intermittent and shock dosage}	≤ 0.2 mg/L (24-hr average) {continuous dosage}
World Bank Pollution Prevention Abatement	≤ 0.2 mg/L (24-hr average) {max shock dosage of 2 mg/L for up to 2 hrs every 24-hrs}	≤ 0.2 mg/L (24-hr average) {continuous dosage}
U. S. Environmental Protection Agency (EPA)	≤ 0.013 mg/L (criterion maximum concentration, [CMC])	≤ 0.0075 mg/L (criterion continuous concentration, [CCC])
California Ocean Plan (COP)	≤ 0.008 mg/L (total residual chlorine maximum)	≤ 0.002 mg/L (6-month median)
Qatar Ministry of Environment	≤ 0.05 mg/L (total residual chlorine maximum)	

[33]Adaptation from "Development of an Environmental Impact Assessment and Decision Support System for Seawater Desalination Plants" by Lattemann, Sabine, 2010.

It is apparent that desalination plants discharge more harmful levels of chlorine than coastal power plants since concentrations near the outlet of desalination plants were observed to be 1.5 to 25 times greater than concentrations at the outlet of coastal power plants. These high concentrations of chlorine intensify when large volumes of desalination concentrate are discharged into relatively small water systems such as the Arabian Gulf, Red Sea, and Mediterranean Sea. The following MENA region water systems are estimated to receive the following chlorine loads: Arabian Gulf at 47,400 kilograms per day (kg/day), Red Sea at 11,144 kg/day, and the Mediterranean Sea at 1,944 kg/day (Lattemann S., 2010). The Arabian Gulf is particularly troubled with an estimated total discharge of 22.2 tons of chlorine per day (Figure 20).

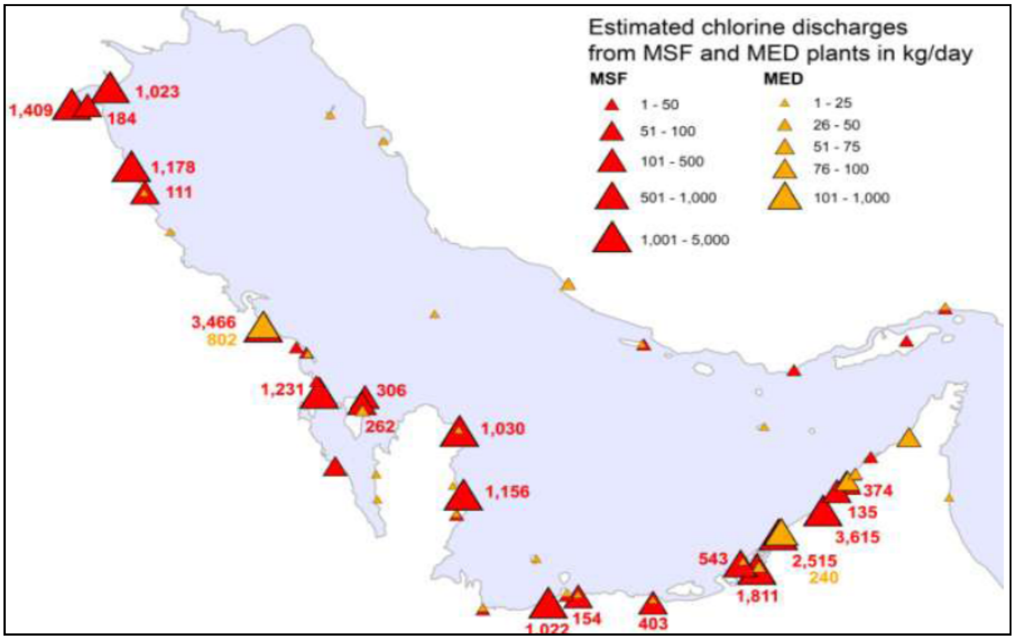


Figure 20: Map of the Arabian Gulf showing the estimated total daily load of 22.2 tons of chlorine per day resulting from desalination operations[34]

The chlorine discharge values are of particular importance because chlorine byproducts can be lethal to marine organisms. Concentrations of residual chlorine were measured near the outlet of various desalination plants at a distance of one kilometer by (Lattemann & Höpner, 2003) and were compared against the ecotoxicity values for given species as defined by the Hazardous Substance Databank. The residual chlorination concentration found at some of the tested populations demonstrated that the concentration level exceeded the mean lethal concentration (LC50) for some marine species (Figure 21).

[34]Adaptation from "Development of an Environmental Impact Assessment and Decision Support System for Seawater Desalination Plants" by Lattemann, Sabine, 2010.

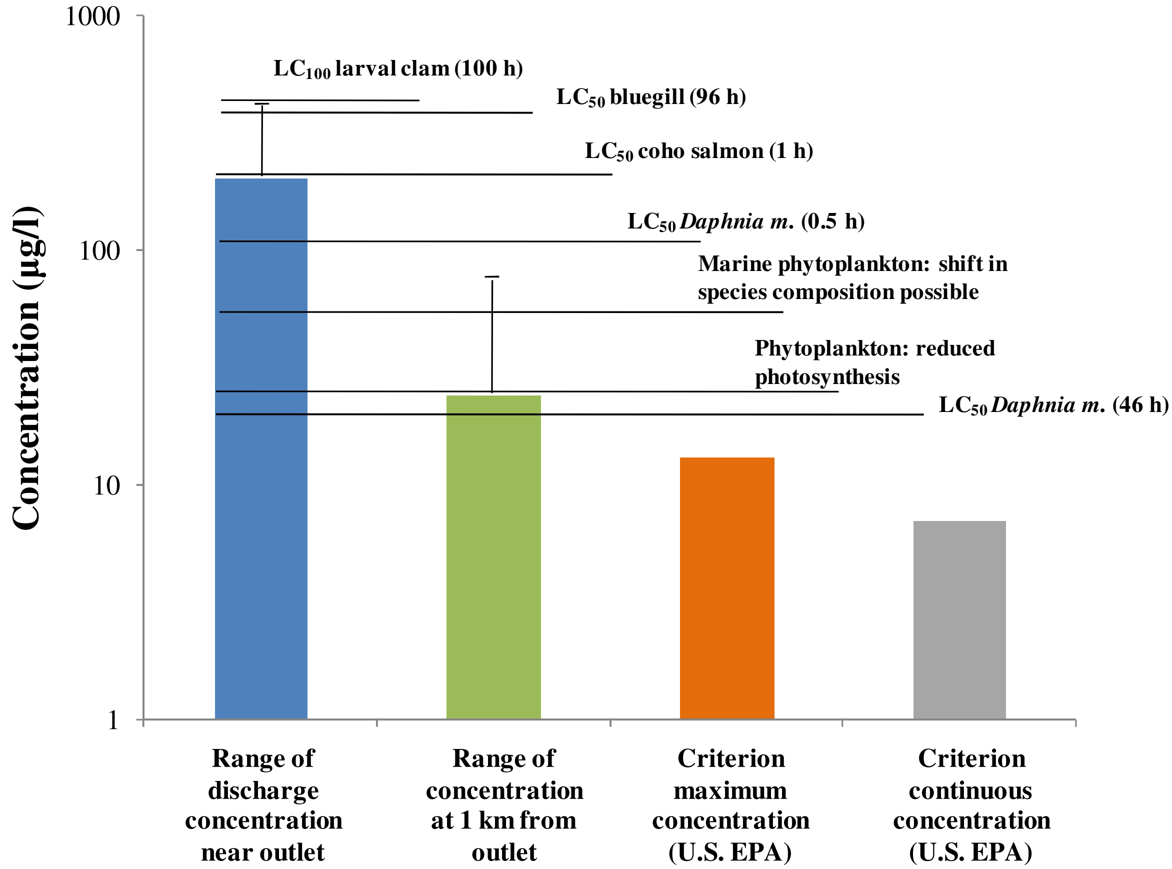


Figure 21: Diagram showing the residual chlorine concentrations near the outfall of a sampling of desalination plants[35]

It is evident that the range of residual chlorine concentrations in the near- and far-field discharge exceeds the criterion maximum concentration established by the U. S. EPA. Organisms inhabiting the area near the outlet are most susceptible to the toxicity of chlorine residuals. Although the toxicity of free oxidants can be high at low concentrations, they tend to decompose quickly and do not bioaccumulate; therefore, toxicity to non-target organisms is limited to the mixing zone (Lattemann S., 2010). Nevertheless, Lattemann (2010), Lattemann hereafter, warns that some chlorine by-products can be more persistent to show bioaccumulation, chronic

[35]Reproduced from "Concentrating Solar Power for Seawater Desalination" by Trieb, F., 2007.

mutagenic and carcinogenic toxicity potentially beyond the mixing zone. Since no alternative biocide has gained wide acceptance over chlorination in desalination applications to date, it is important to minimize chlorine levels as much as possible by using Best Available Techniques (BAT) of low-level or pulse chlorination with a ≤ 0.2 mg/L concentration of chlorine at the outlet (Lattemann S., 2010).

Another environmental challenge is the method employed for brine disposal from large capacity desalination plants. The concentrated brine discharge can be more than twice the salinity of the feedwater and will have to be disposed in a responsible manner to avoid adverse environmental impacts. Many methods of brine disposal exist, but surface water disposal is the most common because the cost is generally lower. The various methods for disposal are shown in Table 16 and are rated for magnitude of challenge with the designations "H" for high, "M" for medium, and "L" for low.

Table 16: Table showing the relative impactof various types of brine disposal for desalination plants[36]

Disposal Method	Capital Cost	O&M Cost	Land Required	Env. Impact	Energy	Public Concerns	Geology
Surface Water	L	L	-	M-H	L	H	-
Deep wells	M-H	M	L	L	M	L-H	H
Evaporation ponds	H	L	H	M	L	H	H
Land spreading	M	L	H	M-H	L	H	H
Thermal evaporation	H	H	L	L	L	L	L
Sewers	L	L	-	M	L	L	-

[36]Adaptation from "Renewable Energy Desalination: An Emerging Solution to Close the Water Gap in the Middle East and North Africa" by International Bank for Reconstruction and Development/The World Bank, 2012.

The magnitude of challenge rating can be greatly affected by the desalination plant's specific sitting factors, but large capacity coastal desalination plants are more prone to employ the surface water discharge method instead of sewers. Although more environmentally safe methods of disposal could theoretically be used instead of surface water discharge, the cost of the alternatives could easily exceed the cost of desalinating the water. The combined annualized capital and O&M costs for surface seawater discharge range between \$0.03-\$0.30/m^3 while the cost of deep well injection and evaporation ponds range between \$0.33-\$2.64/m^3 and \$1.18-\$10.04/m^3, respectively (The World Bank, 2012). Since the cost of desalinated water is already a major inhibitor for meeting global water demands, the added cost of benign concentrate disposal needs to be reduced or it will likely stall the implementation of new desalination projects. Even worse, future desalination projects will move forward without consideration for benign concentrate disposal methods simply because the cost is too prohibitive.

Offshore Desalination Vessels

The recent market for offshore or "floating" desalination has emerged and several companies have planned or deployed offshore desalination vessels. Offshore desalination units have typically been installed on barges and are transported to the region in need of a short-term water supply. The seawater intake is drawn from below the barge and the product water can be transported to a water treatment facility onshore via a high density polyethylene (HDPE) pipeline, water bags, or transfer ships. Some of the very first offshore desalination projects are shown in Table 17.

Table 17: List of temporary floating desalination plants by commissioning date and capacity

Plant Location	Commission Date (year)	Nominal Capacity (m^3/day)	Source
Shuaibah, Saudi Arabia	2008	50,000	(Desalination and Water Reuse, 2010)
Shuqaiq, Cyprus	2010	50,000	(Desalination and Water Reuse, 2010)
Limassol, Cyprus	2009	20,000-50,000	(Hassapi, 2008)

Currently, the primary benefit of offshore desalination vessels is to supply quick, short-term desalination capacity during construction of larger land-based plants at a given coastal location. Conversely, the favorable environmental effects of locating desalination intakes and discharges offshore could become the primary benefit for relocating desalination plants offshore as permanent facilities.

Several companies involved in offshore desalination supply including Water Standard Company (WSC), Israel Desalination Engineering (IDE) Technologies Ltd., and Subsea Infrastructure Ltd. have developed large capacity desalination vessels intended to transfer water back to shore. In particular, WSC's Seawater Desalination Vessel (SDV) has been designed to include several key environmental benefits including reduced water quality issues from discharge recirculation, reduced pre-treatment requirement by using higher quality feedwater, reduced organism entrainment from using low-velocity intake pumps, and increased dilution of discharge plumes (Henthorne, Gong, & Huehmer, 2011). These vessels are intended to desalinate larger capacities of water than barges (i.e. up to 50,000-100,000 m^3/day) and are more realistic as a permanent municipal water source. Permanent offshore desalination is a potential cost reduction strategy since environmental requirements are continuously increasing the cost of intake and discharges for onshore desalination plants.

Although offshore desalination vessels have only operated as a temporary and mobile water supply thus far, municipal water boards from Florida and California have evaluated the potential installation of permanent offshore desalination vessels to meet future water needs. The Monterey Peninsula Water Management District (MPWMD) of California evaluated a proposal from Water Standard Company (WSC) to provide ship-based desalinated water at a capacity of 10 to 20 million gallons per day (MGD) (GEI/Bookman Edmonston; Separation Processes Inc.; Malcolm-Pirnie Inc., 2008). Additionally, a 25-50 MGD vessel-based solution from WSC was also evaluated in the Coquina Coast Seawater Desalination Alternative Supply Project in Florida (Malcom Pirnie, Inc., 2010). Ultimately, a land-based desalination facility was chosen over the vessel-based facility in both cases because the specific sites did not yet have a strong enough case to benefit from the environmental advantages of offshore desalination. Reliability and cost were also cited as concerns for vessel-based solutions, but the integration with OTEC could increase reliability and affordability as OTEC technology becomes more mature.

WSC's concept of using a "mothballed" tankers ship as a cost reduction approach was actually demonstrated first in 1980 by a DoE program known as OTEC-1 (Figure 22). The experiment used a mothballed T2 tanker as a floating plantship to test prototype heat exchangers, CWP, and other OTEC components.

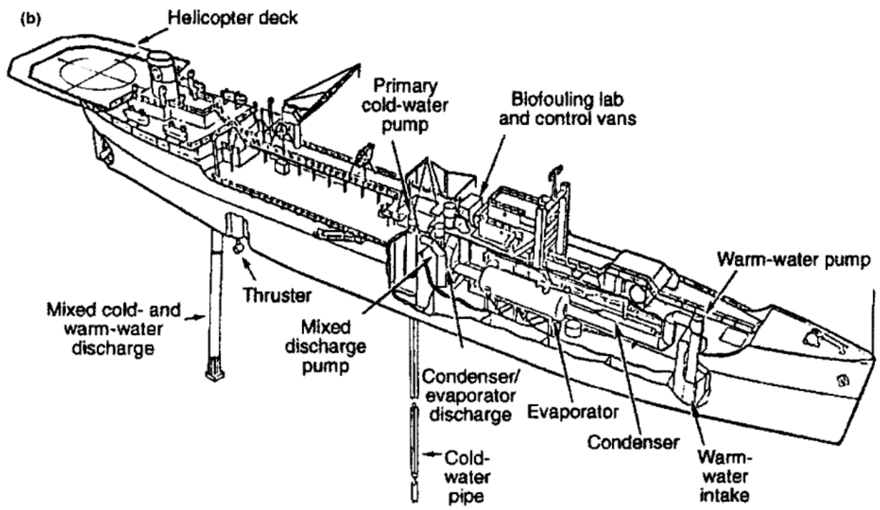


Figure 22: Diagram showing OTEC-1 experiment aboard a retrofitted tanker[37]

Water Standard Company (WSC), has patented a Seawater Desalination Vessel (SDV™) concept that makes use of "mothballed" tankers ship to house the onboard desalination equipment (Kreamer, 2009). These vessels are intended to desalinate larger capacities of water than barges (i.e. up to 50,000-100,000 m^3/day) and could be used as either a temporary or permanent municipal water source (Figure 23).

[37]Adaptation from *Renewable Energy from the Ocean* by Avery, William H.; Wu, Chih, 1994. Reproduced by permission of the author.

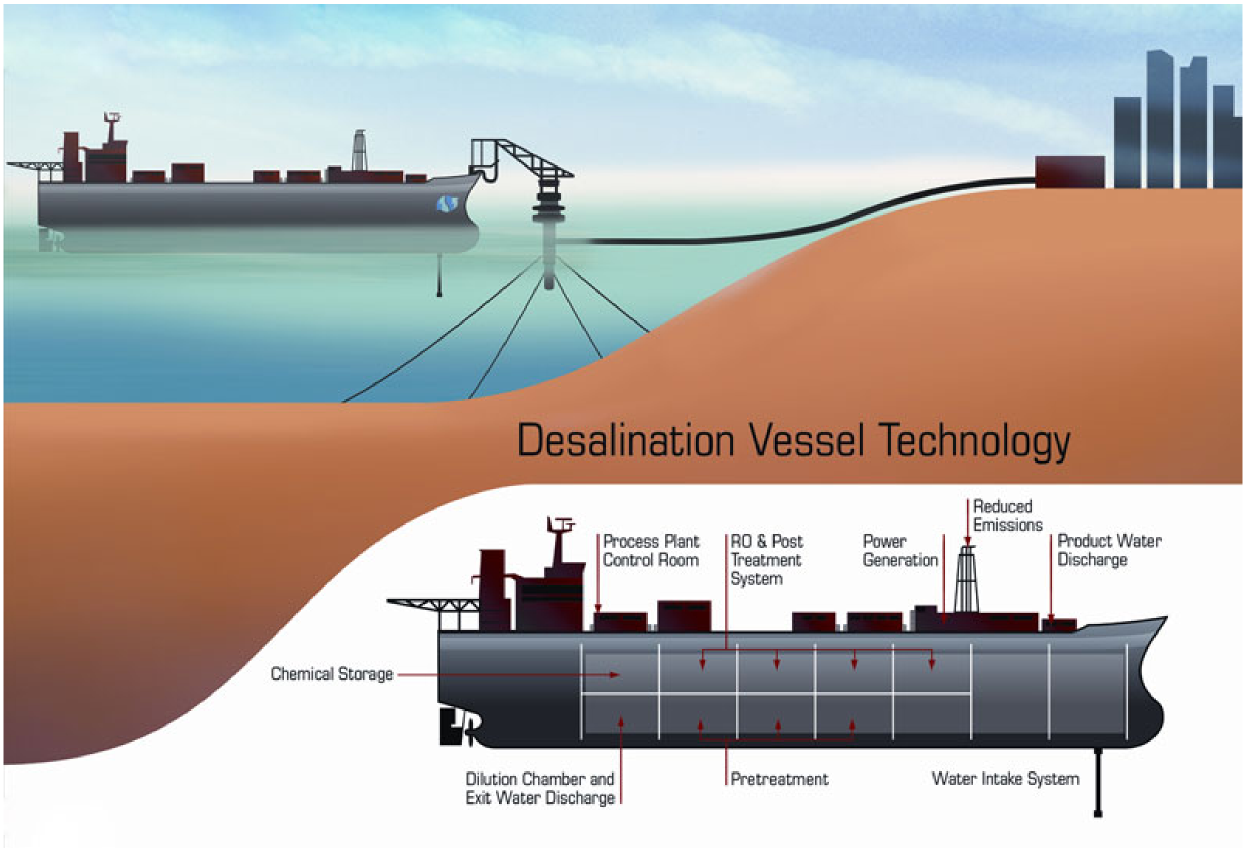


Figure 23: Diagram showing Water Standard's offshore SDV™ concept[38]

Desalinated water aboard a ship this large has the capability to supply much larger volumes of water per day than barge desalination systems. The increased desalination capacity lends itself to supplying water on a long-term basis to water utilities at a potentially competitive rate. Additionally, the advantages of offshore versus onshore desalination include: reduced water quality issues from discharge recirculation, reduced pre-treatment requirement by using higher quality feedwater, reduced organism entrainment from using low-velocity intake pumps, and increased dilution of discharge plumes (Florida Department of Environmental Protection, 2010). WSC responded to a proposal request to supply the Monterey Peninsula Water Management

[38] Reproduced from Adee, Sally (2008). *Water Ship Up: Firm gets $250 Million to Make Oceangoing Desalination Vessels*. Retrieved January 12, 2012 from IEEE Spectrum: http://spectrum.ieee.org/energy/environment/water-ship-up-firm-gets-250-million-to-make-oceangoing-desalination-vessels/brocksb01

District (MPWMD) in California with 18 MGD from their SDV™ solution. They supplied two cost breakdowns where one scenario assumed subsidized fuel energy costs of $0.048/kWh and the second scenario assumed unsubsidized fuel energy costs of $0.093/kWh.

Table 18: Cost breakdown of WSC SDV solution to providing desalinated water to the MPWMD[39]

WSC Seawater Desalination Vessel (SDV™) Cost Structure		
(in millions of dollars)	Subsidized Fuel	Unsubsidized Fuel
RO Capacity (MGD)	18	18
RO Capacity (m^3/day)	68,137	68,137
Desalination Facilities		
Seawater feed and brine disposal (included in ship cost)	$47.10	$47.10
Residuals handling and treatment		
Desalination process	$41.29	$41.29
Finished water storage & pumping facilities		
Subtotal Facilities Cost	$88.38	$88.38
Desalinated Water Pipelines	$31.37	$31.37
Electrical Transmission Upgrades		
Terminal Reservoir and ASR Pump Station		
Segunda/Aquifer Storage & Recovery (ASR) System		
Field Office Overhead (3%)		
Contractor Mark-Ups (16.25%)		
Total Construction Costs	$119.76	$119.76
Engineering, Overhead, Legal (24%)	$28.74	$28.74
Contingency (25%)	$37.13	$37.13
Total Capital Costs	$185.62	$185.62
Operations and Maintenance		
Desalination Facilities/Power		
Desalination Water Conveyance		
Terminal Reservoir and ASR Pump Station		
Segunda/ASR System		
Subtotal O&M Cost		
Repairs and Replacements		
Total O&M Costs	$16.26	$20.85
Total Annualized Cost(7%, 30 yrs)	$31.22	$35.81
Unit Cost (\$/m^3)	$1.32	$1.52
Unit Cost ($/kgal)	$5.00	$5.74

[39]Reproduced from Monterey Peninsula Water Management District. (2008, March 17) MPWMD Comparative Matrix, Part II, Desalination Projects. Retrieved January 12, 2013, from Monterey Peninsula Water Management District: http://www.mpwmd.dst.ca.us/asd/board/boardpacket/2008/20080317/15/item15_exh15b.htm.

At a March 17, 2008 meeting on the MPWMD desalination projects, the final cost of WSC's SDV solution were presented with a breakdown between the subsidized and unsubsidized cost of fuel (Table 18) (Monterey Peninsula Water Management District, 2008).

The approach of utilizing inactive vessels is common among desalination and OTEC developers; however, the desalination industry is close to making this concept a reality while the OTEC industry has not revived the plantship concept since OTEC-1 was decommissioned over 30 years ago in 1981. Some OTEC researchers favor offshore platforms similar to offshore drilling rigs over plantship concepts; however, there is significant potential to integrate desalination vessels with an OTEC offshore platform or a plantship. The evolution of an offshore desalination market presents a unique opportunity for OTEC to garner renewed support for dual-use plants.
The dual use OTEC-desalination schemes will be discussed further in the following discussion sections of this report.

Chapter 2

Methodology

Research papers on the subjects of OTEC and desalination have been evaluated for technical, economic, and environmental similarities. Initially, the OTEC and desalination processes were assessed for technical similarities to justify using desalination plant economic and environmental data to identify trends and formulate useful conclusions for OTEC plants. Appropriate plant cost data from desalination publications were selected and statistical trends were noted. These statistical trends based upon actual plant costs are compared against the theoretical plants costs for OTEC as predicted by various researchers. The power law exponents (as described in Equation 1) were quantitatively evaluated to determine if both models have comparable economies of scale. The results have provided insight as to whether the plant cost predictions for OTEC are reasonable when compared to the recorded evolution of desalination plants.

