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TECHNICAL REPORT

Ocean Thermal Energy Conversion (OTEC) Economics: Updates and Strategies

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PREPARED FOR:

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IEA-OES Technology Collaboration Programme

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This study is conducted as a part of the IEA-OES Task focused on Ocean Thermal Energy Conversion (OTEC). The countries collaborating on this Task include India, Korea, Japan, China, France, and the USA.

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Table of Contents

Foreword

Ocean Thermal Energy Conversion (OTEC) is a promising ocean renewable energy that utilizes the temperature difference found between surface and deep ocean waters. The technology has been evaluated and demonstrated around the world, and a recent White Paper published by OES has elaborated the history and status of development.

Despite the work done on OTEC to date, there is less clarity on the economics of OTEC. This report focuses on understanding the costs and economic cases for various types of OTEC deployment. Luis A. Vega, Ph.D. has updated his previous models and Levelized Cost of Energy (LCOE) calculations. Benjamin Martin, Secretary General of the Ocean Thermal Energy Association supported various aspects of the study including the section on onshore OTEC, LCOE sensitivity analysis, and editing throughout.

This report updates and extrapolates past efforts to understand the economics of OTEC in today's changing world as the demand for environmentally friendly solutions to power, water, and food crises increases. In addition, the report will examine various business scenarios for implementation in the near future. Drawing upon the Ocean Thermal Energy Association, the current active OTEC developers, academics, and government institutions around the world are listed as a reference in Appendix 2.

The initiation for this project stated "studies conducted to date on the economic feasibility of OTEC systems suffer from the lack of reliable cost data. Data needs to be collected from various demonstration plants in several countries for understanding the economics." This paper will answer where OTEC is today and provide hints on how to accelerate deployment around the world.

Executive Summary

Ocean Thermal Energy Conversion (OTEC) is a renewable ocean energy that relies on naturally-occurring temperature gradients in the ocean. Due to the vast resource availability provided by the ocean, it has captured the minds of scientists, academics, and entrepreneurs since Jules Verne's 20,000 Leagues Under the Sea inspired initial research in the 1800s. Still, like many technologies when compared to the status quo, the early-stage economics of OTEC can be a challenge. This report refrains from technical details on OTEC, technical information previously published by Dr. Vega and his colleagues is available online, rather we will explore the current costs of OTEC and in what cases it may be economically applied today.

This updated assessment provides: (i) Capital Costs ($/kWnet) estimates from equipment and installation quotes meeting specifications developed by Dr. Vega and confirmed with the operation of experimental plants; and (ii)Updated Levelized Cost of Electricity ($/kWh) as function of loan rates; including desalinated water production credit for specific open cycle OTEC cases. Where possible new quotations were solicited to update cost figures. As further reference, information from Japan is provided where applicable.

Dr. Vega determined that the major differences in capital cost between new and historic data are due to:

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

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

Levelized Cost of Electricity (LCOE) was estimated using the updated or extrapolated capital costs as detailed in Appendix 1. Depending on the design, manufacturers, location, inflation, and interest rates imposed there is significant variability.

Considering sites with average seawater temperature differential (ΔT) of 21.5 ºC, updated Levelized Cost of Energies ($/kWh) for first-generation, plants were calculated and compared with other sources. In the case of a 10MW closed cycle plantship based on off-the-shelf parts, the new LCOE is between $0.37/kWh and $0.46/kWh when concessionary loans are available. Japan data updated to 2022 dollars expect a semi-submersible platform to cost $0.30/kWh under the same loan conditions. These decrease with scale. For open cycle plantships, even with credit for desalinated water, a higher LCOE of $0.62/kWh was calculated.

As expected with most developing technologies, these first-generation LCOEs are challenging without environmental credits or subsidies. Studies in Japan, such as the New Energy and Industrial Technology Development Organization of Japan (NEDO)'s 2014 report "Research and Development of Next-generation Ocean Energy Power Generation Technology (Ocean Thermal Energy Conversion) cited on page II3-3 of the final report[Okinawa Prefectural Government, 2019] have shown an expected decrease

in onshore facility capital cost of 18% for subsequent commercial facilities, and a reduction in capital cost of 30% for offshore OTEC as structures are optimized. This equates to a $0.26/kWh LCOE for a 50 MW plantship when concessionary loans are applied.

Sites with higher ΔT will yield net output increases such that locations with a ΔT of 24.5 ºC will yield about 40% higher output. This would have a corresponding effect such that the LCOE would be about 30% lower. This equates to a $0.19/kWh LCOE for the commercial 50 MW plantship noted above in warmer waters. This presents a laudable goal in terms of future OTEC implementation, however, currently there are no MW-scale plants in operation. To achieve larger scales, smaller plants with lower economies of scale will be required first.

Given the high cost for first-generation implementation, what scenarios could make sense to support implementation of renewable energy and scale OTEC deployment? Analysis shows that it is possible to provide a business case for OTEC at small-scale under certain special situations. In such cases it may still be possible to yield an LCOE below $0.20/kWh.

As a recent offshore approach, the UK-based Global OTEC calculates that use of alternative platforms and components could achieve LCOE of $0.18/kWh for first-generation 1.5MW offshore OTEC platform with 50% subsidy and 25-year term. Onshore, multiple use of seawater in industry can provide additional economic and social benefits that de-risk the required seawater intake infrastructure investments.

Localizing for improved performance with demonstration to facilitate risk reduction and cost reduction can accelerate OTEC deployment. In addition, factors for which it is difficult to apply economic benefits are not included in this analysis, though they may provide value beyond environmental and monetary benefit. These include OTEC's ability to provide high capacity factors, suitable for baseload power, as well as reactive power for grid stabilization.

This study shows that in terms of economics, OTEC is ready for deployment in certain markets, and with further deployment can be competitive at larger scales.

1. Introduction

Significant research and efforts have been applied to the implementation of OTEC around the world leading to an existing body of technical and economic data. This report refrains from technical details on OTEC beyond what is necessary to define relevant cases to provide an updated summary of the economics of OTEC considering three classes: 1 MW onshore; 10 MW and 50 MW floating/offshore. Current costs of the major components are presented where possible along with archival cost estimates extrapolated to today's market where new data was unavailable.

There are various OTEC designs and cycles available, and over the years various implementations have been confirmed through experimental plants in Japan, South Korea, India, and the USA/Hawaii. Dr. Vega developed technical specifications to solicit vendor quotations for specific components. This step posed a significant challenge in that some potential suppliers of key components do not provide quotes for free, and this study is not expected to lead to an order. Efforts were made to adapt pertinent data to the scenarios selected in this project.

A previously implemented analytical model (Reference 4) was used to assess scenarios under which OTEC might be cost competitive with conventional technologies. First, the capital cost for OTEC plants, expressed in $/kW, was estimated from current costs for the major components of OTEC systems including installation costs. Subsequently, the relative cost of producing electricity ($/kWh) with OTEC, offset by any additional revenues generated by follow-on industries such as desalinated water sales was calculated. Finally, various strategies for implementation are considered for onshore OTEC.

Specifically, this report will summarize previous work on costing OTEC, provide updated costs for OTEC components, evaluate LCOE, and consider the implementation of OTEC onshore.

The major technical, resource, and economic challenges related to the implementation of OTEC systems can be summarized as follows:

Technical

OTEC generates electricity 24/7, which contributes to a high capacity factor suitable for baseload power generation.

Based on lessons learned with preliminary OTEC designs, model basin tests, experimental plants, and the know-how available from offshore engineering firms, it can be stated that no major technical issues remain for the implementation of OTEC. Site specific engineering design processes incorporating operations, maintenance, repair and replacement (OMR&R) protocols must be incorporated into the final design process. In addition, the selection of a site must consider the human and equipment infrastructure required for installation and operations. This is extremely important when considering remote locations and Small Island Developing States (SIDS).