Additionally, appropriate environmental data from desalination plants has been evaluated to determine if seawater discharges are comparable to that of an OTEC plant. The discharge conditions of desalination plants have been evaluated qualitatively with OTEC discharges to determine if similar effects can be expected from the release of chemical constituents such as residual chlorine and trace metals. The concentrations of recorded desalination discharge constituents were compared against results of hydrodynamic modeling from various OTEC researchers. The results of this comparison aids in determining if OTEC discharge models have sufficiently accounted for the residual concentrations of toxic constituents such as chlorine and trace metals. Furthermore, the total daily loads of these constituents has been quantified and mapped for regions that anticipate operating numerous OTEC plants in a concentrated area.

This method of utilizing data from an adjacent industry (i.e. desalination) to plan for OTEC is a non-traditional approach and has not been investigated thoroughly by other OTEC researchers. The economic planning process for OTEC has traditionally used a systems engineering design approach to identify critical components and gather corresponding cost data from a variety of sources such as the offshore oil industry, coastal power plants, and OEMs. The environmental planning processes for OTEC have traditionally included hydrodynamic modeling of discharges as well as Environmental Impact Assessments (EIA) and EIS. Although all of these planning efforts have contributed immensely to the readiness of OTEC implementation, the implementers will still be met with criticism from environmentalists, investors, regulators, and others because these planning methods lack the essential operational data from a demonstration OTEC plant.

This lack of a proven operational record is one of the key inhibitors of commercial OTEC development. Vega (1992) was the first to recognize that "it is futile to convince the financial community to invest in an OTEC plant unless it has a proven operational record". It is clear that Vega's sentiment is true because 20 years after his publication in 1992, the world still does not have a commercial OTEC plant even with the growing domestic and worldwide investment in renewable energy. Although numerous studies have been published theorizing various economic scenarios and environmental impacts for these types of commercial OTEC plant sizes, none of these economic or environmental hypotheses have been proven simply because a large-scale OTEC system has never been attempted anywhere in the world. Until some entity finances a sizeable demonstration plant, these theories cannot be validated by test; therefore, utilizing comparable desalination industry data could be a valuable method for testing these hypotheses.

Lastly, the integration of traditional desalination economic data has not been sufficiently integrated with the design and cost of OTEC-desalination schemes. The desalination industry witnessed an underlying shift from thermal desalination plants to RO plants in larger capacities. Many OTEC desalination schemes have been devised to leverage the available thermal difference in feedwater to assist in a secondary thermal desalination process; however, the poor efficiency and equipment cost of OTEC thermal desalination is likely to keep these schemes noncompetitive when compared with the alternative of using modern RO equipment in conjunction with OTEC. The design and economics of OTEC-desalination schemes using state-of-the-art membrane technologies will be reevaluated later in this report.

Technical Comparison

The use of large seawater flow rates is one of the most important technical factors driving the comparison between OTEC and desalination. The surface seawater flow rates for largest-in-class thermal desalination plants are almost exactly the same as the anticipated surface flow rates for a 10MW OTEC plant; however, the surface seawater flow rates for 100 MW commercial OTEC plants are expected to be 10 times the flow rates of a 10 MW OTEC plant. It would seem that conventional (i.e. fossil fuel or nuclear) coastal power plants would be a worthy candidate for comparison with OTEC instead of desalination since coastal power plants have high flow rates representative of an OTEC plant and also produce power; however, conventional power plants operate at much higher temperatures and pressures than OTEC and desalination plants.

Furthermore, power plant process conditions require much more expensive equipment and maintenance. Coal and nuclear power plants operate with 50 to 70% availability versus projected 85-90% availability for OTEC (Avery & Wu, 1994). The anticipated lifetime of OTEC plants is expected to be between 20-30 years, while most desalination plants are known to last between 20-30 years. Since desalination plants can operate at an availability of 95% (International Atomic Energy Agency, 2001) (Ophir, A., &Lokiec, F., 2006), the technical comparison is much stronger when comparing OTEC technically with desalination rather than coastal power plants (Table19).

Table 19: Comparison of high-level characteristics between OTEC and MED plants

	OTEC	Desalination (MED)
Operating Factor	85 to 90%	up to 95%
Plant Life	20-30 years	20-30 years
Heat Exchanger Capital Cost	30% of total plant cost	40% of total plant cost
Heat Exchanger Tube Material	Aluminum or titanium	Aluminum, aluminum-brass, and/or titanium

Another key similarity is that OTEC typically uses either aluminum or titanium heat exchanger tubing while MED typically uses aluminum or aluminum-brass tubing, sometimes in combination with titanium tubing. Subsequently, both thermal desalination and OTEC plants require largest-in-class evaporators and condensers that must be resistant to seawater corrosion, but also have reasonable lifecycle costs. These heat exchangers can be designed at a lower cost than traditional power plant heat exchangers since temperatures and pressures are much lower. Additionally, the discharge plumes from both plants have a higher salinity than the ambient seawater and contain common discharge chemical constituents including residual chlorine and trace metals.

Of the major thermal desalination methods MSF and MED described earlier, the MED process is closer to the operating conditions of an OTEC plant than the MSF process. Since OC-OTEC plants flash evaporate warm seawater in a vacuum chamber and expand the steam through a turbine-generator, water resource expert Clark C. K. Liu of the University of Hawaii at Manoa made the observation that the OC-OTEC process is "similar to a MED process" (Liu, 2009). Furthermore, MED plants operate at lower temperatures than MSF plants and allow the use of aluminum heat exchanger tubing that is considered the most economical choice for OTEC heat exchangers. The operational parameters of 10MW OTEC plants, 100 MW OTEC plants, and largest-in-class MED plants are compared in Table 20. It is readily apparent that MED plants operate with significantly more chemicals than OTEC plants require. Additionally, OTEC plantdischargeshave lower concentrations of salinity and chlorine that lead to less adverse environmental impacts than MED plants.

Table 20: Comparison of operational parameters of OTEC plants and largest-in-class MED plants

	OTEC (100MW)	OTEC (10MW)	MED Plant[40]
Physical Parameters			
Intake Flow Rate (Q) Surface	420 m^3/s	40-50 m^3/s	47 m^3/s
Intake Flow Rate (Q) Deep Sea	320 m^3/s	30 m^3/s	N/A
Discharge Flow Rate (Q_o)	740 m^3/s	70-80 m^3/s	38 m^3/s
Discharge Temperature (T_o)	5-10°C below ambient	5-10°C below ambient	10-20°C above ambient
Discharge Salinity (ρ_o)	35,000-36,000 mg/L	35,000-36,000 mg/L	50,000-60,000 mg/L
Discharge Plume Buoyancy	Negatively buoyant	Negatively buoyant	Typically positively buoyant, but can be neutral or negatively buoyant
Discharge Dissolved Oxygen (DO)	Slightly below ambient	Slightly below ambient	Slightly below or close to ambient
Biofouling control additives and by-products			
Chlorination Dosage	0.07 mg/L continuous	0.07 mg/L continuous	2.0 mg/L continuous
Chlorine Discharge	0.007-0.018 mg/L	0.007-0.018 mg/L	0.2-0.5 mg/L
Scale Control Additives			
Polymeric antiscalants(e.g. polymaleic acids and phosponates)	N/A	N/A	1-2 mg/L
Acid (H_2SO_4)	N/A	N/A	30-100 mg/L
Foam Control Additives			
Antifoaming agents (e.g. polyglycol)	N/A	N/A	100 mg/L
Corrosion			
Heavy Metals	-Metallic equipment made from steel, aluminum, titanium	-Metallic equipment made from steel, aluminum, titanium	-Metallic equipment made from steel, aluminum, titanium
Corrosion Prevention	-Choice of materials - Galvanic isolation	-Choice of materials - Galvanic isolation	- Feedwater is deaerated -Treated with oxygen scavengers such as sodium bisulfite
Cleaning Solutions			
Cleaning Chemicals	unknown	unknown	Acidic (low pH) washing solution which may contain corrosion inhibitors such as benzotriazole derivatives
Mechanical Methods	-Sponge balls - Brushes	-Sponge balls - Brushes	N/A

[40] Adaptation from "Environmental planning, prediction, and management of brine discharges from desalination plants" by Bleninger, Tobias; Jirka, G. H., 2010.

The typical approach for assembling heat exchangers in an OTEC plant is very similar to that of a thermal desalination plant. Hence, large commercial OTEC plants will require several power modules containing large heat exchangers that are attached to a single offshore platform where all modules are supplied with water from a common network of pumps. This modular approach is typical of how thermal desalination plants scale up in size. For example, desalination developer SIDEM recently constructed a massive MED plant in Marafiq, Saudi Arabia that contains 27 individual evaporator units with surface areas of approximately 156,000 m^2 each, for a total system heat transfer surface area of approximately 4.21 square kilometers (km^2). Likewise, the MED modules receive and discharge seawater by a common network of pumps.

The estimated 4.21 km^2 of heat transfer surface area comprised by the Marafiq plant's evaporators is staggering because this amount of surface area is approximately five times the amount required for a 100 MW OTEC plant. Charlier & Justus (1993) estimated that a 400 MW power plant would require a heat exchanger array with a total heat transfer surface area of 2,600,000 m^2; which was more than 50 times larger than the current largest heat exchanger array in the world, with a total heat transfer surface area of only 46,000 m^2. The Marafiq heat exchangers comprise 90 times more surface area than the "world's largest" heat exchangers reported by Charlier & Justus (1993). This is a clear example that the desalination industry has demolished a benchmark that was once a significant challenge for OTEC.

Chapter 3

Economic Discussion

Plant Scale-Up Costs

The economic projections for OTEC by Vega will be discussed most thoroughly because Vega's publications are the most comprehensive and prevalent among the OTEC research community. One of the cornerstones of Vega's economic discussions is his chart detailing the capital costs for the first and tenth OTEC plants of various electric capacities (Figure 6 on Page 16). In addition to considering the capital costs, it is important to evaluate the levelized cost of electricity that is sold to customers and compare them against competing forms of electricity supply.

As discussed earlier, an alternative approach towards evaluating scale-up costs of OTEC plants is to compare them with desalination plant data. Because of the aforementioned technical similarities between MED and OTEC plants, it is useful to compare the scale-up cost trends for between these two types of plants. The desalination plant cost data from 1970 to 2005 compiled by (Wittholz et. al, 2008) was discussed earlier and will be used to extract specific MED plant cost and associated power law trends. The 34 MED capital cost data points were graphed with their corresponding plant capacities (in m^3/day of fresh water) and yielded a power law exponent of 0.83. Although the authors were not able to publish the actual 34 data points, they summarized the MED capital costs for four different plant capacities that, when plotted on a power law trend line, will represent the 0.83 power law exponent determined from the actual data (Table 21).

Table 21: Summary of MED capital costs for various plant capacities[41]

Capacity (m^3/day)	Capital Cost (X10^6$)
10,000	28.5
50,000	108.4
275,000	446.7
500,000	734.0

[41]Adaptation from "Estimating the cost of desalination plants using a cost database" by Wittholz, Michelle K. ; O'Neil, Brian K. ; Colby, Chris B. ; Lewis, David, 2007.

To provide a useful comparison with the OTEC cost estimations, the above MED cost data must be displayed in an alternative graphical format such that unit cost per capacity is compared with plant capacity. Namely, the MED costs can be converted to thousands of dollars per ten thousand cubic meters a day of capacity [$x10^3/(10,000 m^3/day)]. The transformed units can be displayed graphically with the original power law inverted to demonstrate how the unit cost per capacity decreases with increasing plant capacity (Figure 24).

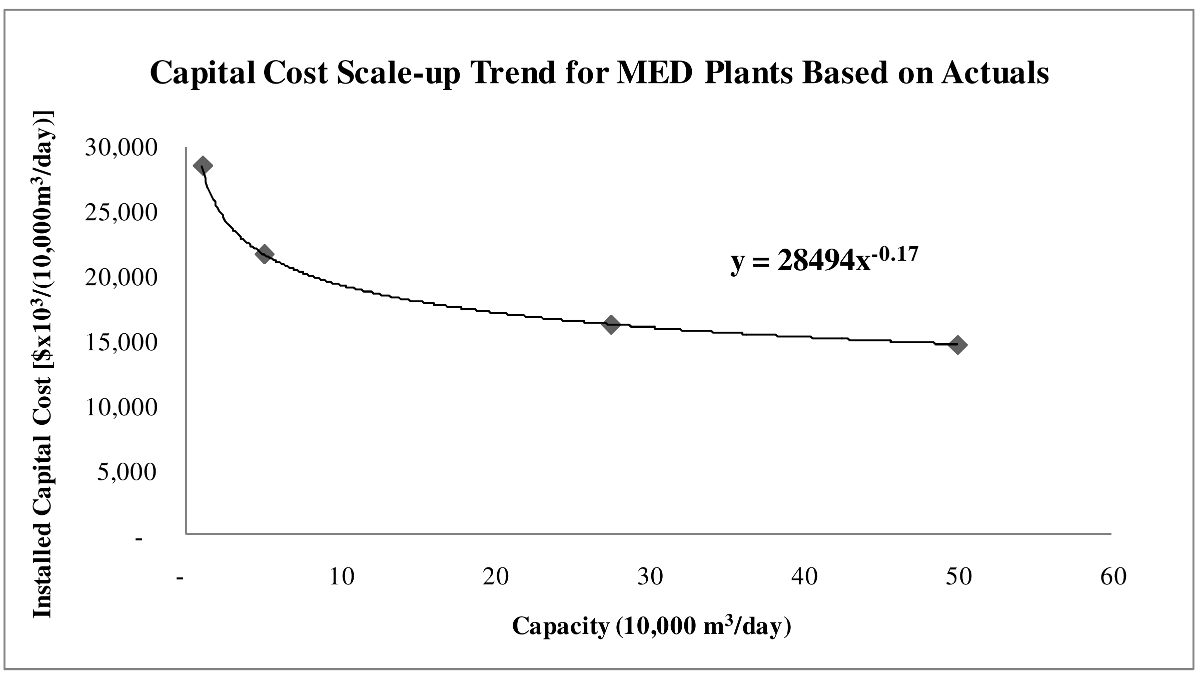


Figure 24: Scale-up trend representing 35 years of MED capital cost data for given plant capacities

The above chart is displaying installed MED capital costs in terms of [$\$x10^3/(10{,}000\ m^3/day)$] whereas Vega's OTEC 10th generation capital costs reported earlier were displayed in terms of $/kW. Vega's 10th generation capital cost curve is more appropriate than his 1st generation capital cost curve because the MED developers are currently reaching or surpassing the 10th generation plant for the given capacities above. It may seem that the direct comparison of OTEC and MED capital costs for a given capacity is meaningless; however, the respective scaling trends can be compared because they both represent the *economy of scale factor* for decreasing capital costs with increasing capacity. Both curves can be fitted on a single graph that can display the differences in the underlying scale-up trends by comparing the power law exponents (Figure 25).

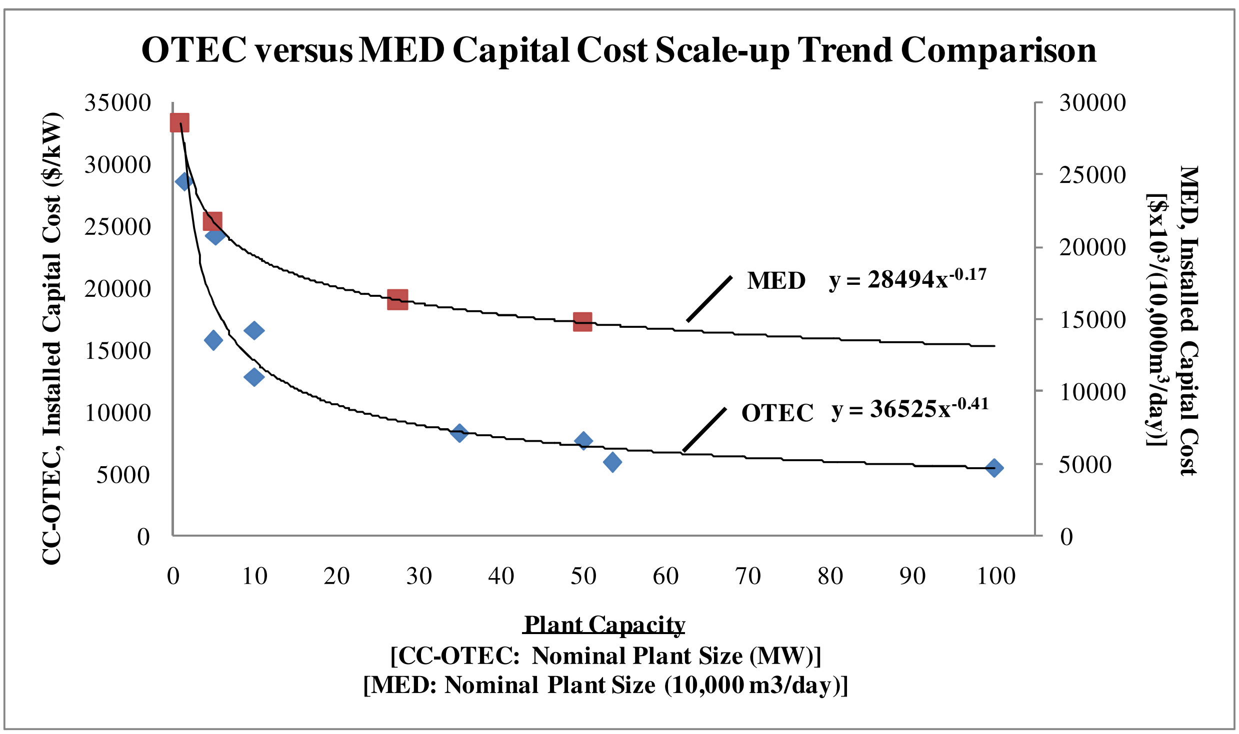


Figure 25: Graph comparing OTEC and MED capital cost scale-up trends for increasing capacities

Although the capital costs for both OTEC plants and MED plants decrease with an increase in plant capacity, it is clear that the economy of scale is significantly different. When evaluating the chart above, it is important to ignore the coefficients in the power law equation for OTEC and MED since these values represent different costs per unit capacity which are not related. The power law exponents are the relevant coefficients for this analysis. It is interesting to note that the MED graph reveals a power law exponent *m* of -0.17 based on actual cost data whereas Vega's estimations generate an *m* value of -0.41. Vega's power law exponent is 2.4 times larger in magnitude, or 2.4 times more aggressive, than the exponent for MED plants. This trend comparison suggests that OTEC will scale-up to larger capacity plants much quicker and more efficiently than thermal desalination plants.

The trend comparison is deemed valid because of the aforementioned technical similarities between MED and OTEC plants in seawater handling, capital equipment, lifecycle cost, and scale-up challenges. The purpose is not to discredit Vega or suggest a new cost scale-up trend for OTEC plants based on data from MED plants, but rather to present the actual economy of scale witnessed in a closely related industry. OTEC plants may have the possibility to scale up to larger capacities with greater reduction in capital costs than MED plants, but the expectations for economy-of-scale should be proposed with caution. Investigation of early thermal desalination publications revealed that the economy-of-scale for larger plants was expected to decrease much more rapidly than it actually did. As desalination plants grew in capacity, they had unexpected cost burdens from operating at less than full capacity, achieving less than the nominal thermal efficiency, and having to absorb increasingly expensive environmental costs.

If the expected economy of scale for power-only OTEC plants is overestimated, it is possible that the coproduction of desalinated water could provide the additional revenue and tax credits to make an OTEC-desalination plant more economical than a traditional power-only OTEC plant. An OTEC plant could also operate as a water-only OTEC plant that would send desalinated water back to shore on a ship at regular intervals, or through use of a flexible pipeline instead of cabling power back to shore. OTEC-desalination scenarios will be presented in more depth later in this discussion.

Heat Exchangers

As previously discussed, heat exchanger cost estimation is a very difficult practice because the overall cost depends on numerous design and operating factors. Material selection has one of the largest impacts on the overall cost of a heat exchanger and forces the end user to consider the lifecycle cost of material alternatives. Additional sensitivity in selecting materials comes from the increasing worldwide demand for metals and other construction materials where the cost of base metal prices has been increasing steadily (and in some cases sharply) within the past 5-10 years. As a result, material selection is exceptionally critical for OTEC since commercial plants will require some of the world's largest arrays of heat exchangers.

OTEC research primarily focuses on titanium and aluminum as the leading candidates for heat exchangers; however, it is evident that the selection criteria must specify the use of welded or seamless tubing to account for critical cost and performance implications. The differences in cost and performance between seamless and welded tubing are not covered thoroughly by other OTEC researchers. One of the few mentions of cost differences between different forms of tubing was described by (Avery & Wu, 1994) in *Renewable Energy From the Ocean: A Guide to OTEC* where the authors explain that roll-welded aluminum tubing costs \$1.5/kg (\$0.68 per pound [lb]), extruded aluminum tubing costs \$2.75/kg (\$1.25/lb), and titanium tubing costs \$10/kg (\$4.54/lb) in \$1994. Although these cost figures are good points of reference, they do not explain whether the tubing is compliant with any particular specification. Heat exchangers constructed and operated in the U. S. and many places elsewhere in the world are strictly governed by the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC) that mandates only tubing produced by specific processes are allowed for use in pressure vessels. As it will be discovered later in this section, all tubing is not created equally and ASME specification tubing can have a much higher cost than non-ASME specification tubing.

It is first necessary to explain the differences and implications of using welded or seamless tubing in OTEC heat exchangers because the lifecycle cost between the two options can vary significantly. Piercing the middle of a solid billet with a bullet-shaped mandrel while the billet is heated and rolled until it stretches to form a hollow tube produces seamless titanium tubing. Since aluminum is a much softer and easier to process, a seamless tube can be produced by piercing a cylindrical cast billet with a solid cylindrical mandrel and extruding over the mandrel and out of the die to the desired length of tubing. Seamless titanium and aluminum tubing have several common specifications published by the ASME BPVC that allow its use in hydraulic or pressure service applications.

Contrary to most industrial welding applications, the process of fabricating welded tubing does not use filler metal and does not leave a raised weld seam. Steel and titanium welded tubing is produced by rolling a strip into a round shape to form a seam that is continuously welded by electric resistance welding. Aluminum tubing can also be formed in this way, but it is not as common as steel and titanium alloys. Interestingly enough, a recent transaction by a Sapa Alutubes resulted in delivery of 880 tons of welded aluminum tubes for a desalination installation in Tianjin, China, indicating a potentially new trend in the use of aluminum welded tubes for seawater desalination (Sapa Group, 2012). Welded aluminum tubing does not have an ASME specification for use in heat exchangers, but can possibly be approved for use if an ASME code case is approved or an exception to an existing code is allowed.

Some tube manufacturers have been using improved welding techniques such as tungsten inert gas (TIG), laser, and plasma to increase reliability of the weld seam of welded tubing. Additionally, manufacturers are employing the use of drawing or cold rolling the tube after the welding process to enhance the material properties of the weld. These manufacturers believe that this drawing process will eliminate preferential corrosion of the weld seam and consequently make performance equivalent with seamless tubing. If these claims are validated by a proven service life, it could allow lower cost welded tubing to replace seamless tubing as a comparable solution for heat exchangers.

Seamless aluminum tubing can be advantageous for OTEC applications because the tubes are better at withstanding hydraulic pressure and are less susceptible to preferential corrosion at weld seams. Various aluminum alloys are included in the ASME specifications as being acceptable for heat exchanger tubing; however, not all alloys are practical in OTEC heat exchangers for cost or performance reasons. A comparison of the various heat exchanger specifications for aluminum tubing is shown in Table 22.