For offshore OTEC, one of the major engineering challenges associated with the first generation of facilities (e.g.,10 to 50 MW) is relying on adapting equipment designed and implemented for other applications. Some subsystems will require multiple units linked together. Most noticeable are the cases with seawater pumps ("low-head high flowrate") and Closed Cycle OTEC heat exchangers (HXs) and Open Cycle OTEC Turbine Generators (TGs).

Per design and as confirmed with experimental plants, the operational control parameters for OTEC are:

(i) mass flow rate of warm water
(ii) mass flow rate of cold water
(iii) warm water temperature
(iv) cold water temperature

Technology-specific Control Parameters:
(v) [closed cycle only] working fluid (e.g., NH_3) mass flow rate and recirculating-to-feed pumps flow ratios
(vi) [open cycle only] vacuum compressors train inlet pressure;

The gross power output from an OTEC power plant can be controlled only with the first two common parameters plus the unique parameter while the water temperatures are dictated by natural processes. During operations with Hawaii's 250 kW Open Cycle OTEC Experimental Apparatus, gross power output was controlled by varying the water streams flow rates with the water pumps and the inlet pressure with the vacuum pumps train to set the appropriate pressure in the Flash Evaporator.

For larger OTEC classes, the combined needs for substantial amounts of cold seawater, such as (≈140 m^3/s) in a 50MW plantship, and minimal pumping power losses result in a relatively large diameter cold-water pipe (CWP). Historic studies selected a 1,000 m long 8.7 m inner diameter fiber-reinforced-plastic (FRP) sandwich construction cold-water pipe, however, HDPE pipes are currently available in larger diameters that can be used in bundles for 10 MW (2 pipes) and 50 MW (8 pipes) resulting in relatively lower costs than previously reported.

OTEC Resource

Dr. Gerard Nihous at the University of Hawai'i led the implementation of a numerical model with state-of-the-art atmosphere-ocean coupling including ocean currents and thermohaline circulation to assess the environmental impact of thousands of plants. He essentially divided the OTEC resource region into 25 km x 25 km squares with a "100 MW/ΔT: 20 ºC" plantship stationed in the middle of each square. His theoretical conclusions can be conservatively interpreted by stating, for example, that 50,000 plants (5 TW) could be installed with "acceptable" world-wide environmental impact. Annual energy generation from these plants would equal about 43.8 petawatt-hours. In 2019 the world total electricity consumption was 22.8 PWh[International Energy Agency, 2021]. In terms of primary energy, which includes other uses of energy such as fuel and transportation, 5TW would have a substantial contribution to the worldwide primary consumption of 18TW x 8760hours.

Figure 1 provides basic information on where OTEC is most applicable, which is driven by the temperature difference between surface and deep ocean layers.

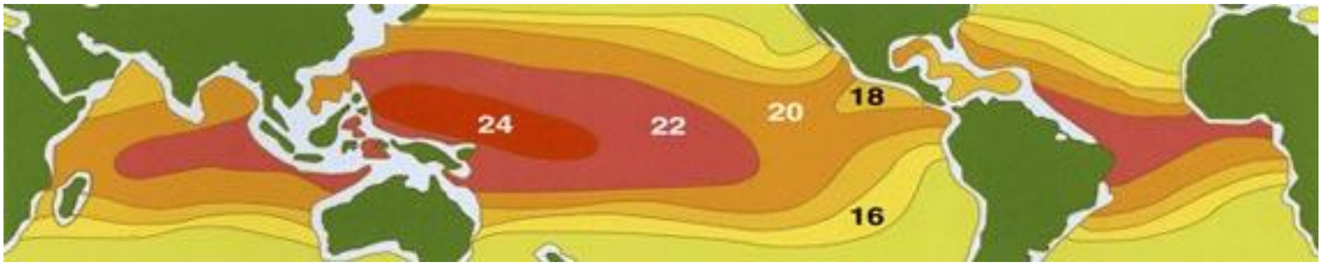


Figure 1 - Worldwide Temperature Difference between surface and 1000m Depth[Institute of Ocean Energy Saga Univesity, 2023]

Figure 2 illustrates areas where hurricanes are not present, a location suggested for future plantship deployment. In areas where hurricanes are a threat, spar or semi-submersible platforms are a preferred option.

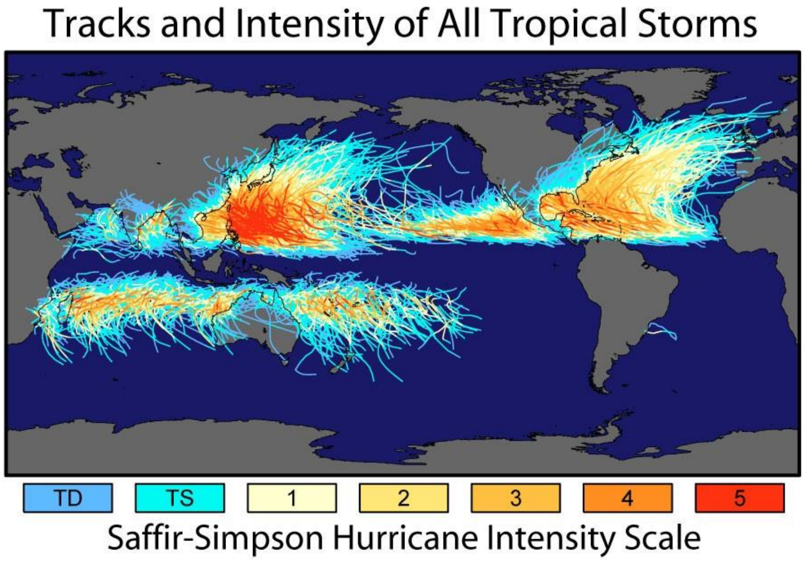


Figure 2 - Historic Hurricane Tracks

The hurricane tracks correlate with Figure 1, showing minimal environmental loading locations along the Equator, off Brazil, and off West Africa.

Government and Policy

In recent years local and national governments have begun including OTEC in their policies towards energy and climate transitions. Examples include the following:

The State of Hawai'i has included OTEC in its definition of renewable energy since 2001, under Session Laws of Hawaii ACT272.

Turk and Caicos included OTEC in their Island Vision published in 2019.

Kumejima Town in Japan prioritized OTEC in its "Energy Vision 2020," where it has a prominent role in the town's decarbonization roadmap.

The 2020-2040 Philippine Energy Plan also includes OTEC.

Sao Tome and Principe's National Renewable Energy Plan includes Global OTEC's proposed plant.

In 2022, the government of Malaysia included OTEC in its National Energy Policy 2022 to 2040.

In 2023, the Government of Mauritius included setting up a 1MW OTEC pilot in their budget newsletter.

Economy

As with other renewable energies, OTEC benefits from low operating costs compared to traditional fossil-fuel-based power generation facilities. The higher capital costs compared to reduced operating costs (removal of fuel costs) present a market challenge for users and operators. Traditionally, the cost of energy can be spread over time, such as when purchasing fuel. This leads to volatility in market prices among other challenges, but accepting higher upfront cost with overall lifetime savings can be challenging in existing financial and insurance markets.

This report will make various cases where implementation of OTEC is economically feasible, however, one of the impediments to OTEC implementation is that traditionally rich and developed countries have limited potential for implementing OTEC domestically. Thus, it is the nations with the highest potential for OTEC that lack the economic tools to implement high capital cost projects and overcome the high hurdle of de-risking technology deployment.

2. Archival OTEC Capital Costs Estimates

Archival capital costs gathered over the last 30 years for different OTEC systems, categorized by net power output for the indicated average temperature difference, are summarized in Table 1. The Table includes source and year of publication with values extrapolated to the present using the USA Manufacturing-Price-Index (MPI) from the date of the original estimate to December 2021. This date was chosen on the advice of manufacturing companies contacted. The companies' consensus was that during 2022, when estimates were sought, a marked raw materials price increase due to the Covid Pandemic was temporary and the expectation was a return to December 2021 costs.

The last three entries are for plants with costs based on current upper limit estimates obtained between January and June 2023. These estimates are at the preliminary design level that is also referred to as Front-End-Engineering-Design (FEED). The FEED estimates will need to be followed with the final or site-specific detailed design to guide construction and operation. This final step is beyond the scope of this report. It is common practice for most Offshore Engineering firms operating in the Gulf of Mexico and the North Sea to add between 30% to 50% to their cost estimates at the FEED stage as indicative of what might be expected after site specific detailed-design-engineering is completed. This means the estimates presented in this report are in line with industry standards but are likely higher than actual commercial installations will be. For this report, the cost estimates received are utilized as is.

Capital costs from various sources extrapolated to the present are plotted in Figure 3 wherein for convenience a curve has been fitted to the archival values identified by the power rating (MW) assigned in the different references (i.e., without correcting for ΔT because not all designs parameters are reported):

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

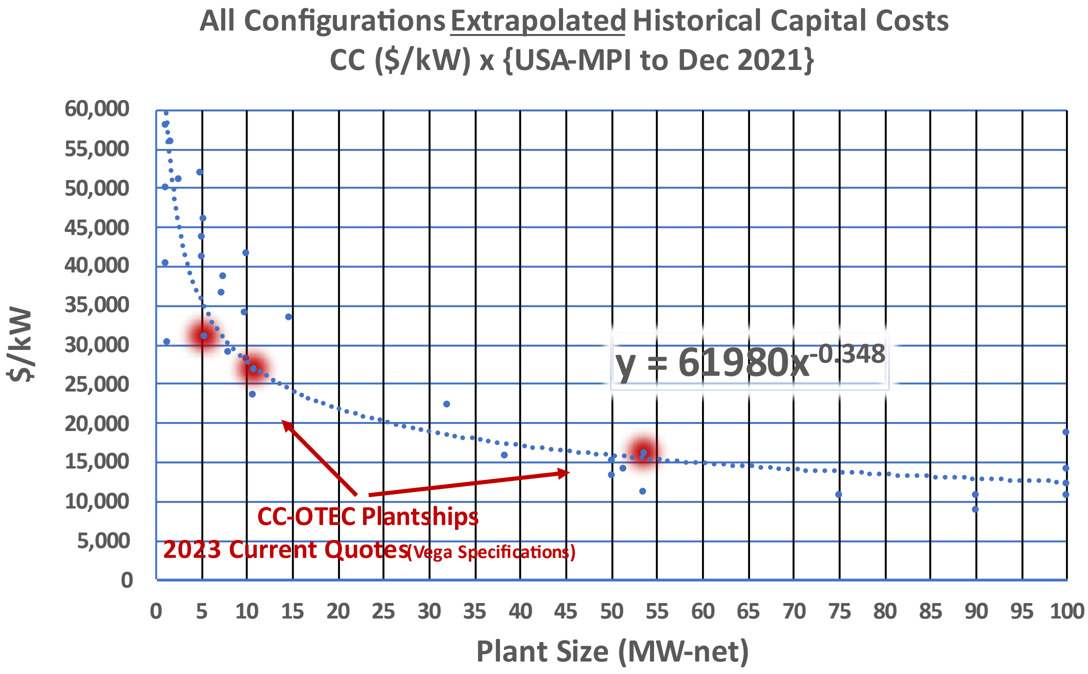


Figure 3 - Archival OTEC Capital Costs

Figure 3 includes archival capital costs of some published estimates for both Closed and Open Cycles extrapolated to 2021 using the US Manufacturing Price Index. Three current estimates (5, 10 and 50 MW-class) from this report based on a temperature difference of 21.5°C are shown.

Table 1 - Archival Cost Estimates Extrapolated to 2021

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

*Note on abbreviations: SOA= State of the Art

For Table 1**,** data labelled E3Tec was supplied by Dr. C.B. Panchal. Technip data is from the 3rd OTEC Symposium (2015) presentation by Jim O'Sullivan. All others from work performed with participation of Dr. Vega.

As OTEC power generation is highly dependent on the available temperature difference, it is important to note the resource availability has significant impact on both capital cost and LCOE. Table 2, for example, provides the variations in output for a 53.5 MW Closed Cycle OTEC plantship (for average ΔT of 21.5 ºC) for sites with different average ΔT. This is indicative of the corrections that would be required to compare the different values obtained by different organizations at the FEED stage.

Table 2 - 50 MW-Class Power Output as a function of ΔT

ΔT	P(MW-net)	Pnet/Pdesign
19.5	39.7	0.74
20.5	46.5	0.84
21.5	**53.5**	**1***
22.5	60.8	1.14
23.5	68.4	1.28
24.5	76.3	1.43

*Design at Tww: 26°C /Tcw: 4.5°C

Table 2 indicates a 43% increase in electricity generation for a plant designed for ΔT average conditions @ 21.5 ºC and keeping the same mass flow rate of working fluid (e.g., the same HXs). For stationary OTEC implementation, optimizing for the site conditions would allow for either a decrease in capital cost or increase in power output (increase in revenue).

3. OTEC Cost Estimates

Equipment Specifications for plants utilizing Closed Cycle and Open Cycle technology were developed for this study by Dr. Vega. He solicited new quotations for equipment, resulting in updated capital cost estimates as presented in this section.

A 50 MW-class Closed Cycle OTEC plantship, for example, requires a 198 m long ship-shaped platform with 39 m beam and an operating draft of 16 m resulting in 120,600 tonnes (metric ton) displacement. The Open Cycle OTEC plant would be shorter at 176 m but have a wider beam at 90 m resulting in a displacement of 247,400 tonnes.

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

For the cold-water pipe, HDPE pipes in bundles for the 10 MW (2 pipes) and the 50 MW (8 pipes) were selected. The cold-water pipe bundle will be attached to a gimbal at midship. Applicable single point mooring systems, including electrical and fluid swivels, are available from the offshore industry. For this case, the heat exchangers considered for the ammonia cycle can be manufactured by various vendors. The electricity produced is transmitted to shore via a submarine power cable and the desalinated water via a flexible pipe (e.g., hose).

As an example, in the 50 MW class plantship, electricity and desalinated water production rates are: 430,000 MWh/year for the Closed Cycle OTEC; and, 410,000 MWh/year and 120,000 m^3/day for the Open Cycle OTEC.

This survey confirms that the equipment for all subsystems (except for turbine generators for Open Cycle OTEC) is available based on off-the-shelf designs that are currently manufactured. However, because they were not designed specifically for OTEC's high seawater flow rates, using off-the-shelf equipment results in numerous units to be installed in parallel to meet the specifications. For example, the Closed Cycle OTEC 10 MW class (5x for the 50 MW class) using plate-frame titanium HXs would require at least 48 evaporator units and 36 condenser units; and 28 warm seawater pumps and 6 cold seawater pumps. As OTEC plants are implemented, it is expected market development for OTEC-specific components will result in a considerable decrease in the subsystems' costs. In addition, systems specifically optimized for OTEC can provide better overall cost performance and reduction in parasitic losses from seawater pumping.

Some long-lead items would require from 18 months to 24 months to be delivered. Based on experience with offshore projects of similar size it is expected that at least two years would be required for deployment and commissioning.

Current cost estimates for all major components of the power block except turbine generators for Open Cycle OTEC were obtained. Archival estimates included information for 2.5 MW units based on the low-pressure end of turbines designed for nuclear plants. Unfortunately, the manufacturer no longer produces such units, and a new supplier could not be identified.