Table 22: Specifications for various aluminum alloys and products approved for pressure applications

Specification	Alloy and Product or Process	Approved for Pressure Applications
ASME SB 241	1060, 1100, 3003, Alclad 3003, 5052, 5083, 5086, 5454, 5456, 6061, and 6063 seamless extruded pipe and tube	Yes
ASME SB 234	1060, 3003, Alclad 3003, 5052, 5454, and 6061 drawn, seamless tube for condensers and heat exchangers	Yes
ASME SB 210	1060, 3003, Aced 3003, 5052, 5154, 6061 and 6063 drawn seamless tube	Yes

Seamless titanium tubing would likely be a candidate for OTEC as well, but seamless titanium tubing is approximately twice as expensive as welded titanium tubing (Purohit, 1983). Fortunately, welded and seamless titanium tubing is acceptable ASME material for heat exchangers. Titanium tubing has fewer specifications than aluminum, but it still has several applicable specifications that need to be specified for OTEC heat exchangers (Table 23).

Table 23: Specifications for various titanium alloys and products approved for pressure applications

Specification	Alloy and Product or Process	Approved for Pressure Applications
ASME SB 337	Grades 1, 2, 3, 4, 7, 9, 11, 12 Seamless and welded pipe	Yes
ASME SB 338	Grades 1, 2, 3, 4, 6, 7, 9, 11, 12 Seamless and welded tube for condensers and heat exchangers	Yes

For OTEC heat exchangers manufactured and operated in the U. S. and its territories, engineers must use ASME approved tubing materials to be compliant with domestic boiler law. OTEC heat exchangers that are operated outside of the U. S. and its territories may not be required to be in accordance with ASME; however, the ASME BPVC is generally accepted as a high standard for pressure vessel construction and represents the quality of workmanship that should be expected for high reliability heat exchanger systems such as OTEC. Using the information above regarding tubing forms and specifications will enable more refined cost estimation.

Estimating the cost of heat exchangers is a difficult practice because of the wide range of end use applications and influence from cost of materials. The estimations will be more accurate if the all the design factors are simplified for a specific application such as OTEC. Material selection will have a profound effect on the overall cost, so the lifecycle costs of the candidate materials must be analyzed. It has been previously introduced that the primary candidate materials for OTEC heat exchangers are titanium and aluminum. Most OTEC researchers have focused the majority of their heat exchanger designs and cost estimations on carbon steel shells with either titanium or aluminum tubing; therefore, these materials will be the focus of the lifecycle cost analysis since they have the greatest interest to the OTEC community. The following paragraphs will apply Purohit's shell and tube cost estimation equations for the OTEC heat exchanger case. Calculations will be derived from the baseline shell and tube heat exchanger defined in Table 24.

Table 24: Definition of baseline shell-and-tube heat exchanger case for developing cost estimations[35]

Parameter	**Base Designation**
Tubes	Welded carbon steel, 14 BWG, average wall
Nominal tube length	20 ft
Number of passes	1 or 2
Shell-side design pressure, psig	≤ 150 psig
Tube-side design pressure, psig	≤ 150 psig
Materials of construction	All carbon steel

[35]Adaptation from "Estimating costs of shell-and-tube heat exchangers" in *Chemical Engineering* by Purohit, G., 1983.

His analysis of purchase prices of many heat exchangers in 1982 generated the following equation for estimating the cost of baseline heat exchanger defined in Table 24 above. The equation establishes the base cost along with cost multipliers to account for deviations in parameters with respect to the baseline heat exchanger (Equation 2). It should be noted that the base price was developed via evaluation of bids from U. S. manufacturers and includes the cost of ASME Section VIII, Division 1 code stamp and exterior paint. The baseline heat exchanger price can be estimated using the following relationship:

$$b = [\frac{6.6}{1 - e^{\left[\frac{7 - Di}{27}\right]}}]pfr \tag{2}$$

Where b = base price (in \$/ft^2); Di= shell inner diameter; p = cost multiplier for tube outside diameter (OD), pitch, and layout angle; f = cost multiplier for Tubular Exchanger Manufacturers Association (TEMA) front head; and r = cost multiplier for TEMA rear head

The cost multipliers are each derived from a table that lists a specific value based on the corresponding heat exchanger design feature (see Appendix for all cost multiplier and correction factor tables). Purohit's baseline heat exchanger case assumes the cost multiplier p = 1.0 for a ¾" tube OD, 1.0" square pitch, and 45° or 90° layout angle; however, for OTEC heat exchangers, the chosen tube configuration for OTEC-1 evaporators and condensers was 1.0" OD titanium tubes with a 1.25" triangular pitch and a 60° layout angle (Avery & Wu, 1994). Likewise, Westinghouse selected 1.0" OD titanium tubes with a 1.25" triangular pitch and a 60° layout angle as their baseline configuration instead of the alternative 1.0" OD aluminum tubes with a 1.25" pitch and a 60° layout angle. Therefore, the baseline OTEC design shall use a p value of 0.98 that corresponds to a 1.0" tube OD with 1.25" pitch and a 60° layout angle. The 0.98 multiplier is lower than the baseline because the triangular pitch has better packing efficiency that translates to slightly lower overall cost.

Next, selecting values for the front-end cost multiplier f and rear-end cost multiplier r could vary based on the installed horizontal or vertical configuration of the heat exchangers. Although both configurations have been proposed by researchers, the vertical orientation is preferred for large diameter heat exchangers to improve waterside flow distribution, reduce pressure drop and optimize assembly of offshore power modules. Bonnets and channels will be simplified for large diameter heat exchangers in the vertical orientation, so the f value can remain as 1.0 for a TEMA B type front-end bonnet and the r value can be 0.8 for a TEMA M type fixed tubesheet rear-end.

The next series of corrections for alternative configurations with respect to the baseline will be summed together and added as a fraction of the base price. The shell type correction accounts for alternative shell designs such as two-pass flow, cross-flow, divided-flow, etc. The baseline assumes a simple, one-pass TEMA E type shell that is common among shell and tube heat exchangers. Because OTEC is water-side limited, one-pass flow has always been a common feature among heat exchanger designs. Thus, OTEC heat exchangers will also have a simple TEMA E type shell and the shell cost correction factor C_S will be zero. Also because of the one-pass flow, the tube pass cost correction factor C_{NTP} will be zero.

Because of the low temperature difference between the water and ammonia, OTEC heat exchangers will not require an expansion joint; therefore, the shell expansion cost correction factor C_X will also be zero. Design pressure of OTEC heat exchangers is typically stated to be 150 psig on the shell side and approximately zero psig on the tube side; therefore, the cost correction factors for shell side pressure C_{PS} and tube side pressure C_{PT} will both be 0 since the baseline heat exchanger case also had shell side and tube side pressures of ≤150 psig. The correction for tube length only affects tubes that are shorter than 20 ft in length because of the extra cutting and scrap costs that manufacturer will bear. The OTEC-1 heat exchangers and Westinghouse heat exchanger designs used longer tube lengths (sometimes twice as long) as the 20 ft standard; therefore, the tube length cost correction factor C_L will be zero.

Up until this point, cost corrections have been minor and it is evident that the OTEC shell-and-tube heat exchanger is very similar to Purohit's baseline heat exchanger. Now, the last set of cost correction factors will be the most controversial because they pertain to the differences in materials of construction. As Purohit notes, material selection can significantly alter the price of heat exchangers, especially since some parts are made from different raw material forms than others. Furthermore, he asserts that the unit labor will decrease with increasing shell diameter while the costs of the shell, channel, and tubesheet will remain constant at 10%, 6%, and 4% respectively relative to the total cost of the baseline carbon steel heat exchanger (Figure 26).

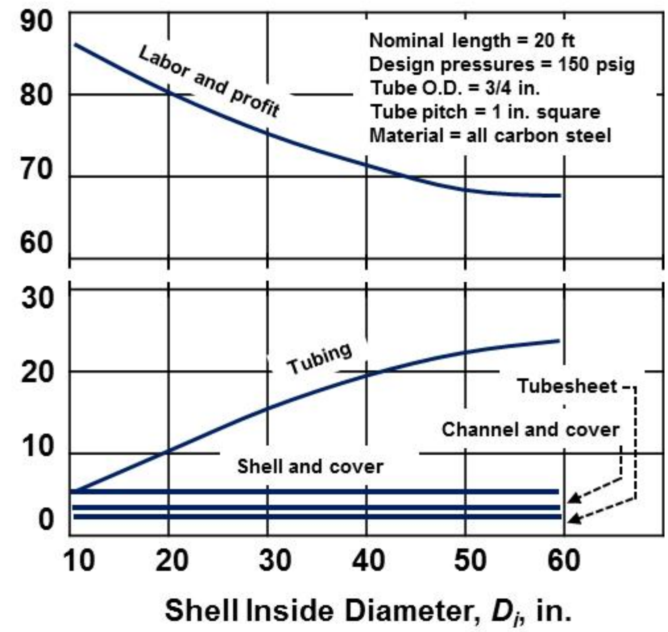


Figure 26: Price breakdown for low-pressure carbon steel heat exchangers[42]

It can be seen from the curves in Figure 26 that the cost of tubing will increase with increasing shell diameter where the cost of carbon steel tubes can be formulated according to Equation 3 below. Because the baseline tube material is carbon steel, the tubing cost will have to be adjusted for OTEC candidate materials titanium and aluminum. The cost correction factor for tube material is shown below in Equation 4. The cost correction factor for shell material is shown below in Equation 5. The cost correction factor for channel material is shown below in Equation 6. The cost correction factor for tubesheet material is shown below in Equation 7.

$$y = 0.129 + 0.0016(Di - 12)\frac{do}{0.75(pi)^2 a} \tag{3}$$

$$C_{mt} = y(M_1 - 1) \tag{4}$$

[42]Reproduced from “Estimating costs of shell-and-tube heat exchangers” in *Chemical Engineering* by Purohit, G., 1983.

$$C_{ms} = 0.1(M_2 - 1) \tag{5}$$

$$C_{mc} = 0.06(M_2 - 1) \tag{6}$$

$$C_{mts} = 0.04(M_2 - 1) \tag{7}$$

Where y = tube cost (in $\$/ft^2$), Di= shell inner diameter, d_o= tube OD, a = pitch pattern, and p_i= tube pitch, M_1 is the ratio of tubing cost (welded or seamless) relative to the cost of welded carbon steel tubes, and M_2 is the ratio of plate materials relative to the cost of carbon steel plate

The M_1 and M_2 cost ratios for carbon steel, titanium, and aluminum are presented in Table 25. Again, these values are based on pricing in \$1982 where Purohit reported ±20% accuracy for price ratios M_1 and M_2. From previous sections, it was determined that seamless aluminum tubing is preferable for corrosion resistance while welded titanium is sufficient to survive 30 years or more in saltwater applications. Furthermore, the shell and channel will likely still be made from carbon steel as discussed previously. For estimating purposes, it can be assumed that the tubesheets will be made from aluminum or titanium plates depending on the corresponding tubes selected. In actual practice, the aluminum tubesheets can be made from forging and the titanium tubesheets can be made from titanium-clad steel plate; however, pricing data for plate are more widely available than specialty, large-size aluminum forgings and titanium-clad steel plates.

Table 25: Price ratios for aluminum and titanium materials relative to carbon steel in $1982[43]

	M_1, Tubing Price Ratio Relative to Welded Carbon Steel Tubes		M_2, Price Ratio for Shell, Channel, and TubesheetRelative to Carbon Steel
Material	Welded	Seamless	
Carbon Steel	1.0 (base)	2.50	1.0 (base)
Aluminum	Not Standard	1.60	1.60
Titanium (grade 2)	11.00	22.00	11.00

[43] Adaptation from "Estimating costs of shell-and-tube heat exchangers" in *Chemical Engineering* by Purohit, G., 1983.

Lastly, these ratios assume the same tube gauge of 14 Birmingham Wire Gauge (BWG) or 0.083" average wall gauge tubing. Since titanium tubing is approximately 50% stronger than aluminum with a higher resistance to corrosion, titanium can have a thinner wall thickness. The aforementioned aluminum tubes considered by Westinghouse had a 0.065" wall, while the titanium tubes had a 0.028" wall (as well as the titanium tubes used in OTEC-1). To correct for the differences in tube gauge, the cost correction as a factor of base price C_g is calculated in Equation 8 and the cost multiplier for tube gauge (g) can be obtained from Figure 27. Since the corresponding gauge for 0.028" wall thickness is 22 BWG for titanium tubes, the corresponding g value for average wall tubing is approximately 0.45. The gauge for 0.065" wall thickness is 16 BWG for aluminum tubes, corresponding with a g value of 0.8 for average wall tubing.

$$C_g = y(g - 1) \tag{8}$$

Where y = tube cost (in \$/ft^2), g = tube gauge or wall thickness, C_g = cost correction as a factor of base price

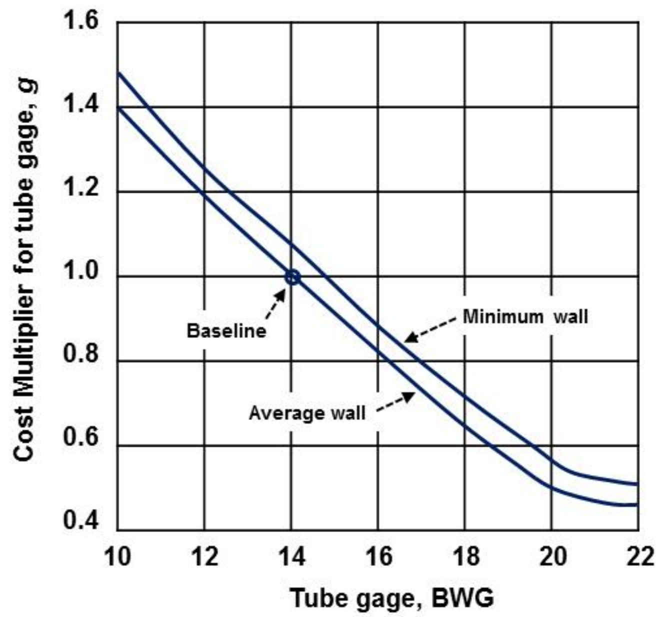


Figure 27: Graph showing values for tube gauge cost multiplier for average wall tubing[44]

It is now appropriate to apply all the equations for the baseline OTEC heat exchangers using the pre-derived cost correction factors. Keeping in mind that Chalier & Justus (1993) estimated a 400 MW OTEC plant would require 2,600,000 m^2 of total heat exchanger surface area, it can be interpolated that a 10 MW OTEC plant would require 1/40th of that figure since the heat exchangers scale linearly with plant capacity. Therefore, the total heat transfer surface area required for a 10 MW OTEC plant would be approximately 65,000 m^2 (700,000 ft^2). Furthermore, it was recently stated by Upshaw (2012) that a 20 MW OTEC plant requires 140,000 m^2 of total heat transfer surface area and it can be assumed that a 10 MW plant would require half the surface area of 70,000 m^2 (753,000 ft^2). Both researchers report surface area totals that are in relative agreement, but the more conservative value of 70,000 m^2 (753,000 ft^2) will be used going forward.

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[44]Reproduced from "Estimating costs of shell-and-tube heat exchangers" in *Chemical Engineering* by Purohit, G., 1983.

Selecting the largest feasible heat exchanger size is beneficial to OTEC since it minimizes pumping and pressure head losses in the system. Thus, a shell diameter of 148” will be assumed for the OTEC baseline heat exchanger calculations after determining in Table 6 on Page 25 that Purohit’s calculations have proven valid up to this large size shell diameter. A tube count estimate for this size shell was determined using a tool called “Process Heat Transfer” developed by Dale Gulley and Gulley & Associates (publically available at www.cheresources.com). It was calculated that a maximum of 12,774 tubes could fit into the 148” diameter heat exchanger assuming 1” OD tubes on a 1.25” triangular pitch. As discussed earlier, tube lengths larger than 20 ftare standard and minimize cutting and scrap costs; therefore, the tube length will be assumed to be 29 ft (approximately 9 m). The tube count and tube length correspond to a heat transfer surface area of 96,983 ft^2 when the entire tube length is utilized for heat transfer; however, because the tube ends are fixed into thick tubesheets, it can be assumed that approximately 4” from each end are not contributing to significant heat transfer. Therefore, the heat transfer surface available per heat exchanger is 94,474 ft^2. A total of eight heat exchangers (four evaporators and four condensers) sums to 755,795 ft^2 of total heat transfer surface area and meets the heat exchanger requirement for a 10 MW plant as discussed above. The design parameters and equation calculations for the baseline titanium heat exchanger is shown in Table 26.

Table 26: Baseline design parameters for OTEC heat exchanger with titanium tubes (top) Equations applied for baseline OTEC heat exchanger with titanium tubes (bottom)

Shell ID (in.) x Nominal Tube Length (in.)	Tube OD (in.) x Pitch (in.) x Layout Angle (degrees)	Tube gauge (in.)	Design Pressures (psig) Shell/Tube	Metallurgy Tube/Shell/ Channel or Bonnet/ Tubesheet
148X 348	$1 \times 1\,{}^{1}/_{4} \times 30$	22 BWG(0.028)	150/10	Ti (Gr2)/CS/CS/Ti(Gr2)

Equation	Result
$\boldsymbol{b = [\frac{6.6}{1-e^{\left[\frac{7-Di}{27}\right]}}]pfr}$	$b = \left[\frac{6.6}{1-e^{\left[\frac{7-148}{27}\right]}}\right]$ 0.98 × 1.0 × 0.8= 5.202 \$/ft^2
$\boldsymbol{y = 0.129 + 0.0016(Di - 12)\frac{do}{0.75(pi)^2 a}}$	$y = 0.129 + 0.0016(148 - 12)\frac{1}{0.75(1.25)^2 \times 0.85} = 0.347$
$\boldsymbol{C_T = C_S + C_X + C_L + C_{NTP} + C_{PS} + C_{PT} + C_{mt} + C_{ms} + C_{mc} + C_{mts} + C_g}$ $\boldsymbol{E_B = [b(1 + C_T) \times A \times N]}$	$C_T = 0 + 0 + 0 + 0 + 0 + 0 + 3.47 + 0 + 0 + 0.4 - 0.19 = 3.68$ $E_B = (5.202(1 + 3.68) \times 94{,}474 \times 1) = \$2{,}300{,}012$

The final estimated cost for the baseline OTEC heat exchanger with titanium tubes is calculated to be \$2,300,012 in 1982. This price is representative of the FOBcost at the manufacturer's shop;Purohit advised that increasing the f.o.b. cost by 1-4% will provide an approximate delivered cost. Furthermore, it was stated earlier by (Sommariva et. al, 2003) that the transportation cost for large MSF and MED evaporators was stated to be 5% of the total cost. Since OTEC heat exchangers are also very large, it is reasonable and conservative to assume a 5% shipping fee. With shipping costs included, the final delivered price of the baseline OTEC heat exchanger with titanium tubes will be \$2,415,013.

Next, it is necessary to apply all the equations for the baseline OTEC heat exchanger with aluminum tubes using the appropriate cost correction factors and equations above. Almost all the quantitative design parameters are the same as for the titanium case except for the tube gauge. The thin wall titanium tubes have an inside diameter of 0.944" while the thicker gauge aluminum tubes have an inside diameter of 0.87". Although the OD and available heat transfer surface area will remain the same, the aluminum tubes have a smaller hydraulic diameter that will result in a slightly higher pressure drop. The higher pressure drop results in slightly more pumping power and can reduce the net efficiency of the plant. Without knowing all of the design factors for pumps and water distribution, it is difficult to estimate the net power loss from the slightly smaller inside diameter; therefore, the added cost for pumping power will be ignored for the moment to allow for a simple cost comparison of heat exchangers on a square footage basis using either titanium or aluminum tubing. The design parameters and equation calculations are shown in Table 27.

Table 27: Baseline design parameters for OTEC heat exchanger with aluminum tubes (top) Equations applied for baseline OTEC heat exchanger with aluminum tubes (bottom)

Shell ID (in.) x Nominal Tube Length (in.)	Tube OD (in.) x Pitch (in.) x Layout Angle (degrees)	Tube gauge (in.)	Design Pressures (psig) Shell/Tube	Metallurgy Tube/Shell/ Channel or Bonnet/ Tubesheet
148X 348	$1 \times 1\,{}^{1}/_{4} \times 30$	16 BWG(0.065)	150/10	Al/CS/CS/Al

Equation	Result
$\boldsymbol{b} = [\frac{\mathbf{6.6}}{\mathbf{1} - \boldsymbol{e}^{\left[\frac{7-Di}{27}\right]}}]\boldsymbol{pfr}$	$b = \left[\frac{6.6}{1-e^{\left[\frac{7-148}{27}\right]}}\right]$ 0.98 × 1.0 × 0.8= 5.202 \$/ft^2
$\boldsymbol{y} = \mathbf{0.129} + \mathbf{0.0016}(\boldsymbol{Di} - \mathbf{12})\frac{\boldsymbol{do}}{\mathbf{0.75}(\boldsymbol{pi})^2\boldsymbol{a}}$	$y = 0.129 + 0.0016(148 - 12)\frac{1}{0.75(1.25)^2 \times 0.85} = 0.347$
$\boldsymbol{C_T} = \boldsymbol{C_S} + \boldsymbol{C_X} + \boldsymbol{C_L} + \boldsymbol{C_{NTP}} + \boldsymbol{C_{PS}} + \boldsymbol{C_{PT}} + \boldsymbol{C_{mt}} + \boldsymbol{C_{ms}} + \boldsymbol{C_{mc}} + \boldsymbol{C_{mts}} + \boldsymbol{C_g}$	$C_T = 0 + 0 + 0 + 0 + 0 + 0 + 0.21 + 0 + 0 + 0.02 - 0.07 = 0.16$
$\boldsymbol{E_B} = [\boldsymbol{b}(\mathbf{1} + \boldsymbol{C_T}) \times \boldsymbol{A} \times \boldsymbol{N}]$	$E_B = (5.202(1 + 0.16) \times 94{,}474 \times 1) = \$570{,}089$

The final estimated cost for the baseline OTEC heat exchanger with aluminum tubes is calculated to be \$570,089 in 1982. With 5% shipping costs included, the final delivered price of the baseline OTEC heat exchanger with aluminum tubes would be \$598,593. Consequently, the cost of OTEC heat exchangers with aluminum tubes is ¼th the cost of OTEC heat exchangers with titanium tubes in 1982. Again, the only quantitative difference is the tube gauge and the only qualitative difference is metallurgy of the tubes and tubesheets; however, Purohit did not detail the type of aluminum he priced for his calculations which has significant impact since marine grade aluminum is significantly more expensive other common grades of aluminum (more detail on aluminum prices will be detailed later in this section). Nevertheless, the 75% savings for choosing aluminum over titanium seems to be an obvious choice, but the lifecycle cost of heat exchangers over 20-30 years must be evaluated as well before deciding on the best candidate material for OTEC.

Now the challenge is bringing these 1982 costs up to 2012 costs with reasonable accuracy. Although some manufacturing technologies now exist that could reduce labor costs, the profit margin may remain the same to offset investments in new technologies and training. In general, Purohit's price breakdown of a low pressure carbon steel heat exchanger should still be accurate by today's pricing structure since heat exchangers are still manufactured using mostly the same methods employed in 1982. Moreover, it will be reasonable to assume that the Purohit'sbaseline carbon steel heat exchanger price in 1982 can be escalated to 2012 prices using the Bureau of Labor Statistics (BLS) annual Producer Price Index (PPI) data. The PPI data accounts for inflation and general increases in raw material and labor for process equipment such as heat exchangers. Although Purohit's baseline heat exchanger is simple enough to apply an index to bring prices up to current, it will not be as simple with the material pricing ratios for aluminum and titanium since these material prices have changed differently with respect to carbon steel over the past 30 years.

Gathering pricing data on titanium has proved to be difficult because the purchase price is influenced heavily by the supplier (i.e. domestic or foreign), quantity being purchased, and other economic factors. Current titanium tubing prices are available from supplier websites such as

Mcmastercarr.com and Onlinemetals.com, but these prices have a large markup and have no volume discounts. Grade 2 titanium tubes with an OD of 0.75" and 1.0" meeting American Society for Testing and Materials (ASTM) B338 specification at McMaster-Carr and Online Metals are priced between $55-$68 per pound for welded tubing and $150-$185/lb for seamless tubing as of mid-2012. Because these are supplier prices for titanium in small lengths and order volumes, this data should not be used since it will make the heat exchanger cost calculations unrealistic.