The current capital cost estimates for the Closed Cycle OTEC examples are summarized in Table 3 and Figure 4 – Closed Cycle OTEC Cost Distribution with Various Heat Exchangers and for the Open Cycle

OTEC class in Table 4 and Figure 5 – Open Cycle OTEC Cost Distribution. For the baseline conditions, the Open Cycle OTEC estimate is higher than the Closed Cycle OTEC estimate by 32% for the 10 MW-class and 47% for the 50 MW-class. Therefore, from an economic perspective, implementation of Closed Cycle OTEC should be prioritized unless sites with relatively high costs of desalinated water are identified.

Table 5 provides a current cost estimate for an onshore1.36 MW Open Cycle OTEC plant including the generation of 2,450 m^3/day desalinated water.

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

Various companies contributed estimates for this study. Each company is assigned a letter value for each component abbreviated to distinguish between variations in cost. For example, for heat exchangers, the abbreviation is Heat Exchange Company (HXC) with each company provided a unique letter value. Thus, in the table below “$/kW (w/ HXC-A)” refers to the total capital cost if Heat Exchanger Company A’s equipment is utilized.

Table 3 – Closed Cycle OTEC Cost Estimates for major Subsystems in a Plantship

	10.6 MW		**53.5 MW**	
Component	**$M**	**10 MW %**	**$M**	**50 MW %**
New Plantship	28.3	10%	84.5	10%
Mooring (MC-A)	22.0	8%	29.0	3%
Power Cable (PCC-A)	3.7	1%	4.2	0%
Pipes (PC-A)	10.9	4%	43.5	5%
Water Pumps (WP-A)	11.5	4%	57.5	6%
NH3 Pumps (WFP-A)	0.65	0.2%	3.4	0.4%
HXs Ti (HXC-A)	84.0	29%	420.0	47%
TG (TG-A)	13.5	5%	67.5	8%
***Generic Installation& Assembly**	111.8	39%	177.3	20%
TOTAL ($M)	**286.3**		**886.9**	
$/kW (w/ HXC-A)	**27,012**		**16,578**	
$/kW (w/ HXC-B)	**21,606**		**11,223**	
****Installation& Assembly***	***$M***		***$M***	
Mooring & Power Cable	*43.5*		*58.4*	
Pipes & Pumps	*8.0*		*34.8*	
Power Block	*33.2*		*57.0*	
Electrical & Controls	*27.1*		*27.1*	

The category “Installation and Assembly” is the same amount independently of HXs supplier and includes educated estimates associated with transportation to a generic site and equipment mobilization and demobilization.

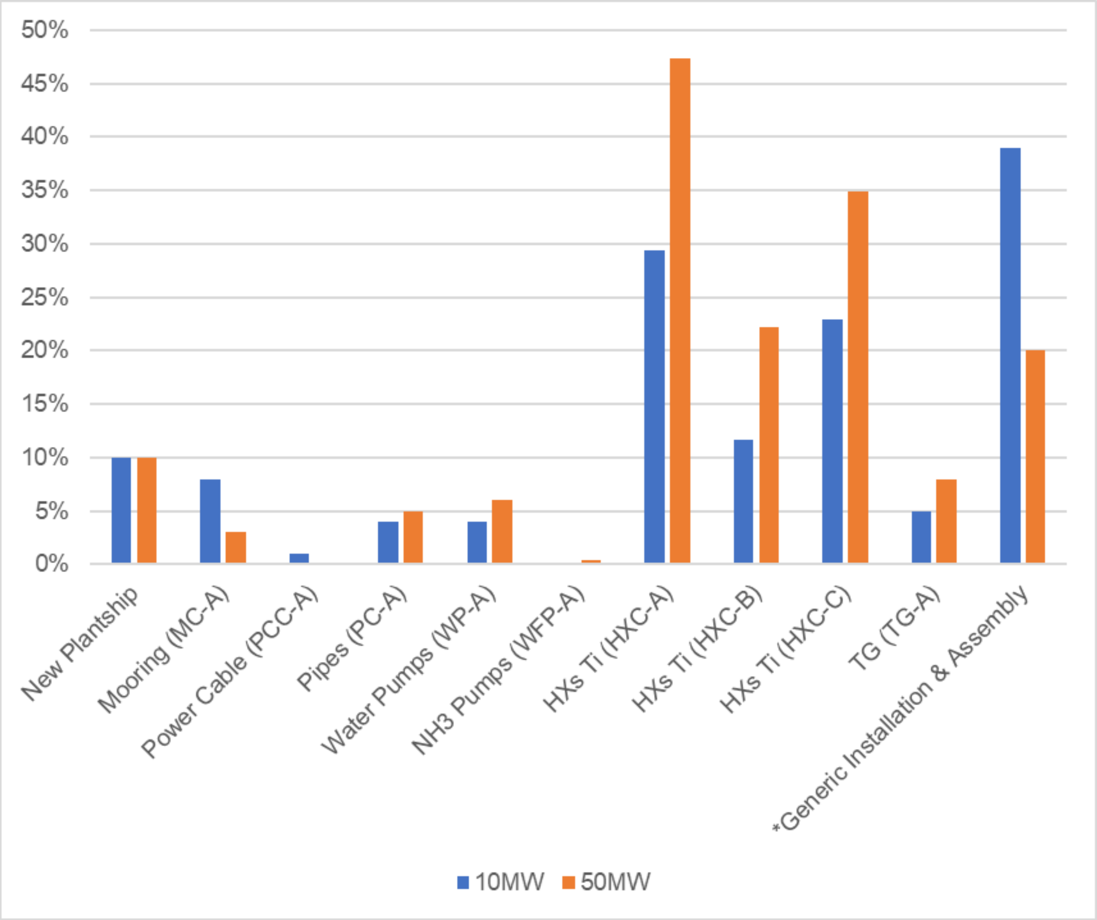


Figure 4 – Closed Cycle OTEC Cost Distribution with Various Heat Exchangers

Heat Exchanger cost distribution varies widely depending on the heat exchanger manufacturer selected. Figure 5 shows the distribution with heat exchange company A (HXC-A). For comparison, two other companies are also included with the associated percentage they would have if utilized. The cost distribution with HXC-B is 12% instead of 29% (10 MW); and 22% instead of 47% (50 MW). With HXC-C, it is 23% instead of 29% (10 MW); and 35% instead of 47% (50 MW).

Table 4 – Open Cycle OTEC Plantship Cost Estimates

	10.2 MW 6.3 MGD*		51.25 MW 31.3 MGD*	
Component	**$M**	**10 MW %**	**$M**	**50 MW %**
New Plantship	47.3	13%	141.0	11%
Mooring (MC-A)	22.0	6%	29.0	2%
Power Cable (PCC-A)	3.7	1%	4.2	0%
Pipes (PC-A)	10.9	3%	43.5	3%
Water Pumps (WPC-A)	11.5	3%	57.5	4%
Compressors (CC-A)	61.40	16.2%	307.0	23.5%
Flash Evaporator/Surface Condenser	56.7	15%	283.5	22%
Turbine Generator	53.1	14%	265.5	20%
Installation & Assembly	111.8	30%	177.3	14%
TOTAL ($M)	**378.4**		**1308.6**	
$/kW	**35,697**		**24,459**	
$/kW (with DCC)	**33,962**		**22,722**	

The category “Installation and Assembly” distribution is the same amount as in the case of Closed Cycle OTEC (Table 3) and independent of condenser type. It includes educated estimates associated with transportation to a generic site and equipment mobilization and demobilization. *Million gallons per day.

Table 5 – Land-Based 1.36 MW-net Open Cycle OTEC with 2,450 m3/day Desalinated Water Production

	1.36 MW-net 2450m3/day	
Component	**$M**	**10 MW %**
Intake Pipes	4	9.3%
Seawater Pumps	1.3	3%
Structure w/ Installation	8.4	19.6%
Flash Evaporator	1.7	4%
Surface Condenser	4.6	10.7%
Turbine Generator	5.9	13.8%
Compressor	3.4	8%
Auxiliary Generator	.8	1.9%
Seawater Pipes and Pumps Installation	11	25.7%
Utility Connection	1.7	4%
TOTAL ($M)	**42.8**	
$/kW	**31,470**	

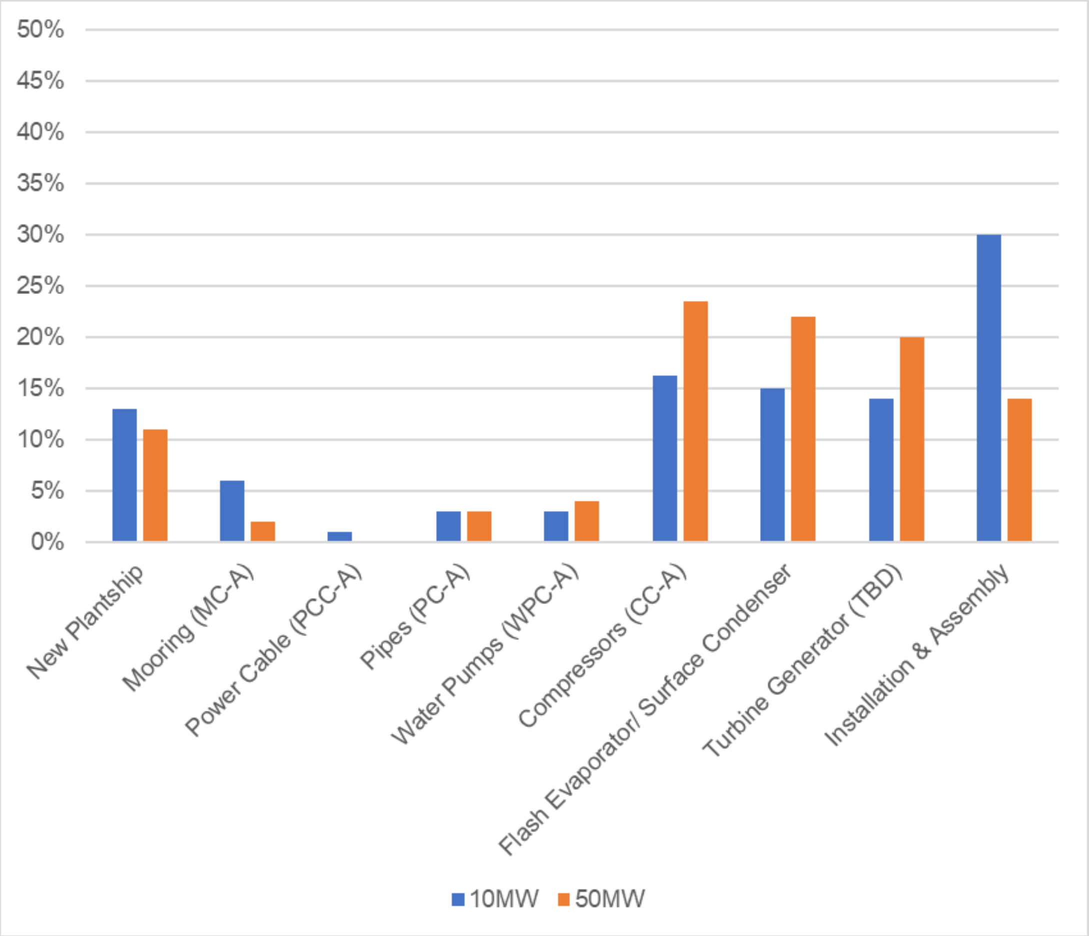


Figure 5 – Open Cycle OTEC Cost Distribution

OTEC Platform

Onshore OTEC requires the same standard building approach as with other power plants, generally, without specialized considerations excepting where a working fluid may require special handling.

For offshore cases, there are multiple approaches to implement OTEC, all with advantages and disadvantages. In the case of spar type or semi-submersibles, generally costs will be higher than a plantship, but the stable platform may have advantages to offset the cost over the long-term. Reutilization of existing offshore infrastructure such as for oil and gas, including floating platforms of various types may also be possible.

In this study, ship-shaped vessels were considered from a cost reduction perspective.

Various shipyards were contacted but it was not possible to obtain new quotations. As an alternative, press releases and trade magazines were examined for information about current orders and costs for vessels of dimensions and dead-weight-tonnage (DWT) matching specifications. Relevant information is given in Table 6 and incorporated into Figure 6.

Figure 6 provides the relationship between the cost of a Vessel ($/tonne) and DWT from all sources. The Korea Research Institute of Ships and Ocean Engineering (KRISO) was also able to share the cost of the 10,000 DWT barge used in their OTEC tests. It matches within 10% the derived relationship.

Note that the cost for a vessel labelled as "New Tankers" in Figure 6 refers to vessels that are brand new and currently available at much lower cost because the purchasers were unable to meet financial obligations. In addition, we include the cost of vessels that are 10-years old and available for purchase "second-hand." For example, a 40,000 DWT product tanker seems suitable for the 10 MW case with plenty additional space (only 18,980 DWT required for the Closed Cycle OTEC components). For the 50 MW case, 95,000 DWT (vs 88,038 DWT required) is sufficient. Considering 10 years old units, the following prices are realistic in 2023:

10 MW Case 10 years: $20 M
50 MW Case 10 years: $30 M

During conversion the hull would be significantly reinforced. The cost of conversion of the hull, integration of the plant, and commissioning is expected to double the platform costs, at a minimum.

From the collected data, the algorithm derived from the curve labelled "Container Ships 2015-2021"(Figure 6 and Table 6) is used for estimating cost as the ships noted above may not be available in the future.

For a pilot plant, a "10-Years Old" vessel would represent a substantially lower cost.

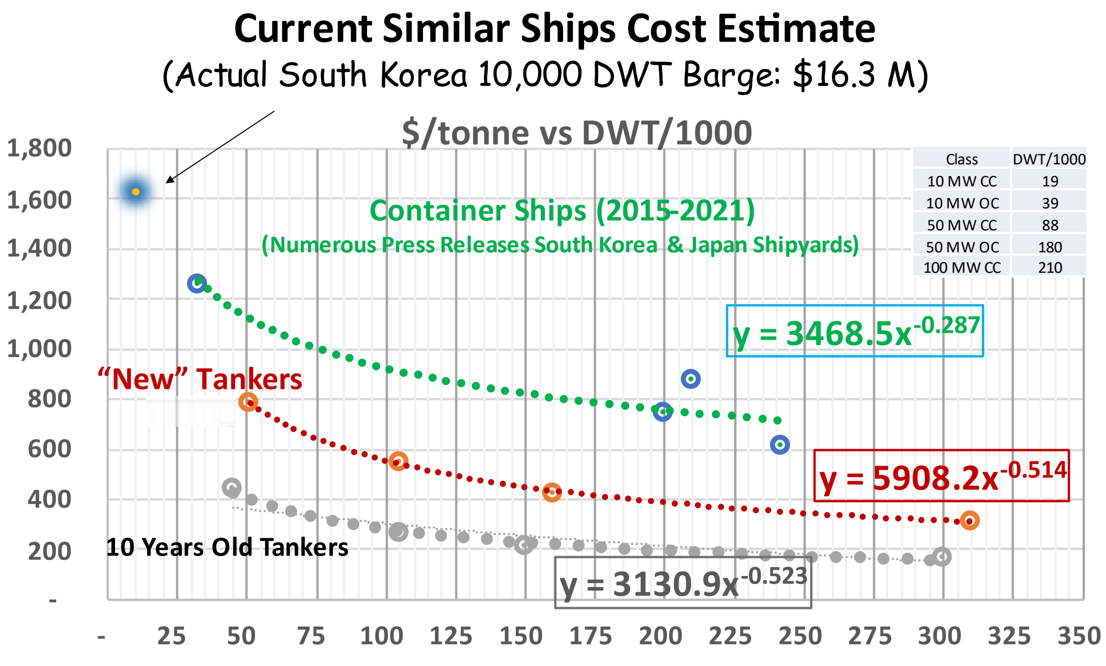


Figure 6 – Plantship Capital Cost

The ship cost estimates include the propulsion system but exclude mooring, OTEC power blocks and seawater piping systems.