Extrapolating pricing data from industry publications is an alternate method of obtaining more accurate pricing data, especiallywhen researchers are taking into account the large volume of materials required for energy systems such as OTEC. The proceedings from an OTEC Workshop held at the University of Miami in 1977 divulge some key pricing data for materials being considered for OTEC heat exchangers. At the time, drawn 5052 aluminum was considered for the heat transfer tubes and 5083 aluminum was considered for pressure vessel components such as the tubesheet.Additionally, another design consideration was using titanium tubes with a titanium-clad carbon steel tubesheet and carbon steel pressure vessel. The cost of these heat exchanger materials was estimated to be $2.20/lb for drawn 5052 aluminum tubes, $1.00/lb for 5083 aluminum plate, $5.50/lb for titanium tubes, and $0.36/lb for high strength steel plate (National Science Foundation, 1977). Furthermore, researchers investigating heat exchanger systems for solar energy conversion in 1976 estimated the cost of titanium-clad steel tubesheets to be $7.00/lb for 3/16" thick titanium plate plus $85/sqft to bond the titanium to the carbon steel backer plate (Böer, 1976). Although this pricing data is old, it provides a summary of the prices for OTEC heat exchanger materials around 1977 when worldwide interest in OTEC was very prominent.

These material prices from 1976-1977 can be brought up to 2012 prices using the PPI trends for each individual material. The PPI for titanium is assigned theindustry classification *Nonferrous metal (except for copper and aluminum) rolling, drawing, and extruding* and the product classification is *Titanium and titanium-base mill shapes*. The annual PPI for titanium mill shapes was 40.9 in 1976 and 185.6 in 2012 (Figure 28).

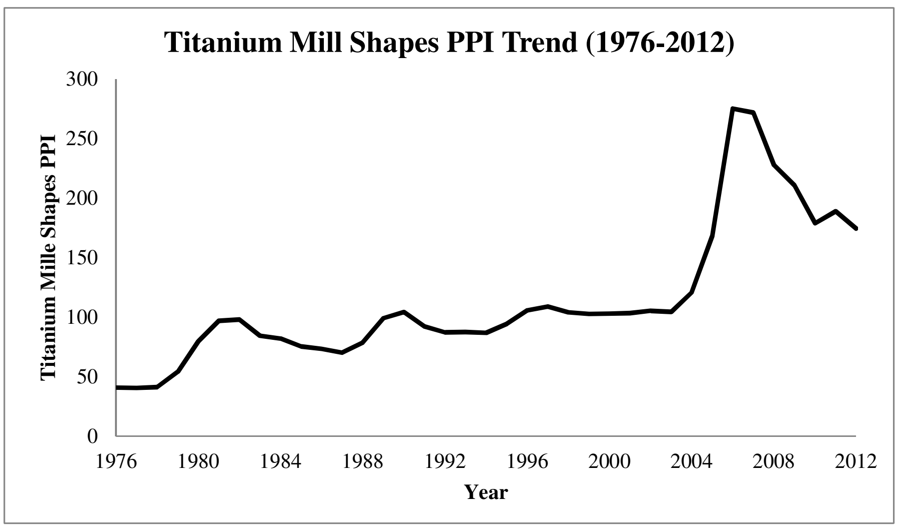

Figure 28: PPI data trend for titanium mill shapes from 1976-2012[45]

Updating the 1977 price for welded titanium tubing at $5.50/lb to 2012 prices using this index generates a price of $23.64/lb. Likewise, using the index of 40.6 in 1976, the $7.00/lb cost of titanium plate would cost approximately $30.09/lb in 2012. It should be understood that titanium mill shapes encompass all mill products such as sheet, plate, forgings, extrusions, etc.; therefore,

[45]Adaptation from Bureau of Labor Statistics(n.d.) Titanium Mill Shapes Producer PriceIndex. Retrieved June 4, 2013, from Bureau of Labor Statistics: http://www.bls.gov

the PPI trend below is tracking an average of mill shape selling prices. Furthermore, the PPI trend does not divulge the periods of supply shortage where end users who typically buy titanium on long-term contracts are forced to purchase titanium on the spot market at higher prices because delivery lead times increase by up to three times during a supply shortage (Seong et.al, 2009). Titanium prices were the highest in 2006 and have since decreased from that level; the drop in titanium prices was predicted by (Thomas & Burlingame, 2007) in 2007 when they anticipated the price for titanium grade 2 would drop gradually over the next two to three years because U. S., Japanese, and Russian titanium producers were making large investments in new production capacity that would enter the market by 2008.

Next, the PPI for aluminum mill shapesis assigned the industry classification *Other aluminum rolling, drawing, and extruding* where the product classification has the same title. The annual PPI for aluminum mill shapes was 58.8 in 1976 and 183.4 in 2012 (Figure 29). Updating the 1977 price for drawn 5052 aluminum tubing at $2.20/lb to 2012 prices using this index generates a price of $6.03/lb. Again, using the index of 66.9 in 1977, the $1.00/lb cost of 5083 aluminum plate would cost approximately $2.74/lb in $2012.

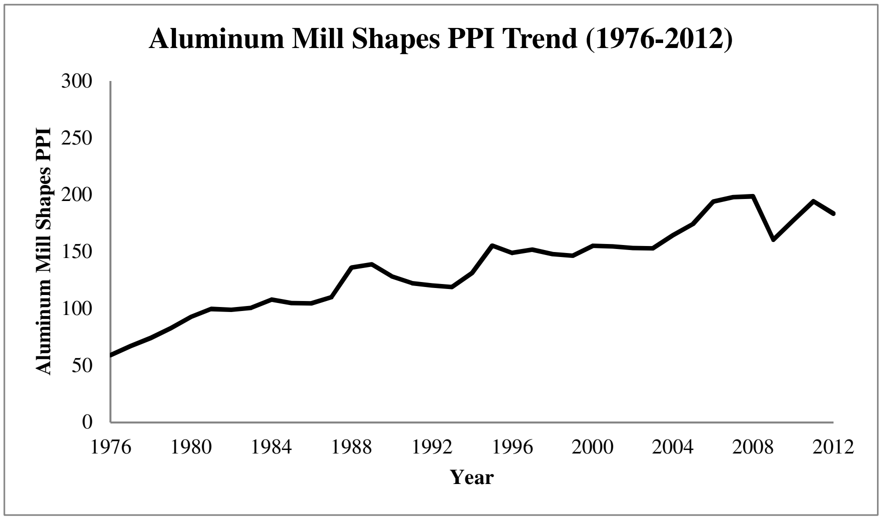

Figure 29: Producer Price Index data trend for aluminum extruded and drawn tube from 1977-2012[46]

The price increase of aluminum mill shapes over this 36 year period is 3.12 whereas the increase for titanium mill shapes over the same period is 4.27; hence, the price of titanium grew about 37% more than aluminum from 1976-2012. Although 2012 titanium prices have leveled off from a drastic spike in 2006, the data trend suggest that the price of titanium is still growing faster than the price of aluminum.In the next section, the PPI data trends will be analyzed to assist with predicting the potential future pricesof titanium and aluminum mill shapes.

Now it is necessary that the baseline carbon steel prices also be updated to current pricing to obtain the proper material price ratios.Carbon steel plate has its own PPI industry classification titled *Iron and steel mills* where the product classification is *Hot rolled steel bars, plates, and structural shapes*. The annual PPI was 64.1 in 1977 and 213.3 in 2012; therefore, multiplying the 1977 high-strength carbon steel plate price of $0.36/lb by (213.3/64.1) yields a 2012 price of $1.20/lb.

[46]Adaptation from Bureau of Labor Statistics(n.d.) Extruded and Drawn Aluminum Tubing Producer Price Index. Retrieved June 4, 2013, from Bureau of Labor Statistics: http://www.bls.gov

Calculating prices carbon steel tubes requires reverse-calculations of Purohit's baseline carbon steel shell and tube equation (Equation 2) to generate the $/lb cost of carbon steel tubes. Taking the data inputs from four all-carbon steel vessels in moderate to large diameters from Purohit's 104 heat exchanger dataset, the reverse calculations yielded carbon steel tube prices of $0.38/lb, $0.46/lb, $0.51/lb, and $0.55/lb. The average price of all four cases is $0.48/lb and will be used as the base price of welded carbon steel tubing in 1982. Once again, current pricing data for large quantities of specific ASTM/ASME grade carbon steel tubing could not be gathered from online metal suppliers; therefore, carbon steel tube prices will be escalated to current prices using the PPI trend. The PPI for carbon steel tubes falls under the industry classification *Iron and steel mills* and the product classification is *Steel pipe and tube, made in steel mills producing semi-finished shapes or plate.* The annual PPI was 99.4 in 1982 and 296.9 in 2012; therefore, multiplying the 1982 carbon steel tube price of $0.48/lb by (269.9/99.4) yields a 2012 price of $1.43/lb. Finally, all these $/lb pricing ratios can now be factored against the base cost of welded carbon steel tubes, M_1, and carbon steel shell, channel, and tubesheet, M_2 (Table 28). Updated pricing for seamless carbon steel and titanium tubes are omitted from Table 28 since these materials are not considered for OTEC heat exchanger estimates.

Table 28: Showing updated 2012 price ratios for aluminum and titanium tubing compared to carbon steel

	M_1, Tubing Price Ratio Relative to Welded Carbon Steel Tubes		**M_2, Price Ratio for Shell, Channel, and TubesheetRelative to Carbon Steel**
Material	Welded	Seamless	
Carbon Steel	1.0 (base)	N/A	1.0 (base)
Aluminum	Not Standard	4.22	2.28
Titanium (grade 2)	16.53	N/A	25.08

Lastly, it is deemed appropriate to escalate the baseline shell and tube equation *b* up to current pricing using the PPI industry data for *Power boiler and heat exchanger manufacturing* where the product being tracked is *Fabricated heat exchangers and steam condensers (except for nuclear applications)*. The PPI index in 1982 was 121.2 and the index for 2012 was 325.0; therefore, the baseline cost equation will be multiplied by (325.0/121.2) or 2.68. The new cost factors for titanium will be substituted into the calculations in Table 29.

Table 29: Baseline design parameters for OTEC heat exchanger with titanium tubes (top) Equations applied for baseline OTEC heat exchanger with titanium tubes (bottom)

Shell ID (in.) x Nominal Tube Length (in.)	Tube OD (in.) x Pitch (in.) x Layout Angle (degrees)	Tube Gauge (in.)	Design Pressures (psig) Shell/Tube	Metallurgy Tube/Shell/ Channel or Bonnet/ Tubesheet
148X 348	$1 \times 1\,{}^{1}/_{4} \times 30$	22 BWG(0.028)	150/10	Ti (Gr2)/CS/CS/Ti(Gr2)

Equation	Result
$\boldsymbol{b = \left[\frac{6.6}{1 - e^{\left[\frac{7-Di}{27}\right]}}\right] pfr \times 2.06}$	$b = \left[\frac{6.6}{1-e^{\left[\frac{7-148}{27}\right]}}\right] 0.98 \times 1.0 \times 0.8 \times 2.68 = 13.951$ \$/ft^2
$\boldsymbol{y = 0.129 + 0.0016(Di - 12)\frac{do}{0.75(pi)^2 a}}$	$y = 0.129 + 0.0016(148 - 12)\frac{1}{0.75(1.25)^2 \times 0.85} = 0.347$
$\boldsymbol{C_T = C_S + C_X + C_L + C_{NTP} + C_{PS} + C_{PT} + C_{mt} + C_{ms} + C_{mc} + C_{mts} + C_g}$ $\boldsymbol{E_B = [b(1 + C_T) \times A \times N]}$	$C_T = 0 + 0 + 0 + 0 + 0 + 0 + 5.39 + 0 + 0 + 0.96 - 0.19 = 6.16$ $E_B = (13.951(1 + 6.16) \times 94{,}474 \times 1) = \$9{,}436{,}965$

The cost for the same baseline titanium heat exchanger design is now estimated to be $9,436,965 in $2012. This estimate is much higher than the 1982 estimate mostly because the total cost is heavily influenced by the cost of the tubes. It was demonstrated earlier that the cost of titanium has increased significantly since 1982, but more importantly, its price ratio to carbon steel has increased as well. Since the price for pure titanium plate was assumed for the tubesheet, it has the opportunity to be reduced using titanium-clad steel instead.Westinghouse described using titanium-clad steel tubesheets in their 1977 design in order to save material costs (Westinghouse Electric Corporation, 1978). Furthermore, titanium-clad tubesheets are more typical than a pure titanium plate tubesheet for this size heat exchanger, so it can be assumed that a 50% reduction in cost can be realized for the tubesheet material. An additional case with this modified material ratio will be presented later in this discussion.

Next, the baseline aluminum heat exchanger design will be escalate to current pricing to evaluate how the cost has changed since 1982. The new calculations for aluminum heat exchangers using the updated cost factors are shown in Table 30.

Table 30: Baseline design parameters for OTEC heat exchanger with aluminum tubes (top) Equations applied for baseline OTEC heat exchanger with aluminum tubes (bottom)

Shell ID (in.) x Nominal Tube Length (in.)	Tube OD (in.) x Pitch (in.) x Layout Angle (degrees)	Tube Gauge (in.)	Design Pressures (psig) Shell/Tube	Metallurgy Tube/Shell/ Channel or Bonnet/ Tubesheet
148X 348	$1 \times 1\,^1\!/_4 \times 30$	16 BWG(0.065)	150/10	Al/CS/CS/Al

Equation	**Result**
$\boldsymbol{b = \left[\frac{6.6}{1-e^{\left[\frac{7-Di}{27}\right]}}\right] pfr \times 2.06}$	$b = \left[\frac{6.6}{1-e^{\left[\frac{7-148}{27}\right]}}\right]$ 0.98 × 1.0 × 0.8 × 2.06= 13.951 \$/ft^2
$\boldsymbol{y = 0.129 + 0.0016(Di - 12)\frac{do}{0.75(pi)^2 a}}$	$y = 0.129 + 0.0016(148 - 12)\frac{1}{0.75(1.25)^2 \times 0.85} = 0.347$
$\boldsymbol{C_T = C_S + C_X + C_L + C_{NTP} + C_{PS} + C_{PT} + C_{mt} + C_{ms} + C_{mc} + C_{mts} + C_g}$ $\boldsymbol{E_B = [b(1 + C_T) \times A \times N]}$	$C_T = 0 + 0 + 0 + 0 + 0 + 0 + 1.12 + 0 + 0 + 0.05 - 0.07 = 1.10$ $E_B = (13.951(1 + 1.12) \times 94{,}474 \times 1) = \$2{,}767{,}825$

The cost for the same baseline aluminum heat exchanger design is now estimated to be \$2,767,825 in \$2012. This estimate is also significantly more than the 1982 estimate and seems appropriate given the increases in tube costs. The cost of this aluminum heat exchanger could be criticized for being too low for a couple of technical reasons 1) this baseline design uses seamless drawn tubes at a 348" length which might limit the number of mills with sufficient drawing length since 240" is typically the standard production length 2) the tube gauge of 0.065" used as a baseline by Westinghouse is a fairly thin gauge for aluminum that might not have adequate resistance to pitting and 3) this cost model uses typical aluminum plate prices and does not consider the more realistic option of using aluminum-clad steel as described by Westinghouse in their baseline aluminum heat exchanger design. In addition, IDE Technologies reported successful use of aluminum tubes when the gauge was 0.069” to 0.098”; thus, 0.065” is less than the lower bound prescribed by IDE for aluminum tube gauge. It would be more conservative to assume a tube gauge of 0.095 (13 BWG) or 0.109” (14 BWG) for first generation OTEC plants since it is at the higher end of IDE’s tube gauge range. The 14 BWG tube gauge will be selected since it is above the upper bound of IDE’s tube gauge range and isa more conservative choice for OTEC. This increase in wall thickness will change the tube gauge correction factor and increase tubing costs because of the increase in the weight of aluminum. Given the new assumptions for aluminum and titanium described above, a modified material ratio table is presented in Table 31.

Table 31: Showing modified 2012 price ratios for aluminum and titanium tubing compared to carbon steel

	M_1, Tubing Price Ratio Relative to Welded Carbon Steel Tubes		**M_2, Price Ratio for Shell, Channel, and TubesheetRelative to Carbon Steel**
Material	Welded	Seamless	
Carbon Steel	1.0 (base)	N/A	1.0 (base)
Aluminum	Not Standard	6.33	4.57 (Al-clad)
Titanium (grade 2)	16.53	N/A	12.54 (Ti-clad)

Inputting these new values into the above calculations for the 2012 baseline titanium and aluminum heat exchangers yields more realistic results. Using the same equations for the previous baseline cases, the new cost of the baseline aluminum heat exchanger is estimated to be \$4,033,116. Adding the 5% shipping cost of \$201,656 increases the total delivered cost to \$4,234,772 per unit. Moreover, the baseline titanium heat exchanger is now estimated to be \$8,777,959. The 5% shipping fee equates to an unrealistic \$438,898; therefore, it is assumed that the shipping cost will be equivalent to the baseline aluminum heat exchanger cost since both heat exchangers are the same diameter, length, and approximate weight. The addition of $201,656 shipping costs brings the total delivered titanium heat exchanger cost to $8,979,615 per unit. Since a 10 MW plant requires eight of these size heat exchangers (assuming a total heat transfer surface area of 70,000 m^2 {753,000 ft^2} used earlier), the total initial investment required for 8 titanium heat exchangers would be $71,836,920 and the total initial investment required for aluminum heat exchangers would be $33,878,178.

The baseline titanium case is 2.12 times more expensive than the aluminum case using the updated estimation equations above. With this modified case, however, the aluminum tube inside diameter is now significantly smaller at 0.782” versus titanium tube inside diameter of 0.944”; which translates to a higher pressure drop, more pumping power, and slightly less net power gain for the aluminum heat exchanger option. Since the pumping design and thermal analysis are outside the scope of this paper, it will be simply assumed that two additional aluminum heat exchangers are required to maintain an equivalent thermal performance and waterside pressure drop with the titanium case. Therefore, the renewed total investment for aluminum heat exchangers is now $42,347,722 and the titanium case is still 1.70 times more expensive. Despite the initial investment cost advantage of aluminum over titanium heat exchangers, the lifecycle cost will be the defining factor in making the proper selection for OTEC. These heat exchanger investment costs presented above will be included in a lifecycle cost analysis in the next section.

Overall, tailoring Purohit's shell and tube cost estimation method specifically for the OTEC application is a comprehensive and progressive approach to understanding the cost breakdown of one of OTEC's largest capital costs. Accounting for significant cost drivers such as shell size and material prices improves the legitimacy of the estimate, but the output can still only serve as a refined estimate of the true cost. Nevertheless, this analysis has created a baseline set of design parameters for OTEC heat exchangers that developers can use as a tool to assist with validating heat exchanger cost predictions. Developers at professional organizations have the ability to acquire more accurate and representative responses to material pricing requests during the planning stages of OTEC projects. Current and accurate material prices can be inputted into this model to provide more reliable estimations that reflect current market prices and material availability.

Lifecycle Cost Analysis

The expected lifetime of titanium and aluminum tubes in seawater service must be defined before performing a lifecycle cost analysis. The knowledge regarding the expected lifetime of titanium is still consistent and has not changed much since Westinghouse's 1977 OTEC lifecycle cost analysis. Titanium tubes can fail if they experience galvanic corrosion or excessive erosion, but the probable life values are expected to remain at the same values that Westinghouse reported. The knowledge regarding expected lifetime of aluminum tubes has changed since aluminum has been used successfully in desalination operations beginning in the 1980s. The operational data of aluminum tubes in MED plants results in three different expected lifetime scenarios: 1) the Virgin Islands MED tubes lasted for 30 years without significant retubing 2) the undisclosed data acquired by the IAEA led them to recommend a service life of 15 years and 3) the Guantanamo Bay Cuba MED plant only lasted for 10 years because of corrosion and scaling problems. Since this information was not able during Westinghouse's 1977 OTEC design phase, it is appropriate to update their lifecycle analysis chart for titanium and aluminum tubes (Table 32).

Table 32: The updated life expectancies for titanium and aluminum tubes in OTEC seawater service

	Titanium	Aluminum
Shortest Probable Life	20 years	10 years
Most Probable Life	30 years	15 years
Longest Probable Life	40 years	30 years

It is important to note that the probable life estimates listed for aluminum are based on service in surface seawater desalination plants. Thus, the probable life estimates for aluminum in Table 32 are only valid for OTEC evaporators processing surface seawater. As mentioned earlier, deep seawater has a lower pH and lower temperature than surface seawater and will lead to accelerated pitting of aluminum. Since insufficient long-term data exists on the corrosion resistance of aluminum in deep seawater, the probable lifetimes cannot be estimated based upon an operating record. Nevertheless, for the purposes of generating a lifecycle cost analysis for both the evaporators and condensers, it can be assumed for now that the condensers and evaporators will both exhibit the probable lifetimes shown above. The probable lifetimes for aluminum survivability in deep seawater can be updated as more testing data and operational records become available.

The expected lifetimes for titanium and aluminum tubes have drastic impacts on the lifecycle cost analysis considering OTEC plants are designed for a life of 20-30 years. A lifecycle cost analysis will be performed for a 10 MW OTEC plant using the heat exchanger costs derived in the previous section. The lifecycle cost analysis will include cases for a 10, 15, and 30 year lifetime of aluminum and a 30-year lifetime for titanium. For both aluminum and titanium heat exchangers the carbon steel pressure vessel shells are expected to last the entire 30 years without refurbishment; however, replacing the aluminum tube bundles at the intervals discussed above will require a substantial effort to remove the heat exchangers from the OTEC plant and relocate back to the OEM for integrating the new tube bundle. As such, it will be assumed that a new investment in tubes and associated labor to reconstruct the heat exchanger will occur.

The cash flow analysis assumes straight-line depreciation with no salvage value for the heat exchanger and tube components after the full useful life is attained. The cash flow comparison between the aluminum and titanium scenarios will only consider the initial cost of the heat exchangers and subsequent cost of tube bundle replacement in addition to tax savings realized through depreciation of the heat exchanger and replacement of tube bundles. The present value of the initial investments and savings will be compared for the full 30-year life of the plant using the present worth factor shown as Equation 9:

$$p = \left(\frac{1+e}{1+m}\right)^n \qquad (9)$$

Present worth factor (p) where e = annual inflation (escalation) rate, m = interest rate, and n = year of transaction

Westinghouse originally assumed the inflation rate to be 6% and the interest rate to be 10%. In a 2010 economic assessment of OTEC by Vega, he has assumed a 3% inflation rate and an 8% interest rate on a commercial loan for his calculations; therefore, these values are deemed more realistic and will be used for the cash flow analysis going forward. Nevertheless, the guidelines assumed by Westinghouse for their cash flow analysis will be used because many items typically included in a discounted cash flow statement are omitted in this analysis because they are not influenced by the choice of material or tube bundle replacement frequency. Namely, the items not considered in this cash flow comparison are:

- Balance of plant financing (platform, turbine-generators, CWP, etc.)
- Routine O&M expense
- Insurance expense
- Taxes other than income tax
- Administrative and general expenses
- Revenue from sale of power

The tax savings realized in this analysis comes from the present value of the annual depreciation expense multiplied by the corporate income tax rate, assumed to be 40% for this case. To maintain a conservative estimate, tax incentives and environmental credits are not considered in this analysis.

Using the same assumptions as Westinghouse, it can be assumed with 97% confidence that the lifetime of titanium tubes fall within a tight range of 20-40 years with an expected average of 30 years. The remaining baseline heat exchanger components are also expected to last for 30 years; therefore, a 30-year case for titanium heat exchangers will be evaluated using a discounted cash flow summary (Table 33). It will be assumed that the scrap value of titanium tubes and other components will be balanced out by the cost of disassembly and transportation to a scrap vendor.