Table 6 – Container Ships with Displacement Matching 10 to 100 MW OTEC Plantships

Existing Container Ships	LBP x Beam x Draught meters	"Displacement" tonnes	Date & Shipyard	All included Cost US $M
Ever Orient **(Evergreen O-Class)**	195 x 32 x 11.4	DWT: 32,500 Displacement: 43,749(Cb:0.6) **2634 TEU** **12.3 t/TEU**	**2021** Cost taken from similar order by Namsung Shipping to Hyundai for 2500 TEU ships	**41 (2021)** **43 (2022)** **CC (\$M)/(LBPxBxD)=** **576 \$/m^3** **CC (\$M)/DWT=** **1262 \$/t** **CC (\$M)/TEU=** **15566 \$/TEU**
Ever Given ***(Evergreen G-Class)*** **Container Ship** **1 of 13 ships** **"Imabari 20000 Design"**	399.94 x 58.8 x 14.5 (Height: 32.9 m) Single Engine: 59 MW **Two Bow Thrusters: 2.5 MW each**	**265,876**(Cb : 0.76) DWT: 199,629 Lightwgth: 66,247 (25%) **20,124 TEU** 9.9 t/TEU	**Sep 2018** Imabari Shipbuilding Japan	**150** **CC (\$M)/(LBPxBxD)=** **440 \$/m^3** **CC (\$M)/DWT=** **751 \$/t** **CC (\$M)/TEU=** **7454 \$/TEU**
Maersk Triple E 2 **11 Container Ships** **2nd Generation**	400 x 59 x 17 (Height: 73 m)	DWT: **210,019** **20,568 TEU** each 10.9 t/TEU	Order placed in 2015 delivered 2017-2019 **Daewoo** **(South Korea)**	**185** each **CC (\$M)/(LBPxBxD)=** **461 \$/m^3** **CC (\$M)/DWT=** **881\$/t** **CC (\$M)/TEU=** **8995 \$/TEU**
Evergreen A-Class **13 Ships**	400 x 61.5 x 16.5	Ever Ace (July 2021) DWT: 241,960 **23,992 TEU** 10.1 t/TEU	**2021 to 2022** **6** (Samsung) **7** (China State Shipbuilding Co.)	**150 ± 10** **CC (\$M)/(LBPxBxD)=** **370 ± 25 \$/m^3** **CC (\$M)/DWT=** **619 ± 41 \$/t** **CC (\$M)/TEU=** **6252 ± 417 \$/TEU**

Note on abbreviations: LBP (Length between Perpendiculars), B (Beam), D (Draught), DWT(Dead Weight Tonnage), TEU (Twenty-foot container Equivalent Units).

Table 7 – Empty OTEC Plantship Cost Estimates per Figure 6

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

Table 7 provides the estimated costs of the plantships. To these acquisition estimates we must add conversion and installation costs for all major components. For a plantship, the associated costs are expected to begin in the $20 M to $30 M range.

Cold Water Pipe

Historically, FRP-sandwich cold-water pipes were selected for offshore OTEC. Designs led to the proof-of-concept NOAA1982 at-sea test. Current developments in the manufacturing of HDPE offer new alternatives. HDPE pipes are currently available in larger diameters of appropriate thickness (3 m inner diameter) such that they can be used as the cold-water pipe for a 5 MW plant and in bundles for the 10 MW (2 pipes) and the 50 MW (8 pipes) cases resulting in relatively lower costs. Depending on design-specific environmental (waves and currents) conditions the cold-water pipes likely need to be attached using a gimbal to decouple pitch and roll vessel motions. The full-length pipe bundles would be towed horizontally and upended at the site where the OTEC platform is positioned.

Table 8 provides the costs estimated for the cold-water pipes. To these estimates we must add transportation costs from the factory to a generic site, assembly, and installation costs incorporating the warm water pipe and mixed return pipe.

Table 8 – HDPE Cold Water Pipe Factory Cost Estimates

Class	Length(m)	OD(m)	DR	PC-A	PC-B*
1.3 MW-net	1200	1.6	32.5	$ 1,057,900	$ 927,048
	600	1.6	26	$ 651,050	$ 570,096
	600	1.6	21	$ 801,860	$ 668,964
5 MW-net	1000	3.26	26	$ 4,733,060	NA
10 MW-net	2x1000	3.26	26	$ 9,466,120	NA
50 MW-net	8x1000	3.26	26	$ 37,864,480	NA

Note on abbreviations: PC-A (Pipe Company A), PC-B (Pipe Company B)
DR = Outer Diameter/t; t = thickness
*PC-B quote in Euros @1.07 $/EUR

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

Mooring System

Based on the two empty plantship cases, industry suggested spread mooring to be optimal for the proposed combination of water depth (≈ 1,000 m) and Hs (6 to 7 m) in locations unaffected by hurricanes. Each mooring leg is preliminary devised as 90 mm bottom chain R4 100m from suction anchor (100 MT) + 1800 m Ø 150-160 mm Polyester Rope + 200 m upper wire Ø77 + Fairleads + Chain Stopper. Estimated at $1.8 M each.

The 10 MW case should require a 4 x 3 legs arrangement for an estimated total of $21.6 M;
While the 50 MW case should require a 4 x 4 legs arrangement for an estimated total of $28.8 M.

In addition, industry indicated that turret mooring should be required under conditions where hurricanes may be present, such as off Hawaii. Such a solution avoids any interference with the cold-water pipes, however, it requires stern thrust to always pull the vessel away. This represents additional capital and operational costs. Moreover, it implies an electrical swivel sitting subsea on the yoke table. A subsea electrical swivel, mounted as a detachable cartridge so that it can be pulled up for IMR is feasible but not straight forward and IMR would be quite costly. For OTEC parameters the cost estimate is $40 M - $45 M.

Mooring Company A (MC-A) evaluated internal turrets with the cold-water pipes suspended in the center of the large moon pool under the internal turret. Given that the cold-water pipe bottom end is free and open it might not be necessary to incorporate a swivel joint as shown in most designs reviewed. In such a central position, it should not slash with the mooring legs.

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

For this report considering generic OTEC sites we utilize the costs estimated for spread moorings. That is, $22 M for a 10 MW open or closed plantship and $29 M for a 50 MW closed cycle OTEC**.** These estimates exclude deck modification and integration.

Submarine Power Cables

Table 9 provides a summary of the information provided by Power Cable Company A (PCC-A), although other companies were also contacted, updated quotations were unavailable. For 10 km cable length, they ship in one or two 8.6 m reels while for 100 km a carousel is required.

Table 9 – Submarine Power Cables

OTEC Class	Cable Length	Power Cable Voltage	Cost at Factory
10 MW	10 km	34.5 kV/ 1.5 % voltage drop	$3.68 M
	100 km	34.5 kV/ 8.1 % voltage drop	$34.8 M
50 MW	10 km	69 kV/ 1.6 % voltage drop	$4.16 M
	100 km	69 kV/ 10.3 % voltage drop	$39.3 M

The cost of cable installation cannot be accurately estimated without specifying location. For example, a deep-water installation off Hawaii will require mobilization of a Jones Act compliant DP cable installation vessel or specialized vessel coming from Europe. Such vessels are available on the east coast of the USA or from Europe which would take several weeks for mobilization and demobilization.