Since it is probable that the aluminum heat exchangers might have to be replaced sometime over the 30-year life, the replacement cost is critical for an accurate lifecycle cost assessment. When the tube life has been fully expended at 10, 15, or 30 years, the remaining components of the heat exchanger (shell, channels, tubesheet, etc.) still have useful life remaining and can be reused and refurbished if necessary. Nevertheless, the cost of replacing all the aluminum heat exchangers will be taken as the original cost since the transportation, disassembly, and refurbishment cost will likely balance out the material savings for reusing the components mentioned above. The discounted cash flow summary for aluminum heat exchangers with 10-year, 15-year, and 30-year tube lifecycles are shown in Table 34, Table 35, and Table 36, respectively. The same assumption applies for aluminum heat exchanger scrap value as stated for titanium above.

Table 33: Discounted cash flow summary for titanium heat exchangers with 30-year tube life

Titanium Discounted Cash Flow Summary				
	Investment	Depreciation		
(in $M)	Heat Exchanger	Heat Exchanger	Tax Savings Due to Depr	Hxs Total
Year	Pres Value	Pres Value	Pres Value	Pres Value
1	71.84	-2.39	-0.96	70.88
2	0.00	-2.31	-0.92	-0.92
3	0.00	-2.22	-0.89	-0.89
4	0.00	-2.14	-0.86	-0.86
5	0.00	-2.06	-0.83	-0.83
6	0.00	-1.99	-0.80	-0.80
7	0.00	-1.92	-0.77	-0.77
8	0.00	-1.85	-0.74	-0.74
9	0.00	-1.78	-0.71	-0.71
10	0.00	-1.72	-0.69	-0.69
11	0.00	-1.65	-0.66	-0.66
12	0.00	-1.59	-0.64	-0.64
13	0.00	-1.54	-0.61	-0.61
14	0.00	-1.48	-0.59	-0.59
15	0.00	-1.43	-0.57	-0.57
16	0.00	-1.37	-0.55	-0.55
17	0.00	-1.32	-0.53	-0.53
18	0.00	-1.28	-0.51	-0.51
19	0.00	-1.23	-0.49	-0.49
20	0.00	-1.18	-0.47	-0.47
21	0.00	-1.14	-0.46	-0.46
22	0.00	-1.10	-0.44	-0.44
23	0.00	-1.06	-0.42	-0.42
24	0.00	-1.02	-0.41	-0.41
25	0.00	-0.98	-0.39	-0.39
26	0.00	-0.95	-0.38	-0.38
27	0.00	-0.91	-0.37	-0.37
28	0.00	-0.88	-0.35	-0.35
29	0.00	-0.85	-0.34	-0.34
30	0.00	-0.82	-0.33	-0.33
Subtotal	71.84		-17.67	54.17
Salvage	0			0
Total	71.84			54.17

Table 34: Discounted cash flow summary for aluminum heat exchangers with 10-year tube life

Aluminum Discounted Cash Flow Summary (10-year tube life)				
	Investment	Depreciation		
(in $M)	Heat Exchanger	Heat Exchanger	Tax Savings Due to Depr	Total
Year	Pres Value	Pres Value	Pres Value	Pres Value
1	42.35	-4.24	-1.69	40.66
2	0.00	-4.04	-1.62	-1.62
3	0.00	-3.85	-1.54	-1.54
4	0.00	-3.67	-1.47	-1.47
5	0.00	-3.50	-1.40	-1.40
6	0.00	-3.34	-1.34	-1.34
7	0.00	-3.19	-1.27	-1.27
8	0.00	-3.04	-1.22	-1.22
9	0.00	-2.90	-1.16	-1.16
10	42.35	-4.24	-1.69	40.66
11	0.00	-4.04	-1.62	-1.62
12	0.00	-3.85	-1.54	-1.54
13	0.00	-3.67	-1.47	-1.47
14	0.00	-3.50	-1.40	-1.40
15	0.00	-3.34	-1.34	-1.34
16	0.00	-3.19	-1.27	-1.27
17	0.00	-3.04	-1.22	-1.22
18	0.00	-2.90	-1.16	-1.16
19	0.00	-2.76	-1.11	-1.11
20	42.35	-4.24	-1.69	40.66
21	0.00	-4.04	-1.62	-1.62
22	0.00	-3.85	-1.54	-1.54
23	0.00	-3.67	-1.47	-1.47
24	0.00	-3.50	-1.40	-1.40
25	0.00	-3.34	-1.34	-1.34
26	0.00	-3.19	-1.27	-1.27
27	0.00	-3.04	-1.22	-1.22
28	0.00	-2.90	-1.16	-1.16
29	0.00	-2.76	-1.11	-1.11
30	0.00	-2.64	-1.05	-1.05
Subtotal	127.05		-41.39	85.66
Salvage	0			0
Total	127.05			85.66

Table 35: Discounted cash flow summary for aluminum heat exchangers with 15-year tube life

Aluminum Discounted Cash Flow Summary (15-year tube life)				
	Investment	Depreciation		
(in $M)	Heat Exchanger	Heat Exchanger	Tax Savings Due to Depr	Total
Year	Pres Value	Pres Value	Pres Value	Pres Value
1	42.35	-2.82	-1.13	41.22
2	0.00	-2.69	-1.08	-1.08
3	0.00	-2.57	-1.03	-1.03
4	0.00	-2.45	-0.98	-0.98
5	0.00	-2.34	-0.93	-0.93
6	0.00	-2.23	-0.89	-0.89
7	0.00	-2.12	-0.85	-0.85
8	0.00	-2.03	-0.81	-0.81
9	0.00	-1.93	-0.77	-0.77
10	0.00	-1.84	-0.74	-0.74
11	0.00	-1.76	-0.70	-0.70
12	0.00	-1.68	-0.67	-0.67
13	0.00	-1.60	-0.64	-0.64
14	0.00	-1.52	-0.61	-0.61
15	42.35	-2.82	-1.13	41.22
16	0.00	-2.69	-1.08	-1.08
17	0.00	-2.57	-1.03	-1.03
18	0.00	-2.45	-0.98	-0.98
19	0.00	-2.34	-0.93	-0.93
20	0.00	-2.23	-0.89	-0.89
21	0.00	-2.12	-0.85	-0.85
22	0.00	-2.03	-0.81	-0.81
23	0.00	-1.93	-0.77	-0.77
24	0.00	-1.84	-0.74	-0.74
25	0.00	-1.76	-0.70	-0.70
26	0.00	-1.68	-0.67	-0.67
27	0.00	-1.60	-0.64	-0.64
28	0.00	-1.52	-0.61	-0.61
29	0.00	-1.45	-0.58	-0.58
30	0.00	-1.39	-0.55	-0.55
Subtotal	84.70		-24.80	59.90
Salvage	0			0
Total	84.70			59.90

Table 36: Discounted cash flow summary for aluminum heat exchangers with 30-year tube life

Aluminum Discounted Cash Flow Summary (30-year tube life)				
	Investment	Depreciation		
(in $M)	Heat Exchanger	Heat Exchanger	Tax Savings Due to Depr	Total
Year	Pres Value	Pres Value	Pres Value	Pres Value
1	42.35	-1.41	-0.56	41.79
2	0.00	-1.35	-0.54	-0.54
3	0.00	-1.28	-0.51	-0.51
4	0.00	-1.22	-0.49	-0.49
5	0.00	-1.17	-0.47	-0.47
6	0.00	-1.11	-0.45	-0.45
7	0.00	-1.06	-0.42	-0.42
8	0.00	-1.01	-0.41	-0.41
9	0.00	-0.97	-0.39	-0.39
10	0.00	-0.92	-0.37	-0.37
11	0.00	-0.88	-0.35	-0.35
12	0.00	-0.84	-0.34	-0.34
13	0.00	-0.80	-0.32	-0.32
14	0.00	-0.76	-0.30	-0.30
15	0.00	-0.73	-0.29	-0.29
16	0.00	-0.69	-0.28	-0.28
17	0.00	-0.66	-0.26	-0.26
18	0.00	-0.63	-0.25	-0.25
19	0.00	-0.60	-0.24	-0.24
20	0.00	-0.57	-0.23	-0.23
21	0.00	-0.55	-0.22	-0.22
22	0.00	-0.52	-0.21	-0.21
23	0.00	-0.50	-0.20	-0.20
24	0.00	-0.47	-0.19	-0.19
25	0.00	-0.45	-0.18	-0.18
26	0.00	-0.43	-0.17	-0.17
27	0.00	-0.41	-0.16	-0.16
28	0.00	-0.39	-0.16	-0.16
29	0.00	-0.37	-0.15	-0.15
30	0.00	-0.36	-0.14	-0.14
Subtotal	42.35		-9.25	33.10
Salvage	0			0
Total	42.35			33.10

Using the discounted cash flow analyses presented above for the most probable tube lifetimes, there is a 50% probability that the lifecycle cost of aluminum tubes will be 1.1 times more expensive than the titanium tubes over the 30-year life of a 10 MW OTEC plant. This factor tells us that the even if the aluminum heat exchangers are completely replaced once in a 30-year period, the overall lifecycle cost will be 1.1 times as expensive as the titanium heat exchangers. In the worst-case scenario that the aluminum tubes last only 10 years and require a complete heat exchanger replacement two times over the 30-year period, the lifecycle cost of the aluminum heat exchangers will be 1.6 times more expensive than the titanium heat exchangers over the 30-year period. Lastly, in the event that the aluminum tubes could last for 30 years without replacement, the titanium heat exchangers would cost 1.6 times more than the aluminum heat exchangers over the 30-year period (Table 37).

Table 377: Summary of present value and overall cost for aluminum relative to 30-year life titanium

	Total Present Value (in $M)	**Cost Relative to Titanium** (30-yr life)
Titanium (30-yr life)	54.17	1.0
Aluminum (10-yr life)	85.66	1.6
Aluminum (15-yr life)	59.90	1.1
Aluminum (30-yr life)	33.10	0.6

Whether titanium or aluminum heat exchangers are used, the future of OTEC plant production is dependent on substantial investments in heat exchanger capital expenditures. As discussed earlier, it is assumed that 3-5 TW is the maximum OTEC capacity available in the tropics without causing adverse effects to the ocean environment. Assuming the more conservative estimate, the maximum number of OTEC plants operating in the tropics (with suitable distribution around the world) can be up to 3 TW at any given time. Nevertheless, it could take 50-100 years to reach the steady-state production of OTEC plants where the network of plants are sustainably producing 3 TW of power while older plants are replaced with new plants every 30 years to maintain the 3 TW maximum capacity. Consequently, if the oldest 100 gigawatt (GW)-worth of OTEC plants reached their full useful life every year, then 100 GW of new plants must be commissioned that same year to replenish the deficit.

Because the heat exchanger costs scale linearly for larger sizes of OTEC plants, the heat exchanger costs derived earlier can be applied to match the steady state demand for a100 GW-worth of OTEC heat exchangers every year. The cost for 30-year life titanium and 30-year life aluminum heat exchangers will be considered as a high and low cost scenario with no adjustments for inflation, raw material price escalation, or production efficiencies. At steady state, the OTEC market at full capacity would require a heat exchanger investment of approximately $220B to $800B every year. It can be assumed that aluminum is the long-term solution for OTEC at steady state based upon sheer availability of aluminum versus titanium in the Earth's crust. With aluminum tubes being approximately 50% of the total heat exchanger cost for large OTEC heat exchangers, the cost of aluminum tubing alone would exceed $100B a year at steady state. To put it in perspective, there were approximately 386 companies operating within the aluminum extrusion industry in 2009, of which, their shipments totaled $2.1B for all extruded products (High Beam Business, 2010). If tubes represented even half of the total products shipped in 2009, then the aluminum tube production is currently a $1B industry. Thus, in order for OTEC to reach its maximum global capacity of 3 TW, the industry production of aluminum tubes would have to increase a *hundredfold* solely to meet the demands of OTEC.

Chapter 4

OTEC and Desalination Integration

The concept of using an OTEC plant for the multi-mode function of producing power and desalinated water has changed greatly since it was first proved by experiment in the late 1980s. Land-based OC-OTEC plants up to 50 MW conceived by Vega and others would include a second stage condenser that converts water vapor rejected from the turbine into fresh water. Alternatively, it has been proposed to deploy 100 MW CC-OTEC floating plants co-located with RO equipment aboard the offshore rig to produce fresh water using a small portion of the net power produced (Vega, 2010). To date, *offshore* OTEC-desalination has never been demonstrated; however, offshore desalination vessels have emerged on their own using diesel generators to power onboard RO equipment for customers with short-term desalination needs. Now that offshore desalination vessels have become a reality, a substantial opportunity exists to integrate the commercialization path of OTEC with the need for offshore desalination capacity.

It is necessary to evaluate the cost-effectiveness of using OTEC as a method for desalination versus conventional and alternative energy-supplied methods. The option for co-locating desalination with a CC-OTEC system is more tangible and can provide the lowest cost of desalinated water. The space requirement for a given desalination process is drastically important considering it will be located aboard an offshore vessel. In a typical land-based desalination plant, MSF units typically required almost twice the amount of space as required by RO units with an equal discharge (El-Gamal & Abdrabbo, 2004). Consequently, RO has been the only desalination method used in offshore desalination plants and should be the only consideration for OTEC-desalination schemes as well.

In the case of OTEC desalination, another major advantage is that the high salinity brine associated with RO effluents will be combined with the OTEC discharge for maximum dilution that could not be achieved onshore. The RO discharge is independently negatively buoyant because of the higher salinity and close-to-ambient temperature. Combining the RO discharge with the normal OTEC mixed discharge will allow the more hazardous RO discharge plume to sink faster with a higher rate of dilution. This concept of a common discharge can reduce adverse environmental effects from coastal desalination discharge while improving the economics of OTEC.

The target regions for OTEC-desalination should be begin with water-stressed regions in wealthier nations and territories such as the U. S. (Florida, Hawaii, U. S. Virgin Islands, Guam, Puerto Rico), China, and Australia since these countries can afford to make the large capital investments required. As the technology becomes more mature, it becomes more affordable and practical to implement second generation plants in SIDS nations. Various U. S. states and territories are considered water-stressed regions and pay above average rates for fresh water supply. The states and territories with best OTEC-desalination potential are Florida, Hawaii, U. S. Virgin Islands, Puerto Rico, and Guam. The cost of water supply in these regions is shown in Table 38.

Information regarding sufficient temperature difference (ΔT) and corresponding distance to thermal resource has not yet been thoroughly identified for specific sites in China; however, the need for desalinated water as far south as the Hainan Islands has been verified by recent investments from Organica and Veolia (among others) and confirms the need for desalination capacity near the OTEC resource in the South China Sea.

Table 38: Comparison of monthly residential water utility rates U. S. states and territories with OTEC resource near shore

Country/State	City/County	ΔT (°C)0-1000 m	Distance from resource to shore (km)	Monthly Residential Rate (per 1,000 gallons)
U. S. - Virgin Islands	All counties	21-24	1	$31.08
U. S. - Puerto Rico	All counties	22	10	$7.57
U. S. - Guam	All counties	24	1	$6.13
U. S. - Florida	City of Port Lucie	18-23	45	$4.79
U. S. - Florida	City of Stuart	18-23	45	$4.20
U. S. - Hawaii	Hawaii County	21	6-10	$4.15
U. S. - Florida	Miami-Dade County	19-24	42	$3.90
U. S. - Hawaii	Honolulu County	21	6-10	$3.35
U. S. - Hawaii	Maui County	21	6-10	$3.20
U. S. - Hawaii	Kauai County	21	6-10	$3.20

The rates listed in Table 38 are rates are valid for a monthly usage of approximately 5,000 gallons per month and do not take into account the addition of base fees and/or fees for the first 1,000 gallons. The water rates are publically available at the water municipality's website for each city/county listed above and are current as of December 2012. The change in temperature (ΔT) values at 0-1000 m in depth and the corresponding distance away from shore were gathered from the following sources [(World Energy Council, 2010), (Van Ryzin J. , 2012), (Vega, 1992), and (Leland, 2009)].

The highest cost of water paid by the Virgin Islands is a bit skewed because residents are also paying a Levelized Energy Adjustment Clause (LEAC) fee that allows the VIWAPA to recover the cost of fuel directly from the consumer since the utility has to hedge the volatile cost of fuel. Because the Virgin Islands produces the majority of its electricity from burning imported oil, the electricity supplied to the RO equipment is directly affected by the cost of oil. Therefore, a resident on the Virgin Islands using 10,000 gallons of water per month will have a bill of \$299.02 where \$19.28 is the cost of the first 1,000 gallons, \$196.84 is the cost of the next 9,000 gallons, and \$82.90 is the LEAC surcharge. Ignoring the cost of the first 1,000 gallons, the next 9,000 gallons will cost the consumer \$31.08 per 1,000 gallons; however, the LEAC accounts for \$8.29 of every 1,000 gallons.

Interestingly, the Virgin Islands has one of the best OTEC thermal resources located only 1 km offshore of St. Croix. If the Virgin Islands had invested in OTEC before the oil spike in 2008, it would have likely avoided the extreme costs it is now forced to pass on to its consumers. Interestingly enough, Hawaii has always beenthe most targeted option for OTEC while Virgin Islands residents currently pay about 10 times as much for water than Hawaiian residents and residents in Puerto Rico and Guam pay about two times as much. This is evidence that more emphasis needs to be placed on using OTEC as a solution for meeting water demands in water-stressed regions with reasonable access to the thermocline. Unfortunately, the Virgin Islands recently signed a 20-year contract with Seven Seas Corporation (SSC) to install RO plants of 3.7 MGD on St. Croix and 3.3 MGD on St. Thomas that are intended to meet future water needs in the Virgin Islands (Beamguard, 2009). Since 7 MGD is expected to meetthe Virgin Islands' water shortages, it would not be a likely candidate for an OTEC-desalination plant in the near future. Furthermore, Guam supplies its residents with 30 MGD of groundwater pumped from an underground aquifer that has an estimated sustainable yield of 90 MGD (Guam Waterworks Authority). Because of the sufficient groundwater source, it does not appear that any municipal-scale desalination plants would be required anytime in the near future.

Puerto Rico is a much larger island state that currently produces 541 MGD of drinking water to meet the demands of its residents; however, the Puerto Rico Aqueduct & Sewer Authority (PRASA) still looks for ways to better meet the needs of their population (Amundsen, Ferrari, & Millar, 2009). In a 2012 article about desalination in the Caribbean titled "*High Energy Costs Keep P. R. Out of Global Desalination Wave*" provided detailed information about the desalination potential in Puerto Rico. Author Alex Diaz reported that desalination remains out of reach for Puerto Rico because the cost of energy is among the highest in the world. Furthermore, he discovered that the PRASA has a RO plant in Culebra, but it is inactive because of high energy prices. SSC has already engauged in talks with PRASA to meet their desalination needs once Puerto Rico starts to require desalination; hence, this agreeement would be similar to the contract SSC signed with the Virgin Islands to supply all the water in St. Thomas for the next 20 years at a cost of approximately \$1.50/m^3 (\$5.68/kgal) that includes approximately \$0.50 for power at a rate of \$0.18/kWh (Diaz, 2012).

An additional RO plant planned by PRASA for Arecibo, Puerto Rico was described by researchers performing an assessment of using alternative energy sources such as solar, wind, waste-to-energy, and hydro-kinetic energy to power the potential RO plant. For conventional operation of the RO plant, thePuerto Rico Electric Power Authority (PREPA) charges PRASA

$0.21/kWh of electricity that corresponds to a cost of $9.5M a year for a 10 MGD plant (Amundsen, Ferrari, & Millar, 2009). Apparently, the RO plant was never implemented, but it is clear that Puerto Rico has interest in low-cost desalination options that potentially use alternative energy as the source of power.

The challenge of implementing OTEC in water-stressed regions such as the Virgin Islands, Puerto Rico, and Guamstill remains a problem of economics and risk. In a recent energy roadmap analysis for the Virgin Islands performed by the National Renewable Energy Laboratory (NREL), OTEC was not included as a technology that could help the Virgin Islands achieve a 60% reduction in fossil fuel demand by 2025 (Lantz, Oli, & Warren, 2011). Since OTEC is not a commercially available technology, it has to compete with other marine energy technologies that are already proven. This age-old kunudrum still seems to be the biggest hinderance to OTEC being initiated unless some entity is willing to fund a pilot plant that has no guarantee of being feasible or even profitable.

The opportunity exists for OTEC to enter the renewable desalination market as the leading solution for technical capacity and low-cost water production. In some scenarios, the OTEC-desalination plant can be designed as a “water-only” plant that has the sole purpose of providing desalinated water to island or costal communities. The net electricity generated by the OTEC cycle will be used in situ to power the onboard RO equipment as well as associated process pumps. Seemingly, this approach does not change the risk of producing OTEC power simply by using it in situ on an offshore platform; hence, investors and developers still have no gaurantee that OTEC power will be generated or that desalinated water will be provided to a utility.

However, if large diesel generators were installed on the offshore platform, the supply of desalinated water *can* be gauranteed in the event that the OTEC system encounters delays or failures.

This “water-only” OTEC scheme uses all of its net power to operate the desalination equipment and send product water back to shore using a flexible water pipeline, water bags, or transfer ships. Consequently, an undersea power cable would not be required for operation. Furthermore, the diesel generators are already sized such that they have sufficient power to start the seawater and ammonia pumps and allow the OTEC cycle to commence. Initiating the OTEC cycle with in situ generators is much less complex and eliminates the cost of cable deployment and cabling power from the land-based grid (Figure 30).

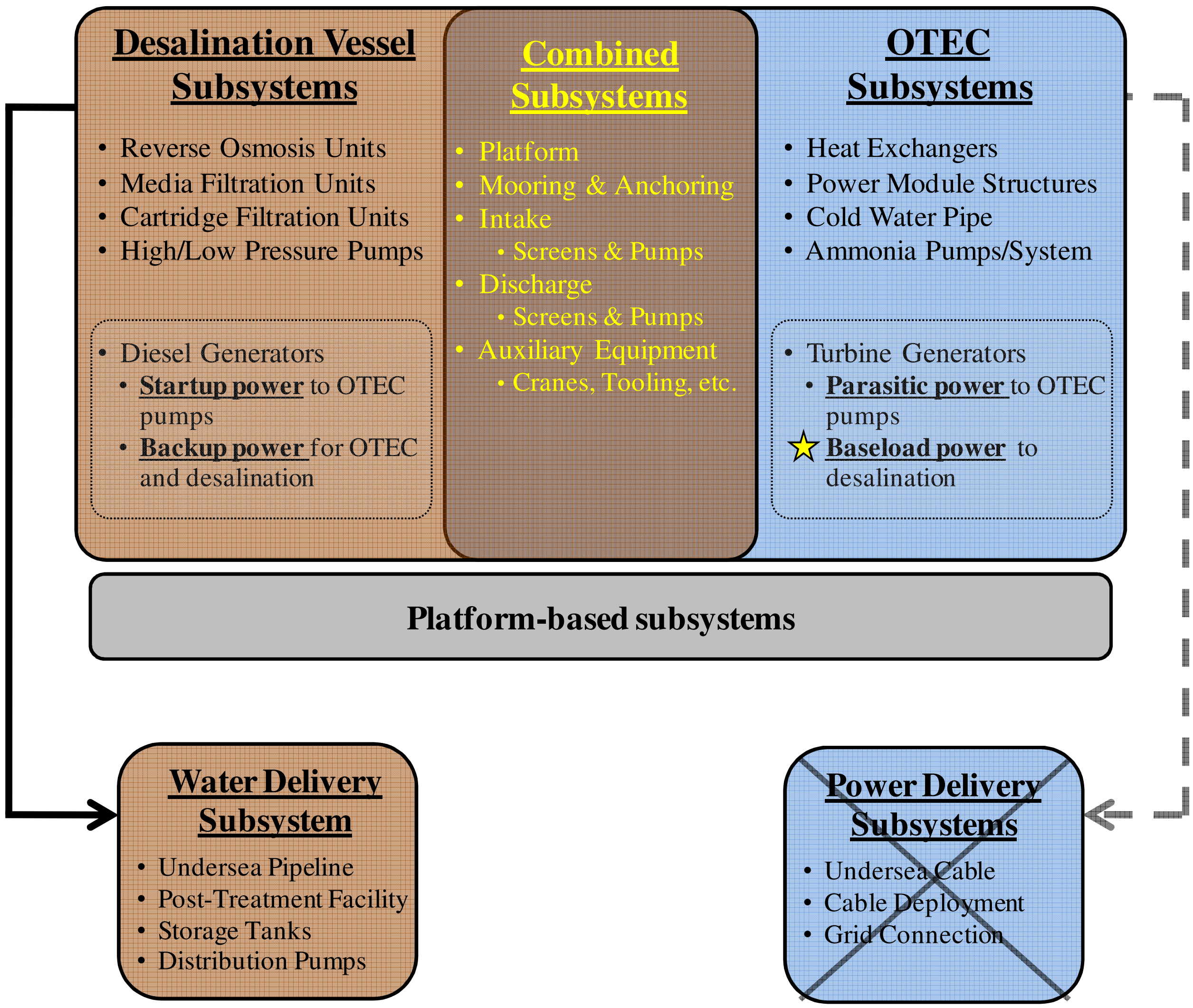

Figure 30: Diagram showing the integration of an offshore OTEC and desalination plant

The cost of water transfer using a pipeline must be added to the capital budget, but those costs can be minimal when a water pipeline only has to span a short distance to sites located very close to the thermal resource as shown in Table 32. It was estimated by (Stuyfzand & Kappelhof, 2005) that 0.1 kWh is required to transport one m^3 of water of desalinated water over a distance of 10 km from their floating desalting-energy island to shore. Deploying a water pipeline that connects an offshore platform or ship with a shore based facility was completed by the Cyprus Water Board in 2008 when they installed a water pipeline 1.32 km from the shore to a tanker ship that transported water from Greece (AFP, 2008). Furthermore, Cyprus has began a more ambitious water supply project that transfers water from Turkey under the Mediterrenean Sea using an HDPE pipeline. The 1.6 m diameter pipeline will stretch 107 km long with 80 km running under the sea at a depth of 280 meters and will have its 0.5 km spans connected to the seabed with a tether and anchor system (DHI, 2009). Although this pipeline project will be an expensive endeavour since it is the first of its kind, it sets a precedent for transferring large volumes of water at extreme undersea distances. Moreover, the success of this water pipleine project makes it conceivable to transfer OTEC-desalinated water over similar distances using this method.

This type of approach uses the offshore platform as a sustainable and envirionmentally-responsible desalination solution as well as a testbed for OTEC commercialization. It is envisioned that the plant will be sized for a specific water delivery volume per year to the local utility. The desalination equipment should then be sized at a capacity that can operate reliably from ayear-round average of 10 MW of net electricity. An important benefit of this approach is the possibility to segment the OTEC developer role into two distinct entities: a water provider and a power provider. The water provider is responsible for desalinating seawater and transporting the fresh water product back to shore for distribution. The power provider is responsible for providing the necessary power to the water provider to run their equipment. Lastly, since the power provider would finance the offshore platform, the water provider would have to rent the space. The platform rental generates additional revenue for the power provider while the water provider will not have to raise capital funding for a ship or vessel of their own.

The cost structure for a water provider in an OTEC-desalination plant is compared against WSC's cost structure shown earlier where they supplied their own diesel power as well as desalinated water (Table 39).

Table 39: The cost structure for a water provider in an OTEC-desalination plant compared against WSC's cost proposal to supply water to the MPWMD

WSC SDV™ versus OTEC-Desalination "Water Provider" Cost Structure		
(in millions of dollars)	SDV™ with Unsubsidized Fuel	Platform-based Desalination with OTEC
RO Capacity (MGD)	18	18
Desalination Facilities		
Seawater feed and brine disposal (included in ship cost)	$47.10	
Desalination process	$41.29	$41.29
Subtotal Facilities Cost	$88.38	$41.29
Desalinated water pipelines	$31.37	$31.37
Total Construction Costs	$119.76	$72.66
Engineering, Overhead, Legal (24%)	$28.74	$17.44
Contingency (25%)	$37.13	$22.52
Total Capital Costs	$185.62	$112.62
Operations and Maintenance		
Desalination Facilities/Power		
Generator power (at a cost of $0.093/kWh)	$9.49	
OTEC power (at a cost of $0.21/kWh)		$17.48
OTEC platform space rental fee		$2.53
Water provider profit (8% of total annualized cost)	$2.86	$3.03
Balance of original O&M costs	$8.50	$8.33
Total O&M Costs	$20.85	$31.37
Amortized Capital Cost (Original WSC financing: 7%, 30 years) (OTEC financing: 4%, 30 years)	$14.96	$6.51
Total Annualized Cost	$35.81	$37.88
Unit Cost ($/m^3)	$1.52	$1.60
Unit Cost ($/kgal)	$5.74	$6.07

The cost of water supplied by WSC was kept constant at $5.74/kgal to match the water supply cost from their MPWMD proposal. The estimated cost of supplying water from an OTEC-desalination plant was determined to be slightly higher at $6.07/kgal which is still competitive with water utility rates in Puerto Rico. The costs for the desalination vessel including intake, discharge, and diesel generators were eliminated for the water provider's cost structure since these will be included in the power provider's capital costs. The O&M cost for the platform rental was added, as well as the purchase cost of power from the OTEC provider at $0.21/kWh. All other cost percentages were maintained as they were in WSC's original proposal, with exception of financing rates. Other desalination providers who responded to theMPWMD cited 4% municipal bonds as the financing rate for a 30-year desalination plant. For the OTEC-desalination plant, it is assumed that 4% financing will be required from municipal or government bonds. Similarly, the financing for the power provider would also require a 4% interest rate for the cost structure shown in Table 40.

Table 40: The cost structure for a power provider in an OTEC-desalination plant

OTEC-Desalination "Power Provider" Cost Structure	
(in millions of dollars)	Platform-based Desalination with OTEC
OTEC Capacity (MWe-net)	10
Plant Subsystems	
Offshore Platform	
Mooring & Anchoring	
Power Modules	
CWP	
Seawater Pumps/System	
Ammonia Pumps/System	
Turbine Generators	
Backup Diesel Generators	
Total Capital Costs	$254.40
Operations and Maintenance	
O&M cost at 1% of total capital costs	$2.54
R&R cost at0.5% of total capital costs	$1.27
Power Provider Profit (8% of total annualized cost)	$1.48
Amortized Capital Cost (OTEC financing: 4%, 30 years)	$14.71
Total Annualized Costs	$20.01

Since WSC factored in an 8% profit margin on their total annualized costs, the same profit margin was assumed in the cost structure for the OTEC-desalination power provider above. The total capital costs was backcalculated to $254.40M based upon achieving the 8% profit target. Thus, the cost of plant subsystems are not detailed and total capital cost has been derived solely as a target cost that would enable this OTEC-desalination scenario to be economically feasible. Recall that Vega estimated a 10 MW OTEC plant to cost $203M, so the derived capital cost in Table 40 is not completely out of bounds; however, it has been discussed in previous sections that Vega may have underestimated the scale-up of capital costs as OTEC plants get larger in capacity. Nevertheless, this analysis is intended to show that an OTEC-desalination plant could be feasible if the capital cost targets are met and the demand for water in a given region is high enough.

The OTEC-desalination scenario could be economically practical if the water provider achieved an 8% profit from the sale of water to a utility such as PRASA, and the power provider also achieved an 8% profit from the sale of power to the water provider. An income statement for this scenario is shown in Table 41 using the cost structure for the water provider and power provider detailed earlier in this section.

Table 41: Income statement for OTEC-desalination plant showing profit margins for both water provider and power provider

OTEC-Desalination Water & Power Provider Income Statement	
(in millions of dollars)	**18 MGD Capacity**
Water Provider Income Statement	
Revenue	
Sale of water to PRASA ($6.07/kgalat a production of 6,241,500 kgal/yr)	$37.88
Expenses	
Annualized Cost (without profit)	$34.85
Net Profit	**$3.03**
Profit Margin	**8%**
Power Provider Income Statement	
Revenue	
Sale of power to water provider ($0.21/kWhata production of 83,261,610 kWh/yr)	$17.48
Rent from water provider for use of platform	$2.53
Expenses	
Annualized Cost (without profit)	$18.53
Net Profit	**$1.48**
Profit Margin	**8%**

Transforming the OTEC pilot plant into a water plant with two providers reduces the overall cost and risk of implementation. The cost reduction comes from the combined subsystems between a standalone offshore desalination plant and a standalone OTEC plant: platform, mooring & anchoring, intake, discharge, and auxilary equipment. Electricity transmission expenes to shore are eliminated and efficiency of eletricity usage is maximized since the desalination plant is colocated with the power plant. Additionally, the desalination of deep seawater reduces filtration costs since suspended solids and turbidity are very low at the depth of the deep seawater intake. Subsequently, a power only OTEC plant would add back the capital costs of the undersea cable, deployment, and grid connection that can be assumed to add 15%to the OTEC-desalination capital cost of $254.40M. The new capital cost of $292.56M corresponds to higher annualized costs and would make the power-only provider operate at a loss by selling power at $0.21/kWh (Table 42).

Table 42: Income statement comparison for an OTEC-desalination power provider versus a OTEC power-only provider showing negative margin for power-only scenario

OTEC-Desalination Power Provider vs. OTEC Power-Only Provider Income Statement		
(in millions of dollars)	**OTEC-Desalination Power Provider**	**OTEC Power-Only Provider**
Power Provider Income Statement		
Revenue		
Sale of power to land-based utility grid ($0.21/kWhat a production of 83,261,610 kWh/yr)		$17.48
Sale of power to water provider ($0.21/kWhata production of 83,261,610 kWh/yr)	$17.48	
Rent from water provider for use of platform	$2.53	$0
Expenses		
Annualized Cost (without profit)	$18.53	$20.73
Net Profit	**$1.48**	**($3.25)**
Profit Margin	**8%**	**-15.7%**

If the power provider were to experience extended delays where OTEC power is not being produced, they would be responsible for importing diesel fuel to power the water provider's equipment using backup generators until the OTEC power came back online. Likewise, if the water provider experiences extended delays where water could not be transmitted to shore, they would still be required to pay for OTEC power that is generated. The financing and risk is segmented between the two providers and encourages them to hold eachother accountable. Altnernatively, if one provider assumed both roles, they are only held accountable by themselves and their financial backers where a failure could risk defaulting on a very large loan. Furthermore, if one entity were to provide only power instead of water,all of the risk and upfrontinvestment hinges on sending OTEC-generated electricity back to the grid. If the power-only scenario were to experience extended delays, it would not make sense to employ diesel generators to trasmit power back to shore since the single entity would simply operate at a loss with no rental revenue from a second provider.

This type of approach is practical for second generation OTEC plants deployed near an island where water costs are high.This approach could continue to be an option for commercial OTEC plants if land-based conditions are not adequate for desalination to be cost-effective because of plant sitting factors and discharge management. The segmented approach to first generation plants reduces the risk of a complete failure in the event that OTEC power is not achieved, or only achieved for a brief period of time. A successful OTEC-desalination pilot plant will allow future commercial plants to provide electricity and desalinated water without the need for large diesel generators because the undersea cable would be more cost-effective for startup power at a commercial size. Lastly, although OTEC-desalination plants are challenged to be cost-competitive with traditional land-based plants, the environmental benefits and reduced capital cost of an offshore discharge could become increasingly attractive as environmental regulations become more strict for traditional land-based plants. Further analysis of the favorable envirionmental benefits of OTEC-desalination will be discussed in the next chapter.

Chapter 5

Environmental Discussion

Commercial OTEC planning and permitting in the U. S. will most likely have to overcome scrutiny from the public regarding its environmental impact. Comparatively, the planning of the first large-scale SWRO desalination plant in Carlsbad, California began in 1998 with a commissioning date not expected until 2011 (Lattemann, Kennedy, Schippers, & Amy, 2011). Being a first-of-its-kind process plant, OTEC could be subject to the same types of permitting delays because its environmental impacts have never been proven. Proper planning is critical to ensure OTEC is implemented in a cost-effective and timely manner while still demonstrating to environmentalists and the public that OTEC will not be harmful to the environment.

OTEC Discharge

The high level goal for OTEC in the U. S. centers on attaining energy independence for Hawaii. One of the visions for OTEC in Hawaii developed by Vega called for installing a total OTEC capacity of up to 1,900 MW (1.9 GW) to meet all present and future power and water needs in the State of Hawaii. Based on the capacity of OTEC plants around the Hawaiian Islands, it is clear that tremendous amounts of water will be displaced around these small islands. It is necessary to evaluate the Hawaii islands at “full capacity” of OTEC plants for the corresponding total chemical discharge load. It was reported earlier that many water systems in the Middle East suffer from enormous desalination runoff that combine all the chemical discharge effects into one concentrated water system. First, it is useful to consider a discharge diagram of the 100 MW flows to show the warm and cold seawater flows and corresponding densities (Figure 31). The temperature and flow rate data for the warm and cold seawater flows were taken from hydrodynamic modeling performed by Grandelli & Rocheleau (2010).

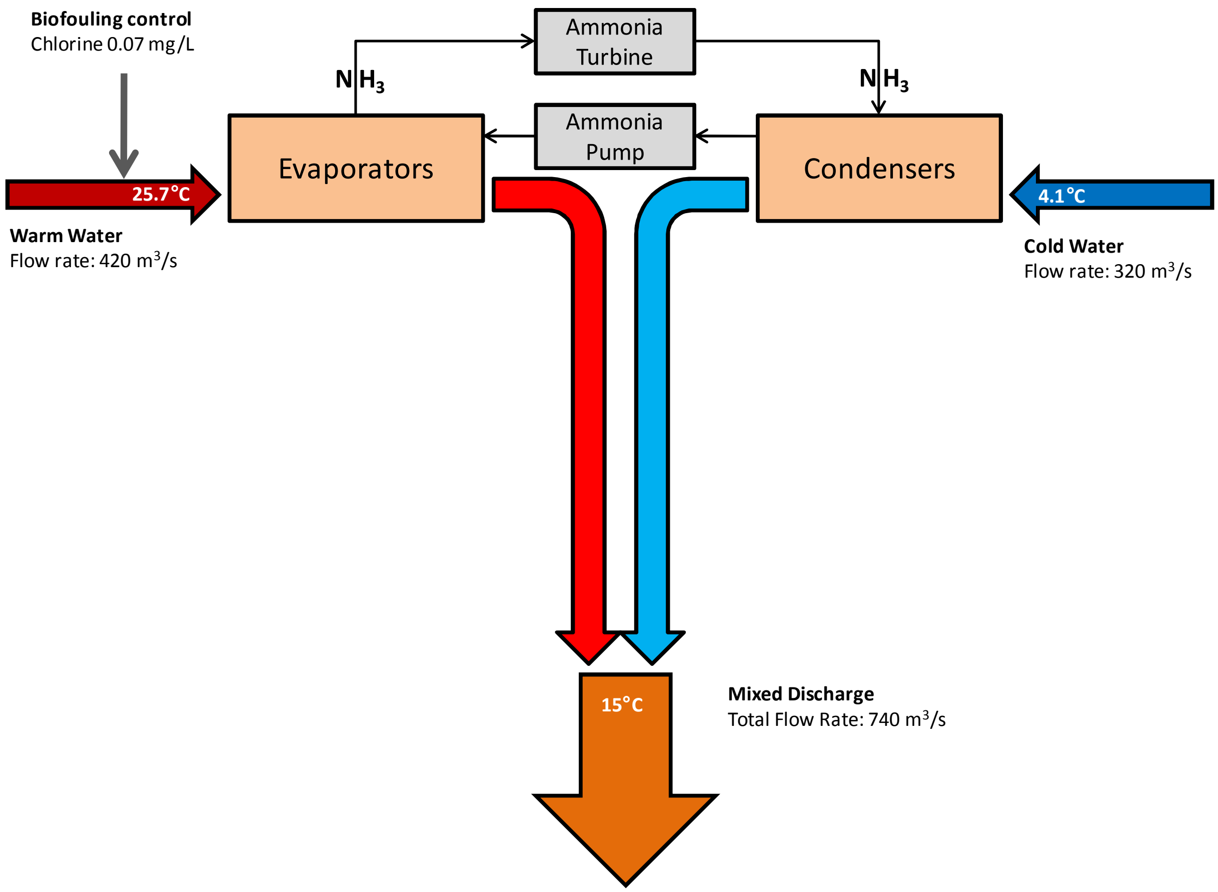

Figure 31: Schematic of OTEC discharge from a 100 MW plant shown with seawater temperatures and flow rates

It was discussed earlier that various chlorination dosages have been reported to be successful in controlling biofouling growth in OTEC heat exchangers, but the most recent experiments performed by (Eldred, et al., 2011) shows the highest of all chlorination dosages at 0.07 mg/L continuous. Using this rate of continuous chlorination with the 420 m^3/s surface seawater flow rate for a 100 MW OTEC plant, the total chlorine demand per 100 MW plant would be 2,540 kg/day. For all 1,900 MW of potential OTEC capacity around the Hawaiian Islands, the total chlorine demand would be 48,260 kg/day. If we assume the discharge concentration is 10% of the dosage based on Lattemann'sresidual chlorine concentration benchmarks, the residual chlorine in the Hawaiian Islands region would amount to only 4,826 kg/day.

Since the 320 m^3/s deep seawater is not chlorinated, the residual chlorine concentration in the surface seawater discharge will become rapidly diluted by the deep seawater in the mixed discharge of the OTEC plant. If a one-to-one dilution ratio is assumed, then the total residual chlorine load of 4,826 kg/day for the Hawaii Island OTEC system reduces to 2,739 kg/day for the total 740 m^3/s mixed discharge flow rate (Figure 32). Comparing these to previously discussed heavily-chlorinated marine systems in the MENA region (i.e. the Arabian Gulf with a residual chlorine load of 47,400 kg/day and the Red Sea with a chlorine load of 11,144 kg/day); the full capacity OTEC system in the Hawaiian Islands has much less threatening levels of residual chlorine.

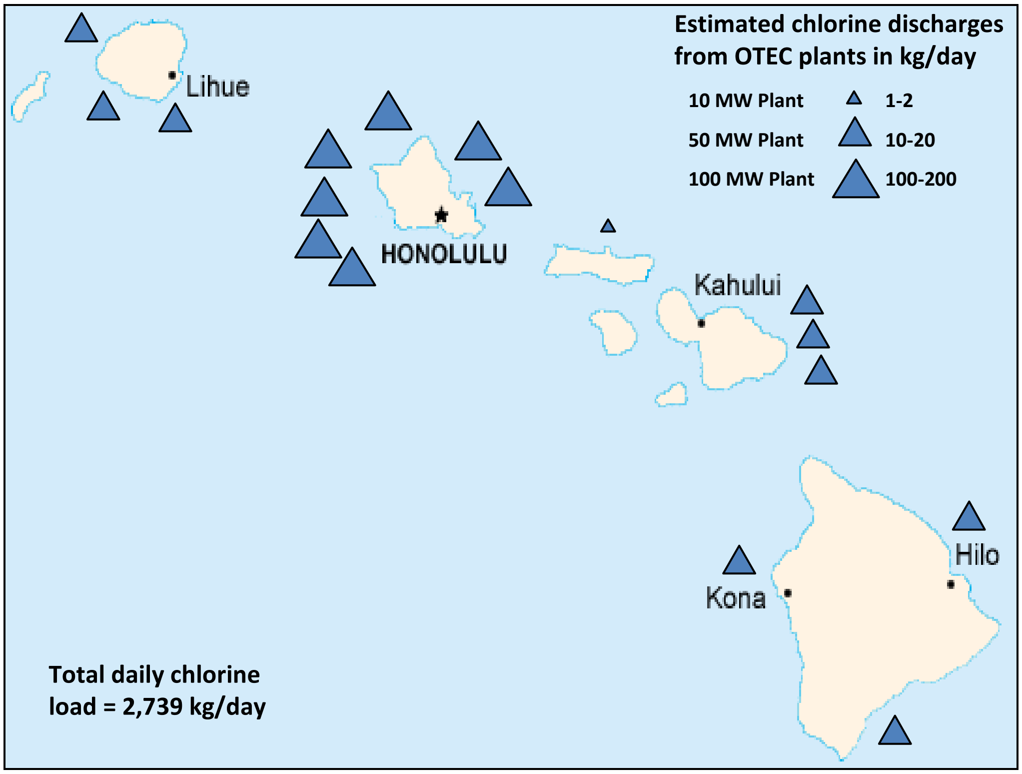

Figure 32: Map of the Hawaii Islands showing OTEC plants sized according to Vega's OTEC vision with estimated total load of chlorine per day assuming residual concentration is 10% of dosage

The other discharge consideration for OTEC is the trace metal loss from the enormous amount of heat exchanger surface area required for a full capacity Hawaiian OTEC system. Using the expected 30-year trace metal loss for aluminum heat exchangers presented earlier by (Panchal, et al., 1990) the uniform corrosion rate is expected to be 56-84 μm for warm water exposure and 108-198 μm for cold water exposure. Assuming the worst case scenario, the warm water heat exchanger tubes will lose 84 μm of wall thickness and the cold water heat exchanger tubes will lose 198 μm of wall thickness. The calculation of total metal loss is derived assuming a 10 MW OTEC plant has five evaporators and five condensers with aluminum tubes of 1" OD, 0.109" wall thickness, a length of 348", and a density of 0.098 pounder per cubic inch (lb/in^3). Over 30 years, the 10 MW OTEC evaporators will have lost 16,605 lbs of aluminum and the condensers will have lost 44,553 lbs of aluminum. Assuming the 1,900 MW OTEC capacity in Hawaii is at steady state, the total amount of trace metal loss for each 30-year period would be 11,619,987 lbs of aluminum. On a daily basis, at steady-state, the total daily load of aluminum contained within the discharges will be approximately 1,061 lbs (481 kg) (Figure 33).

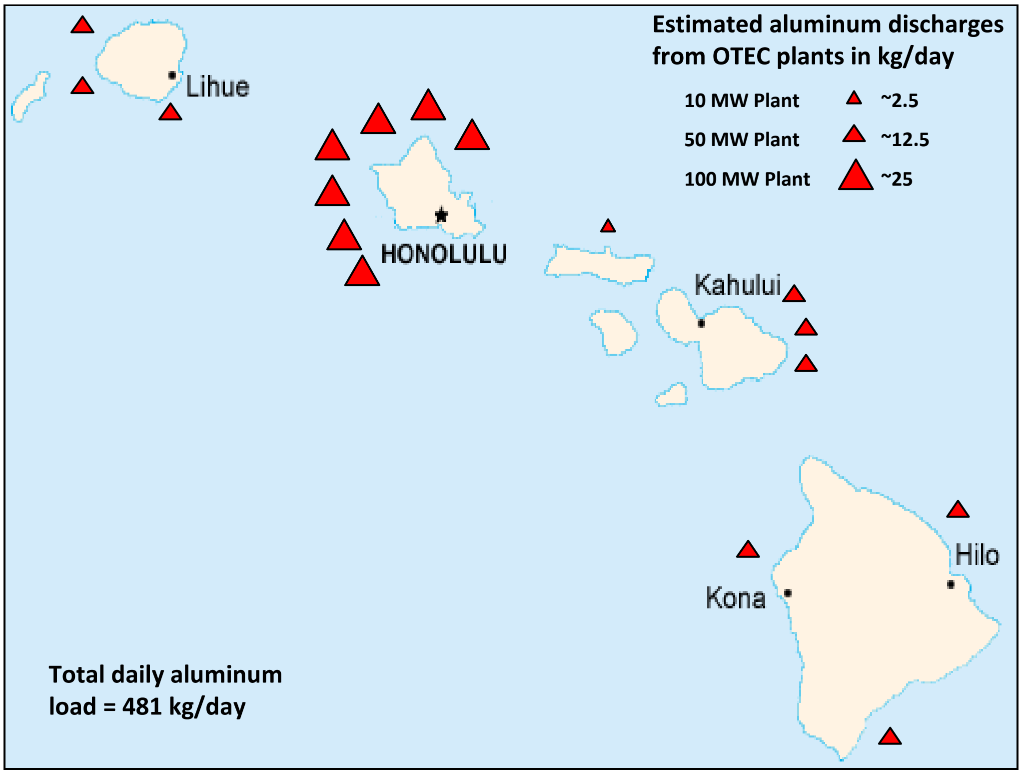

Figure 33: Map of the Hawaii Islands showing OTEC plants sized according to Vega's OTEC vision with estimated total load of aluminum per day assuming steady-state of 1,900 MW of continuous OTEC power

As discussed earlier, aluminum has very low toxicity to humans and marine species with low risk of bioaccumulation. Although the daily load of 1,061 lbs may seem striking, it is consistent with the total trace metal losses observed from desalination plants in the MENA region. Hence, MSF plants discharge an estimated 296 kg of copper per day in the Arabian Gulf and 74 kg per day in the Red Sea. The OTEC daily aluminum load of 1,061 lbs (481 kg) is about 63% higher than the copper load in the Arabian Gulf; however, aluminum is much less toxic to marine life than copper, so trace metal in OTEC discharges will have a lower impact to the environment than the Arabian Gulf trace metal discharges.