For this study, a simple case under optimum circumstances is assumed. Installation from the shoreline to 10 km offshore with a specialized cable laying vessel requiring as much as $6 M for mobilization/demobilization alone plus on-site charges requiring a budget of as much as $15 M. In addition to about $1 M for the survey and, in some cases, horizontal-directional-drilling for shore landing adds to the cost. An installation budget of $20 M is allotted for a generic site. PCC-A noted that appropriate cable laying vessels are booked through 2028-2029 and installation costs for some OTEC locations would be twice generic site in this study. Installation cost is in addition to the actual cable cost from Table 9.

Seawater Pumps

Current cost estimates for submersible seawater pumps required for the OTEC plants (same flow rates for both Open and Closed Cycle) were acquired, other vendors were unable to meet the specifications provided.

Given the total flow rate of the quoted pumps, numerous pumps will be required. They will be installed submerged in a sump (moon pool) in parallel requiring substantial piping and appendages. The total cost given in Table 10 below excludes freight and installation costs.

Table 10 – Seawater Pump Cost Estimate

Class	Warm Water Pumps	Cold Water Pumps	Total Cost
10 MW	28 @ $8 M total	6 @ $3.5 M total	$11.5 M
50 MW	140 @ $40 M total	30 @ $17.5 M total	$57.5 M

Due to the requirement of “low head-high flow rate,” the number of “off-the-shelf” warm water pumps is challenging. Manufacturers will consider implementing bigger pumps once a real market is available.

Table 10 provides the costs estimated for the seawater pumps. To these estimates we must add transportation costs from the factory to a generic site, assembly, and installation costs.

The number of “off-the-shelf” pumps that would be required are also included in Table 10. For a 50 MW warm water stream 140 pumps represent an installation challenge. As with some other components, an optimized design would reduce the number of units and associated equipment.

Closed Cycle Heat Exchangers (Evaporator and Condenser)

Heat exchanger design and optimization is a critical part of achieving economic net power. For this section, off-the-shelf parts are utilized so a strict requirement was imposed for closed cycle OTEC heat exchangers (HXs), which is the goal of achieving low values for what is called the “Pinch Point”. That is, the temperature difference between the working fluid (NH_3) and the seawater temperature:

Condenser Pinch Point = Liquid NH3 Temperature outlet of Condenser Cold– Seawater Temperature outlet

Evaporator (Boiler) Pinch Point = Warm Seawater Temperature outlet – Liquid NH3 Temperature into Boiler

For this study pinch points of 1.1ºC and 1.2ºC were included respectively. Plate frame or plate fin heat exchangers are preferred because typical tube &shell cannot meet such stringent requirements.

In addition, pressure drop through the heat exchanger has a large impact on net power, as higher pressure drop increases pumping capacity and parasitic power loss. Heat Exchangers can be designed to reduce overall costs vs off-the-shelf.

Table 11 provides the costs estimated for the 10MW-class HXs delivered at the factory. To these estimates we must add transportation costs from the factory to a "generic" site, assembly, and installation costs.

Table 11 – Closed Cycle OTEC Heat Exchanger Estimates

Supplier	Evaporator	Condenser	Total	Note
Plate Frame Titanium				
HXC-A	$48.0 M	$36.0 M	$84.0 M	*Off-the-Shelf*
HXC-B	$15.2 M	$11.5 M	$26.7 M	*Off-the-Shelf*
HXC-C	$24.0 M	$36.0 M	$60.0 M	*Conceptual Design*
Plate Fin Aluminum				
HXC-D	$20.8 M	$31.2 M	$52.0 M	*Conceptual Design*
HXC-E	$48.0 M	$40.0 M	$88.0 M	*Off-the-Shelf Units*

Given the lower life expectancy of Aluminum Plate compared to Titanium and the similarity of costs estimates, only Titanium will be included in this study. Given the range of costs presented, a range for capital cost and levelized cost of energy will be included.

Table 12 provides a summary of the information obtained from the potential suppliers of heat exchangers for a 10 MW-net (ΔT = 21.5 ºC) Closed Cycle OTEC plant. Interconnecting in parallel numerous units that are currently manufactured for other applications will be challenging. HXC-A, for example, indicated that having to use 48 Evaporator units and 36 Condenser units for the 10 MW plant was *"not a good fit for their equipment."*

In the case of HXC-A and HXC-B their total weights are similar. These companies indicated that depending on potential additional orders they could ensemble their plates into larger single units such that installations would be less cumbersome, but at first the cost would be similar.

Table 12 – Dimensions and Weight of 10 MW Closed Cycle OTEC Heat Exchangers

	HXC-A	HXC-B	HXC-C	HXC-D	HXC-E
Evaporator					
Unit Size	*4.93m x 1.69m x 3.12m*	*2.13m x 0.9m x 1.39m*	*1.1m x 1.5m x 3.2m*	1.3m x 1.46m x 3.3m	1.2m x 4.4m x 2.4m
Unit Area (m^3)	*26*	*2.7*	*5.3*	6.3	13
Unit Weight (tonnes)	*12*	*3.9*	*11*	10	19
Number Required	48	141	80	32	64
Total Weight (tonnes)	570	556	880	320	1,203
Condenser					
Unit Size	*5.82m x 1.13m x 3.39m*	*2.13m x 0.9m x 2.3m*	*1.1m x 1.5m x 3.2m*	1.3m x 1.77m x 4.3m	1.2m x 6.4m x 2.4m
Unit Area (m^3)	22	4.4	5.3	9.9	18.9
Unit Weight (tonnes)	10	5	11	15	26
Number Required	74	36	120	32	64
Total Weight (tonnes)	367	370	1,320	480	1,674

The “volume” entry [m^3] in Table 12 is provided as guidance to estimate first generation volume requirements in the HXs plantship compartment.

Ammonia Pumps

New quotations were obtained for pumps that have the motor shaft magnetically coupled to the impeller shaft across a stainless enclosure, which means that there are no moving process fluid seals to fail and leak. The costs are included in Table 13 and exclude freight and installation costs.

Table 13 – Anhydrous Ammonia (NH3) Pumps

Class	NH_3 Feed Pumps	NH_3 Recirculation Pumps	Total Cost
10 MW net	4 @ $285 K	6 @ $368 K	$653 K
50 MW net	20 @ $1,537 K	30 @ $1,837 K	$3,374 K

Transportation costs from the factory to a generic site, assembly, and installation costs are separate.

Closed Cycle Expander Generator (Turbine Generator)

The largest Radial Turbo Expander unit for which we could obtain quotation corresponds to 5.8 MW at the generator terminal. This unit can be delivered 65 weeks after the order is placed. The cost at the factory would be $4 to $5 M. Three units for the 10 MW class and fifteen units for the 50 MW class would be required.

Table 14 – NH3 Turbine (Expander) Generator

	TG System at Factory Cost
TGC-A Unit: 5.8 MW-gross at generator	$4.5 M
16 MW-gross (10 MW-net)	$13.5 M
80 MW-gross (50 MW-net)	$67.5 M

Table 14 provides the costs estimated for the turbine generators at factory, to these estimates we must add transportation costs to a generic site, assembly, and installation costs.

Archival cost estimates, extrapolated to current estimates for the 10 MW-net and 50 MW-net designs are $12.2 M and $43.8 M respectively.

Figure 7 represents the conditions in a Closed Cycle OTEC turbine.