The residual chlorine and trace metal in OTEC discharges benefit from enhanced dilution from strong background currents that are not nearly as high in the MENA region seas. The MENA region marine systems are mostly closed basin systems with only a few river sources supplying additional diffusion. It is interesting to note that the combined discharge of the desalination plants in the Arabian Gulf have an estimated total flow rate of only 1,100 m^3/s (Lattemann S., 2010). The 1,900 MW full-capacity OTEC plants in Hawaii would have a combined discharge flow rate of approximately 14,060 m^3/s. These OTEC discharge flow rates produce a very modest increase in effluent salinity because of the slightly higher salinity content of the deep water with respect to the surface receiving waters. This salinity increase should not be alarming because it is an insignificant increase in salinity when compared to the increase in salinity from the concentration of desalination plants in the MENA region. All the desalination plants in the Arabian Gulf account for an annual water loss of 0.05% compared to a loss of 5.7% caused by natural evaporation; therefore, a further increase in salinity in the Gulf system is not viewed as a likely scenario (Lattemann S., 2010).

The addition of deep seawater dilution is something unique to OTEC and is not easily achieved by typical land-based desalination plants. Some desalination projects have considered the use of deep seawater intakes to reduce organism entrainment, but it would require site-specific studies to determine larval abundance and species composition to ensure that the deep seawater intake is more benign than surface intake (Foster, Cailliet, Callaway, Raimondi, & Steinbeck, 2012). This approach is a potentially effective method of reducing entrainment, but the deployment of a deep seawater pipe is risky and likely cost-prohibitive for a desalination plant. Furthermore, other desalination plants have considered modifying surface seawater intakes for the primary purpose of diluting the discharged brine in an effort to meet toxicity objectives. This approach was not recommended by (Foster et. al, 2012) because many more organisms may be killed as a result of entrainment and impingement than saved from exposure to high brine concentrations.

Combined OTEC-Desalination Discharge

As discussed earlier, an OTEC-desalination scheme has several advantages from an economics standpoint. The environmental advantages could be equally as attractive for developers and investors. The most benign desalination discharges are combined with power plant cooling water discharges to dilute the brine concentration and residual chemicals to very low levels. The OTEC seawater discharge for a 10 MW plant is larger than the cooling seawater discharge for most commercial power plants. Additionally, OTEC discharges are designed at a depth of 70 m below the surface where the colder than ambient discharge water has negative buoyancy that causes the plume to sink faster than it would with warm discharges. A typical desalination plant usually has an open ocean intake that draws seawater from a relatively shallow depth. The surface water requires extensive filtration and pretreatment before entering the RO membranes since membranes are sensitive to fouling, chemicals, and suspended solids. If a 10 MW OTEC-desalination plant used the surface seawater as its feedwater, it would still require the same level of pretreatment as a typical desalination plant (Figure 34).

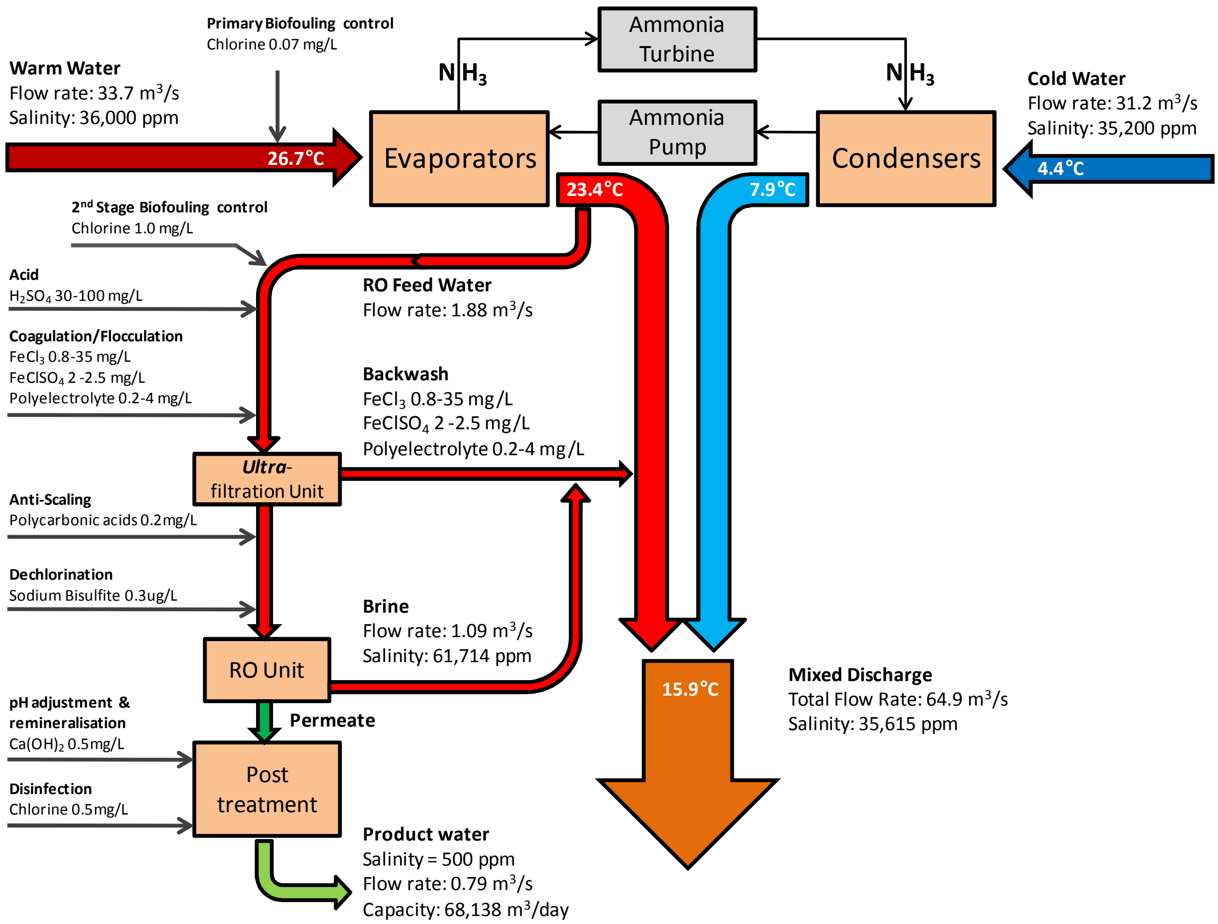

Figure 34: Schematic of RO flows and pretreatment steps in an OTEC-desalination scheme where surface water is used as the feedwater

The salinity data was recorded near Punta Cana, Puerto Rico by (Myers, Hoss, Matsumoto, Peters, Seki, Uchida, Ditmars, & Paddock, 1986). The salinities of the different seawater flows can be converted to density using a water density calculator developed by NOAA and the University of Michigan (publically available at http://www.csgnetwork.com/h2odenscalc.html). The seawater temperature and pressure drop across the heat exchangers was taken from a 10 MW OTEC system developed by (TRW Inc. Systems and Energy, 1978). Consequently, the surface water with a salinity of 36,000 ppm at 23.4°C equates to a density of 1024.61 kg/m^3 and the deep water with a salinity of 35,200 ppm at 7.9°C equates to a density of 1027.47 kg/m^3. The subsequent mixed discharge density was calculated to be 1025.99 kg/m^3 using equations 10 and

11. Since the warm and cold seawater discharges are combined at the same pressure, the change in temperature was calculated to be 15.9°C using the energy balance equation 12 below (small differences in specific heat between the warm and cold seawater flows will be ignored). Assuming this mixed flow has reached steady state, the salinity of the mixed discharge is calculated to have a salinity of 35,615 ppm using the mass balance equation 13. In this example, the addition of the brine flow and subsequent salinity is ignored, but will be included in the next example.

$$\dot{m}_{mixed\ discharge} = \dot{m}_{surface\ water} + \dot{m}_{deep\ water} \tag{10}$$

$$Q_{mixed} \times \rho_{mixed} = Q_{warm\ water} \times \rho_{warm\ water} + Q_{cold\ water} \times \rho_{cold\ water} \tag{11}$$

$$Q_{mixed} \times T_{mixed} = Q_{warm\ water} \times T_{warm\ water} + Q_{cold\ water} \times T_{cold\ water} \tag{12}$$

$$Q_{mixed} \times C_{mixed} = Q_{warm\ water} \times C_{warm\ water} + Q_{cold\ water} \times C_{cold\ water} \tag{13}$$

Energy balance equations where Q = volumetric flow rate (in m^3/s), and T = temperature (in °C). Mass balance equations where $\dot{m}$ = mass flow rate (in kg/s), ρ = density (in kg/m^3), and C = salinity concentration (in g/L)

As described earlier, Rabas & Panchal (1991) conceived an OTEC-desalination scheme using a MSF and RO process that used primarily surface seawater along with warmed cold seawater as the feedwater. Thus, the RO process schematic from Rabas & Panchal (1991) would look much like Figure 34. Conversely, desalinating the deep seawater could have advantages for the RO process that should be considered. If the deep seawater is utilized as the feedwater in an OTEC-desalination plant, as it was described earlier, the deep seawater RO process schematic would look like Figure 35.

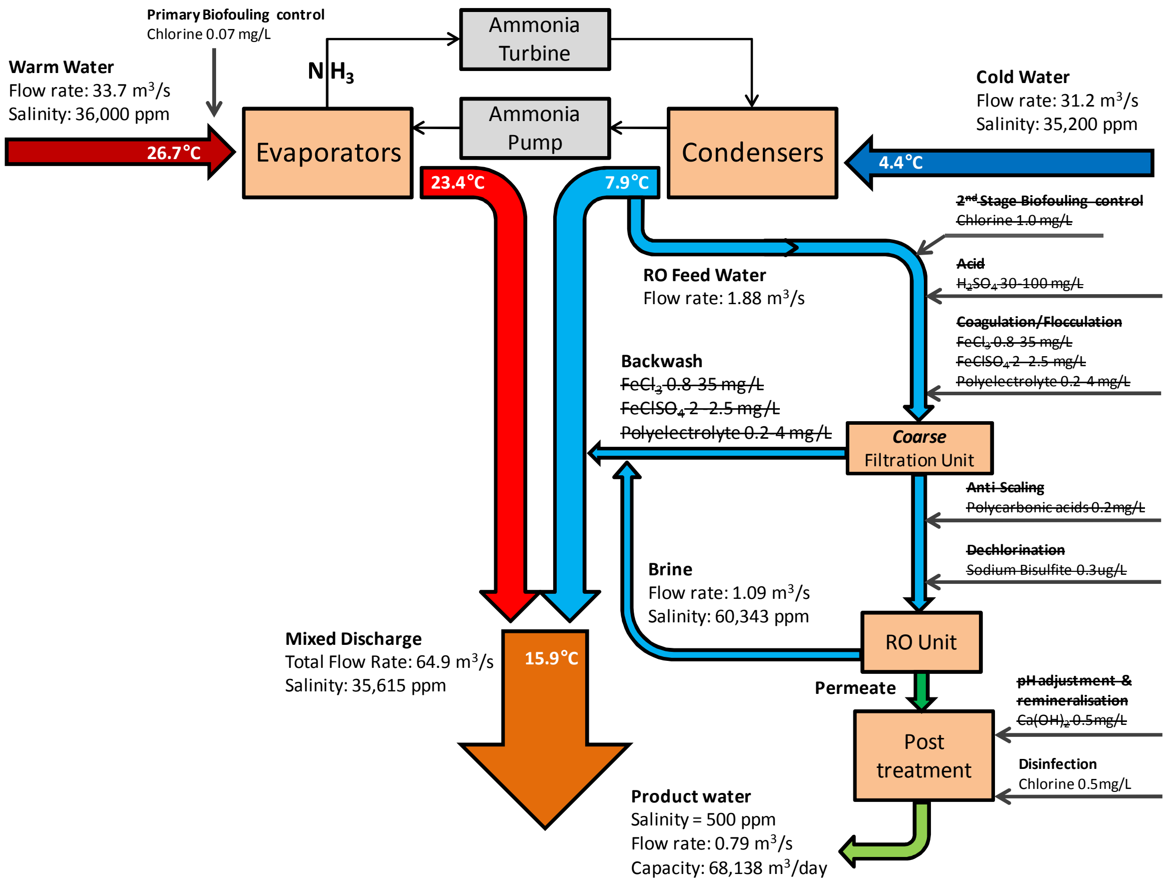

Figure 35: Schematic of RO flows and pretreatment steps in an OTEC-desalination scheme where deep water is used as the feedwater

The OTEC seawater temperatures and flow rates from Figure 34 are reused in Figure 35. The RO flow rates were assumed using a product delivery rate of 68,138 m^3/day (0.79 m^3/s) with a product recovery ratio of 42%. The OTEC mixed discharged is combined with the brine discharge and the mass balance analysis for the total discharge can be calculated using equations 14. Since the brine discharge is typically the same temperature as the feedwater (7.9°C), the density of the brine flow at 60,343 ppm is calculated to be 1047.43 kg/m^3. The addition of the brine flow to the OTEC mixed discharge results in a total discharge density of 1026.34 kg/m^3

which is a mere 0.35 kg/m^3 increase in discharge density. Using equation 15 below, the total discharge salinity increases by 408 ppm to 36,023 ppm, which is only 23 ppm higher than the surface water salinity.

$$Q_{total} \times \rho_{total} = Q_{OTEC\ mixed} \times \rho_{OTEC\ mixed} + Q_{brine} \times \rho_{brine} \tag{14}$$

$$Q_{total} \times C_{total} = Q_{OTEC\ mixed} \times C_{OTEC\ mixed} + Q_{brine} \times C_{brine} \tag{15}$$

An OTEC-desalination plant has a tremendous advantage over conventional land-based desalination plants because of the superior mixing characteristics between the brine discharge and the normal OTEC mixed discharge. The salinity is decreased to near ambient levels almost immediately and no additional chlorination is discharged with the brine. It is evident that a 10 MW OTEC-desalination plant using deep seawater RO process as the feedwater has the potential to eliminate all the chemicals with exception of the chlorine disinfection before distributing to customers. Since the pH of deep seawater is already at an ideal value of 6.7 to 7.0, it would not have to be adjusted for drinking water. Furthermore, since deep seawater is already rich in minerals, selective filtering can be used to achieve the requirement for drinking water; this process can either reduce or eliminate the traditional remineralization requirement employed for surface seawater desalination systems. The elimination of discharged chemicals, enhancement of mixing characteristics, and the minimization of carbon dioxide (CO_2) emissions could this OTEC-desalination scheme potentially the most benign seawater desalination plant in the world.

Barriers to Entry

As OTEC enters into developmental and commercial phases, it will undoubtedly be faced with environmental resistance. It was reported that Poseidon Resources spent approximately $15M in permitting costs for deploying a large-scale desalination plant in Carlsbad, CA and was imposed with a Climate Action Plan that added $76M to the capital cost of the plant over its 30-year life (Global Water Institute, 2008). Since estimates of the first 10 MW OTEC pilot plants are in the range of $200-$400M, an environmental levy such as this would add an additional 19-38% to the total cost. Developers need to formulate a fully comprehensive environmental plan far in advance of deploying an OTEC plant; otherwise, costly environmental studiescould be required by environmental regulators after investments in the plant have already been made. A costly study such as the Climate Action Plan could delay implementationof an OTEC plant or potentially prevent the project from moving forward indefinitely.

Renewable energy projects in Hawaii have been met with cultural barriers that have delayed implementation and further growth. Geothermal energy companies have recently been planning to explore and expand electric production capacity by tapping additional wells near volcanically active sites on the Big Island of Hawaii. Local community activists, such as those from The Pele Defense Fund, have voiced their concerns against tapping geothermal resources for cultural and environmental reasons; they believe that drilling wells would harm their goddess Pele and would insult native Hawaiians who practice their traditional religion on the Big Island (Callis, 2012). It appears that the activists are losing the battle after the Hawaii Environmental Council made a decision on May 17, 2012 to exempt an EIS for future geothermal exploration; furthermore, the Hawaii Electric Light Co (HELCO) received approval to begin drafting request for proposals to add 50 MW of geothermal power on the Big Island that is estimated to cost $500 million

(Shimogawa, 2012). In this case, the need for renewable energy on Hawaii proved to be a high enough priority that cultural disputes were finally put to rest; however, the cultural resistance may have contributed to delaying geothermal expansion in Hawaii.

Conclusion

Since OTEC's inception in 1881 by D'Arsonval, it has always been promoted as an enormous source of renewable energy. Over the years researchers have proposed and demonstrated the secondary benefits of desalinated water to increase the attractiveness of investing in OTEC. The environmental effects of OTEC have always been considered unknown and they must be better understood before the OTEC industry can become a major contributor of clean energy. The first OTEC researchers, namely D'Arsonval and Claudes, invested their own money to fund early OTEC designs and demonstrations. Following a long OTEC research drought, rising fuel prices in the 1970s led some governments to investigate and occasionally fund small-scale demonstrations. The initial strategy involved convincing these governments to invest in a pre-commercial OTEC plant that would convince developers and financers to cultivate a market for commercial OTEC plants. As fuel prices leveled out later in the 1980s, government interest in OTEC had waned and researchers began to strategize that small-scale OTEC plants could generate power and fresh water to meet the needs of SIDS nations. Since SIDS nations already pay high costs for power and water, first generation OTEC plants would potentially have a better opportunity for providing electricity and water at competitive prices. Although several SIDS nations showed interest, none of these governments or private investors ever made the investment.

An OTEC-desalination plant is an alternate strategy that should be promoted primarily as an enormous source of benign renewable desalination. The economics of OTEC-desalination have been shown to be much more favorable than any other renewable energy-supplied desalination technologies. The potential municipal scale capacity and favorable economics could make OTEC-desalination competitive with conventional coastal desalination plants. Secondary opportunities of this strategy are the favorable environmental effects of using enormous OTEC flow rates to provide enhanced dilution of desalination brine flow when compared to land-based desalination plants. In a large commercial plant scenario, the third opportunity of this strategy is the capability to supply a surplus of electricity back to the mainland grid (Figure 36). It is important to note that other opportunities and risks exist, but the key factors listed below are the highest level priorities for OTEC evaluation.

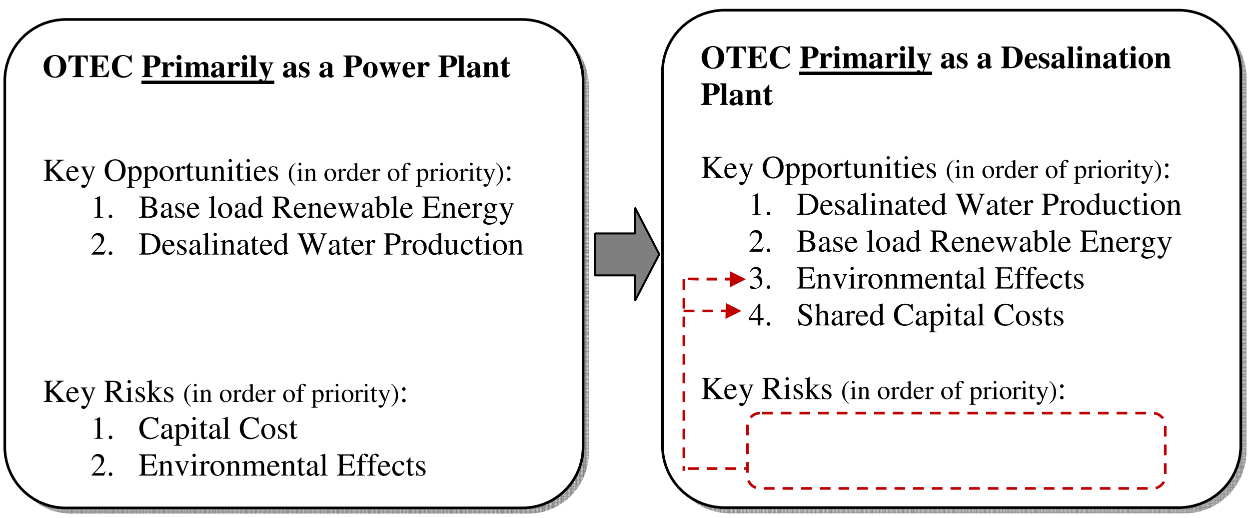

Figure 36: Visual demonstration of the shift in OTEC paradigm when a plant is implemented primarily as a desalination plant instead of a power plant

This represents a bold shift in the OTEC strategy model and requires developers to seek out nations with high water costs, and governments or municipalities that are willing to finance the project with low interest rates. Many SIDS nations have the best thermal resource and plant sitting factors in addition to having the best economic scenarios for cost-competitive electricity and water from OTEC; however, these nations are sometimes second or third world countries with much smaller financial resources for capital intensive renewable energy projects such as OTEC. Hawaii is still a favorable candidate because it is a U. S. state, but Hawaii does not pay the highest water rates among U. S. states and territories. The U. S. states or territories with the highest water rates are the U. S. Virgin Islands, Guam, and Puerto Rico; however, the Virgin Islands and Guam have a drinking water demand of 7 MGD or less while Puerto Rico demands 541 MGD of drinking water. The initial target for a pilot OTEC-desalination plant should be Puerto Rico. The second and third generation OTEC plants could potentially be implemented in other SIDS nations once the initial cost and risk has been driven down from the Puerto Rico pilot plant.

The water-stressed regions located on the U. S. mainland could be other future options for second and third generation OTEC-desalination plants if water scarcity continues to be an issue. The mainland U. S. states with the largest water scarcity issues are California, Florida, Arizona, and Texas which areeither land locked or not ideally situated for access to significant ocean temperature differences. Florida has reasonable access to the ocean thermocline that could make an OTEC desalination and power plant feasible. Florida has been dealing with significant water crises and has recently made upgrades and expansions to their current desalination capacity. Moreover, Florida's desalination capacity is growing at such an alarming rate that concerns have been raised that plant discharges are becoming increasingly more hazardous. Hazardous desalination discharge is more of an issue near mainland coasts such as Florida's since strong tides and weaker currents can concentrate discharges near the shore. Island desalination plants have the benefit of strong ocean currents to disperse and dilute desalination discharges to much safer levels.

When the time comes for an OTEC plant in Florida, it is important to consider the potential economic incentives for initiating a potentially large industry in Florida. The State of Florida has an aggressive economic incentive plan, like most states, to attract high-technology and high-paying jobs to their local economy. The State of Florida will offer High Impact Performance Incentive (HIPI) grants to companies in major high-impact sectors that create at least 50 new full-time equivalent jobs and make a cumulative investment in the state of at least $50M over a three-year period. Their tax refund incentive provides companies with refunds up to $3,000 per new full-time job created ($6,000 in an enterprise zone or rural county) that create high-wage jobs in select high value-add businesses. Furthermore, the state has Capital Investment Tax Credits that provide annual corporate income tax credits of up to 100% of investment issued in installments over a 20 year period, providing that the company creates a minimum of 100 jobs with an investment of at least $20M in eligible capital costs. The state will also allow the following items to be exempt from sales and use tax: manufacturing equipment and machinery, electricity and steam used in manufacturing, commercial space activities, labor cost in R&D expenditures, and R&D machinery and equipment.

The amount of jobs created for a single OTEC demonstration plant or commercial plant can be quite substantial (Figure 37). Being the first state or region to implement a demonstration or commercial plant gives the state the added benefit of becoming a center of excellence for OTEC industry. The OTEC industry for a populated state like Florida will be long-lasting and lead to energy independence as well as water independence.

DEMONSTRATION PLANT	Duration (years)	Number of Jobs	Job Years
Development and engineering	2	15	30
Equipment Manufacturing	2	15	30
Construction	2	25	50
Operations	25	4	100
G&A Staff	25	1	25
Total Proposed Action		60	235
COMMERCIAL PLANT			
Development and Engineering	6	30	180
Equipment Manufacturing	4	200	800
Construction	3	150	450
Operations	30	100	3000
G&A Staff	30	15	450
Total Commercial Facility		495	4880

Figure 37: Potential jobs created for OTEC demonstration and commercial plants[47]

Because the incentives provided by the State of Florida have various facets and eligibility criteria, it is difficult to determine the actual amount of savings developers would receive for bringing an OTEC plant to Florida. It is useful to evaluate examples of incentive packages given to other technology companies that have created jobs in Florida. The Tampa Bay Time reported that a recently released database revealed Lockheed Martin Mission Systems and Sensors would receive an incentive package of $2.18M for the creation of 117 electrical equipment jobs in Pinellas, FL while Embraer Aircraft Holding stands to receive $8M in incentives for creating 450 jobs in Brevard, FL (Harrington & Edds, 2012).

Given that Lockheed Martin is currently a leading developer in the OTEC industry, it is reasonable to assume that creating 60 jobs for implementing an OTEC demonstration plant would garner an incentive package of approximately $1.09M (i.e. half of the $2.18 million received for the 117 jobs created). Furthermore, Embraer Aircraft Holding is a high-technology

[47]Adaptation from Ocean Thermal Energy Conversion Technology, Research, and Development and Demonstation Facility Ke'Ahole, North Kona, Hawai'i Environmental Assessment, published by OTEC International, LLC., 2012.

sector that requires heavy investment in capital similar to the monetary capital investment required for commercial OTEC plants, so it is reasonable to assume that the 495 jobs created for a commercial OTEC plant would receive approximately the same $8M incentive package as Embraer anticipates for creating its 450 jobs. Although these estimates for incentive packages are simply orders of magnitude assumptions, these cost savings should be included in the total cost of bringing OTEC to Florida when the economic conditions are favorable.

Outside of the U. S., other water stressed regions with potential for OTEC have also been considered. In 2007, the Japan Cooperation Center for the Middle East (JCCME) performed a study for the production of power and water using OTEC and Discharged Thermal Energy Conversion (DTEC) (Xenesys Inc.). Furthermore, a recent group of researchers expect that the maximum depth of the Arabian Sea being 4,652 m makes OTEC energy feasible near Oman (Kazem, Abdulla, Hason, & Alwaeli, 2011). Although very few studies have investigated the possibility of OTEC in Oman, it is clear that the need for renewable energy and desalination capacity is influencing OTEC interest in regions that have not been seriously considered in the past.

Finally, the capital cost of an OTEC plant has always been the primary risk and inhibitor to implementing an OTEC plant, but the strategy above leverages similarities between vessel-based desalination and OTEC subsystems such that capital costs have the opportunity to be shared. Additionally, the environmental effects evolve from a key risk when OTEC is primarily a power plant, to a key opportunity when OTEC is primarily a desalination plant. Historically, OTEC power plants have been viewed as having adverse environmental impacts because plants discharge large volumes of ocean water at elevated levels of salinity, nutrients, and residual biocides. Nevertheless, water-stressed regions with large coastal desalination plants have much higher carbon footprints, brine pollution, and biocide concentrations than an OTEC plant. Therefore, in comparison, the environmental effects of an OTEC-desalination plant become much more favorable considering OTEC-desalination minimizes carbon footprints, enhances brine dilution, and reduces residual biocides. As the need for desalination continues to grow and OTEC technology continues to mature, OTEC-desalination will be an imminent solution since it has the potential to be the largest capacity, lowest cost, most reliable, and most environmentally-responsible renewable desalination technology in the world.

Future work

Desalination using OTEC has been proposed as an environmentally responsible method of desalination that is less sensitive to operating costs because its power is supplied in situ; however, more research is needed to further validate the cost and environmental benefits of this system. It is interesting to note that very few publications have thoroughly analyzed the potential for OTEC desalination, whereas publications for nuclear desalination are very prominent (Figure 38).

Query: “nuclear”

Search result statistics	see all
desalination.com	***646***
Museum	2
Suppliers	4
WDR News	640

Results from related websites	
americanwaterintel.com	***13***
Insights	1
News	12
desaldata.com	***925***
Companies	21
Country Profiles	4
News	871
Project Tracker	22
Projects	7
desalyearbook.com	***4***
Featured plants	1
Global Water Awards	1
Year in Desalination	2
globalwaterintel.com	***71***
Company Profiles	1
Desal Tracker	2
GWI Premium » Global picture	11
Insights	2
News	54
PPP Tracker	1

Query: “OTEC” or “ocean thermal energy conversion”

Search result statistics	see all
desalination.com	***5***
WDR News	5

Results from related websites	
americanwaterintel.com	***1***
News	1
desaldata.com	***6***
News	6
desalyearbook.com	***2***
Year in Desalination	2
globalwaterintel.com	***2***
News	2

Figure 38: Comparison of query responses for desalination articles for nuclear versus OTEC desalinationfrom www.desalination.com

Searching for publications on Global Water Intelligence website www.desalination.com (and its related websites) revealed 1,659 articles for “nuclear desalination” while only 16 articles for OTEC which is two orders of magnitude less publications for OTEC. The amount of interest in nuclear desalination is a bit curious especially in light of the overwhelming public concern with nuclear meltdowns like the recent Fukushima nuclear reactor meltdown. With such prevalent concerns with nuclear safety, it is apparent that nuclear desalination will have more extreme barriers to entry than desalination using OTEC because of the perceived safety and environmental risk. Therefore, a paradigm shift is needed to start considering OTEC as a real desalination potential instead of the controversial alternative of using nuclear power.

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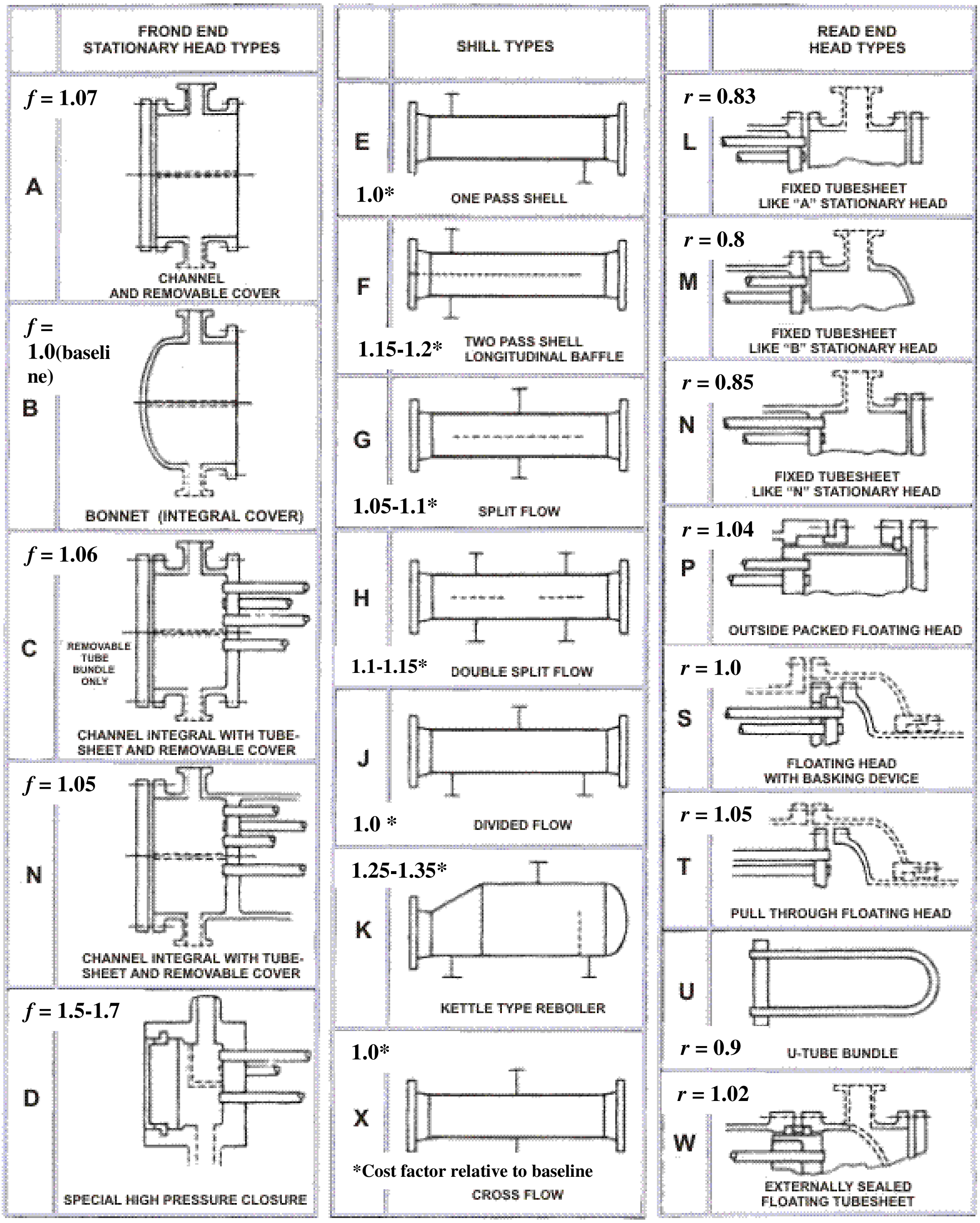
Appendix



A1: Diagram showing TEMA heat exchanger classifications adapted with Purohit cost correction factors (Source: www.thermopedia.com)

TEMA Type	Multiplier, *f*
No front end (special case)	0.95
B Bonnet (integral cover) (base)	1.0
A Channel and removable cover	1.02-1.03
N Channel integral with tubesheet, and removable cover	1.05
C Channel integral with tubesheet, and removable cover	1.06-1.07
D Special high-pressure closure	1.5-1.7

A2: Adaptation of Purohit cost multipliers for TEMA front-end stationary head type

TEMA Type	Multiplier, *r*
S Floating head with backing device	1.0
M Fixed tubesheet, like B stationary head	0.80
L Fixed tubesheet, like A stationary head	0.83
N Fixed tubesheet, like N stationary head	0.85
U U-tube bundle	0.9
T Pull-through floating head	1.05
P Outside-packed floating head	1.04
W Externally sealed floating tubesheet	1.02

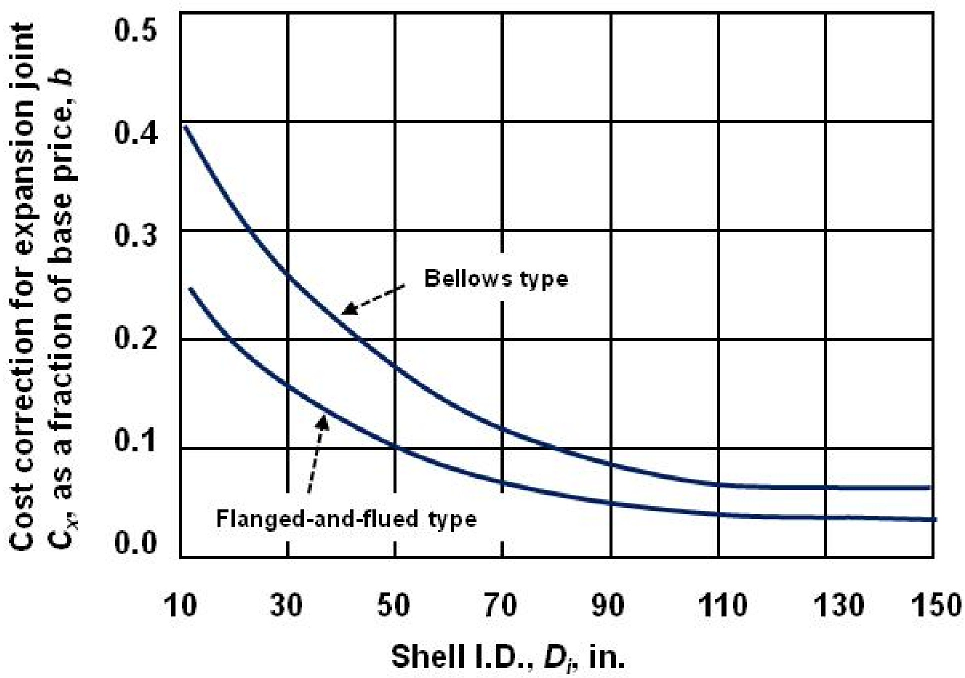
A3: Adaptation of Purohit cost multipliers for TEMA rear-end head type

	Multiplier, *p*	
Tube O.D. x pitch	**Triangular pitch (30- or 60-deg)**	**Square pitch (45- or 90-deg)**
5/8 in x 25/32 in	0.62	Not common
3/4 in x 15/16 in	0.80	Not common
3/4 in x 1 in	0.85	1.0 (base)
7/8 in x 1 3/32 in	0.87	Not common
1 in x 1 1/4 in	0.98	1.16
1 1/4 in x 1 9/16 in	1.23	1.45
1 1/4 in x 1 37/64 in	1.29	1.49
1 1/2 in x 1 7/8 in	1.47	1.73
1 1/2 in x 1 57/64 in	1.56	1.80
1 3/4 in x 1 3/16 in	1.72	2.03
1 3/4 in x 1 13/64 in	1.81	2.13
2 in x 2 1/2 in	1.97	2.32
2 in x 2 17/32 in	2.08	2.45

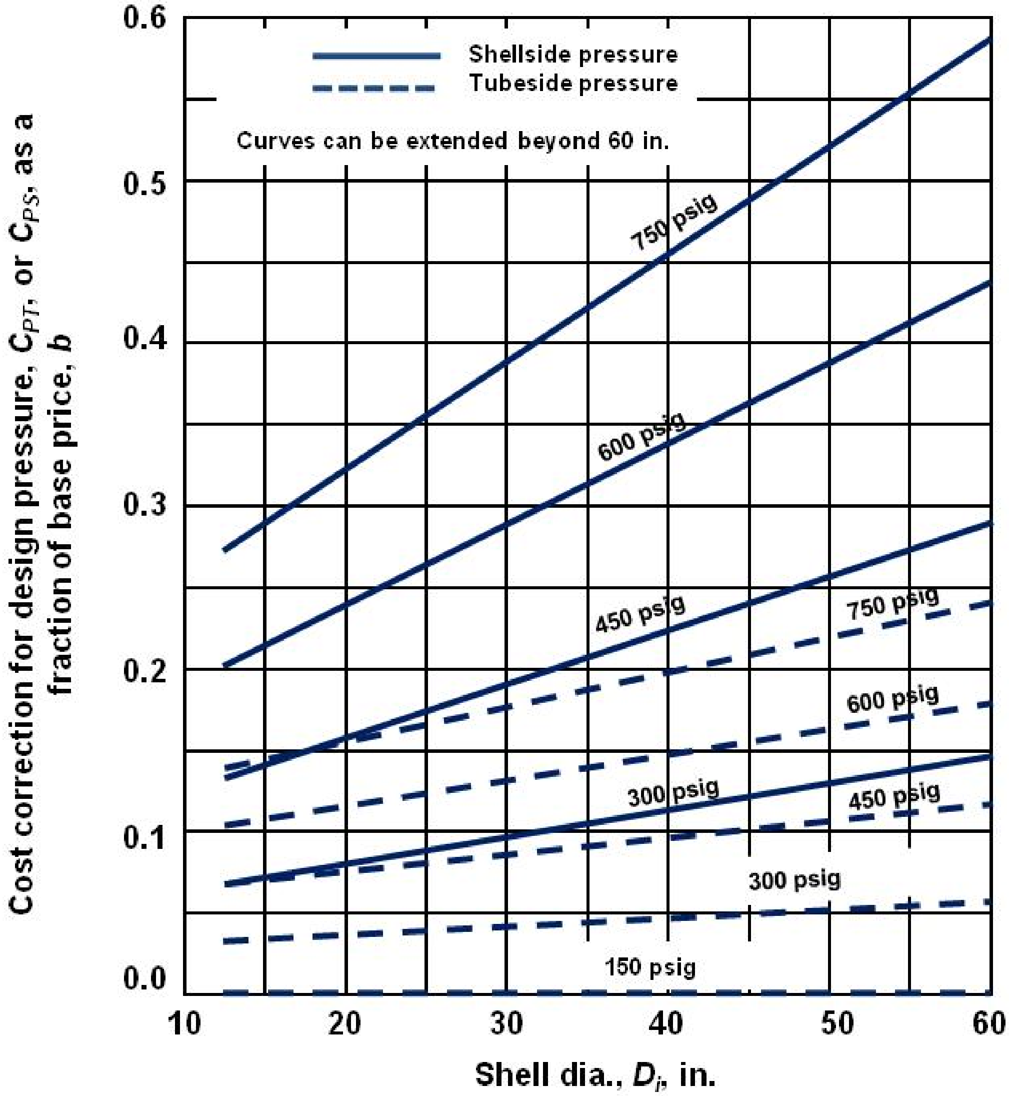
A4: Adaptation of Purohit cost multipliers for tube O.D., pitch, and layout angle

TEMA Shell Type	Correction C_s
Open-tube exchanger (no shell) (special case)	-0.2
E One-pass (base)	0
J Divided flow	0
X Cross-flow	0
G Split flow	0.05-0.1
H Double split flow	0.1-0.15
F Two pass with longitudinal baffle	0.15-0.2
K Kettle rebolier	1.02

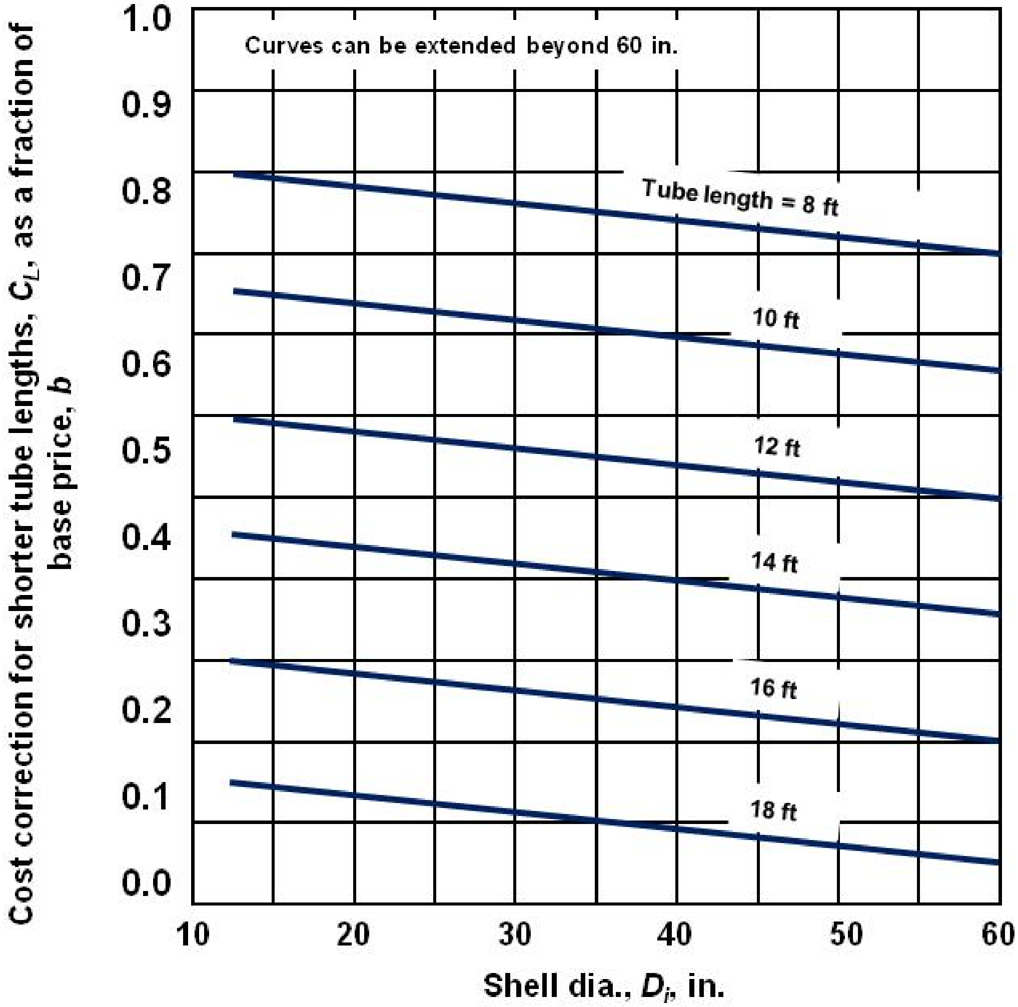
A5: Adaptation of Purohit cost corrections for TEMA shell type



A5: Adaptation of Purohit cost corrections for shell expansion joints



A6: Adaptation of Purohit cost corrections for shell- and tube-side design pressures



A7: Adaptation of Purohit cost corrections for tube lengths shorter than 20 ft

____
From: Mandsager, Kathy [kathy.mandsager@unh.edu]
Sent: Friday, October 04, 2013 4:33 PM
To: Michael Russell Eller
Subject: RE: OTEC workshop proceedings

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Dear Miss Kathy Mandsager,
I am completing a doctoral dissertation at the University of New Orleans on the topic of Ocean Thermal Energy Conversion (OTEC). I would like permission to reprint in my dissertation excerpts from the following publications:

Coastal Response Research Center. (2010). Ocean Thermal Energy Conversion: Assessing Potential Physical, Chemical and Biological Impacts and Risks. (p. 39 pp and appendices). Durham, NH: University of New Hampshire.

Coastal Response Research Center. (2010). Technical Readiness of Ocean Thermal Energy Conversion (OTEC). (p. 27 pp and appendices). Durham, NH: University of New Hampshire.

The figure to be reproduced from Luis Vega's presentation in the 2010 Technical Readiness of OTEC workshop is: “**Figure 39: Vega’s first and tenth generation OTEC plant capital cost estimates for increasing plant capacity”**

The figure to be reproduced from Grandelli & Rocheleau's presentation in the 2011 OTEC Environmental workshop is:**“Figure 40: Hydrodynamic model with OTEC plant located within a near-field EFDC grid nested within a far-field HiROM grid”**

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Sincerely,
Michael Eller

A8: Permission letter from University of New Hampshire Coastal Response Research Center to reprint the figures noted above

Vita

Michael Eller was born in Hoffman Estates, IL. He received his Bachelor of Science in Mechanical Engineering from the University of Michigan and a Master of Science in Engineering Management from Drexel University. He currently works for Lockheed Martin Information Systems and Global Services (IS&GS) at the NASA Michoud Assembly Facility in New Orleans, Louisiana. He has been pursuing his PhD in Engineering and Applied Sciences-Engineering Management at the University of New Orleans since 2009.