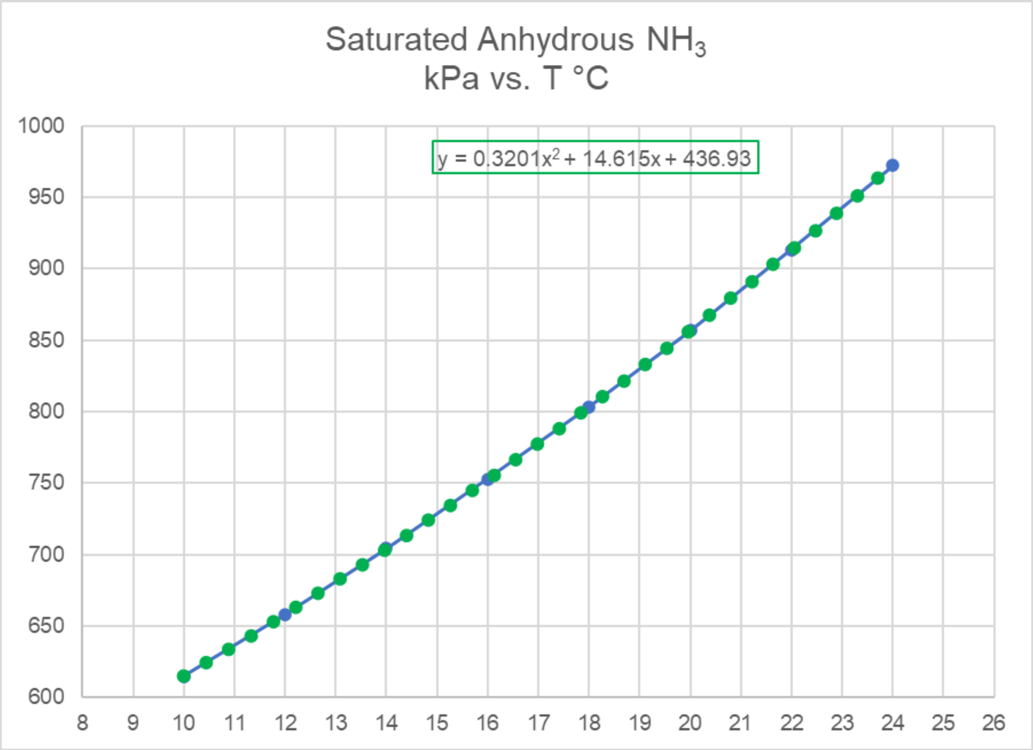


Figure 7 – Saturated Anhydrous Ammonia (NH_3)

The design at ΔT of 21.5 ºC corresponds to average conditions off Hawaii. For locations closer to the equator the increase in surface water temperatures will yield higher power outputs. For example, keeping the NH_3 mass flow rate constant at 550 kg/s and the cold seawater temperature at 4.5ºC the pressure of the saturated working fluid at the turbine inlet will change following the data in Figure 7 yielding a different value of ΔP and consequently a higher net output as indicated in Table 15. In the OTEC region along the Equator with surface water temperatures at 29ºC the output will increase to ≥14 MW from 10 MW. These values are comparable to those shown in Table 2 following more precise analysis.

Table 15 – Empirical Power Increase from ΔT ºC

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

It is possible to use other working fluids other than NH_3 in a closed cycle OTEC system. The working fluid will have a significant impact on design, materials, and cost. In this study, only NH_3 is considered as the most economical working fluid.

Open Cycle Heat Exchangers (Flash Evaporator and Condensers)

The design and capital cost estimates of the flash evaporator and surface condenser are based on design work conducted for a 1.8 MW gross open cycle OTEC plant incorporating lessons learned during five years of operation of the 250 kW experimental plant in Hawaii. The extrapolated 2023 cost estimate is $1.7 M and $4.6 M.

Table 16 – Open Cycle OTEC Flash Evaporator and Surface Condenser Cost Estimates

	Evaporator System Factory Cost (2023)	Condenser System Factory Cost (2023)
1.8 MW-gross	$1.7 M	$4.6 M
16 MW-gross (10 MW-net)	$15.3 M	$41.4 M
80 MW-gross (50 MW-net)	$76.5 M	$207 M

Table 16 provides the costs estimated for the Open Cycle OTEC flash evaporator and surface condenser systems. It is reasonable, given the cost differential between HXC-A and HXC-B in the case of Closed Cycle OTEC (Section 3.6), to expect that the open cycle OTEC surface condensers for the 16MW-gross case could be manufactured for $23 M instead of $41.4 M. Assembly and installation costs are separate.

Vacuum Pumps (Non-Condensables Gas Removal for Open Cycle OTEC)

Specifications for vacuum pumps, part of the requirements for the open cycle OTEC non-condensables gas removal system were based on the design of a 1.8 MW-gross plant.

Table 17 – Open Cycle OTEC Vacuum Compressors

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

Table 17 provides the costs estimated for the vacuum compressors for open cycle OTEC with surface condensers. To these estimates, transportation costs from the factory to a generic site, assembly, and installation costs are added.

Open Cycle Turbine Generator

Companies contacted for this study do not have designs meeting the design specifications. The extrapolated cost from the 1.8 MW gross design for a unit delivered at the factory was $5.9 M. Table 19 provides the cost estimates for this study.

Table 18 – Open Cycle OTEC Turbine Generators from Archival Records

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

Table 18 provides archival costs estimated for the open cycle OTEC turbine generator units. To these estimates transportation costs from the factory to a generic site, assembly, and installation costs must be added.

Technical Developments

In the course of this study the following technical developments have been highlighted:

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

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

Seawater Pumps
Due to the required “Low Head-High Flow Rate” the number of “off-the-shelf” warm water pumps is challenging (28 units for the 10 MW-class and 140 units for the 50 MW-class). Manufacturers will consider implementing bigger pumps once a real market is available.

In addition, additional technology development may lead to alternative intake solutions in the near future.

Closed Cycle Heat Exchangers
Several suppliers of heat exchangers for Closed Cycle OTEC were identified. With off-the-shelf units, currently, numerous units with interconnection challenges would be required. HXC-A for example, would require 48 Evaporator units and 36 Condenser units for the 10 MW-class plant (5x for the 50 MW-class). HXC-B would require 141 Evaporator units and 74 Condenser units. The total weight of the HXs units is essentially the same between these suppliers. These companies indicated that as

OTEC is implemented they would design bigger units minimizing the number of interconnections for future generations.

Heat exchangers specifically optimized for OTEC are available to minimize these challenges, however, production capacity is currently limited as there is yet no OTEC market.

The marked cost differential between quotes from HXC-A and HXC-B was confirmed via repeated correspondence. At this stage of development, both were considered and resulting in ranges for Capital Cost ($/kW) and LCOE ($/kWh).

4. Levelized Cost of Electricity

The analytical model detailed in Appendix 1 is used to estimate the Levelized Cost of Electricity (LCOE) and to assess scenarios under which OTEC might be competitive with current technologies. The OTEC capital cost is expressed in \$/kW-net. Subsequently, the relative cost of producing electricity (\$/kWh), offset when applicable by revenue generated by byproduct industries such as desalinated water, is estimated to determine the scenarios (*i.e., electricity cost and cost of desalinated water production*) under which OTEC could be competitive.

The worldwide current cost of Reversed Osmosis (RO) desalinated water from plants sized at 2,000 to 6,000 m^3/day ranges from \$1 to \$1.5/m^3. There are some larger plants generating as much as 900,000 m^3/day that can generate at \$0.5/m^3. When analyzing the cost effectiveness of open cycle OTEC plants, credit for the desalinated water is set at \$1.5/m^3 to evaluate the equivalent LCOE. For the 50 MW case, using the lower freshwater value of \$0.5/m^3 would result in an LCOE \$0.10/kWh higher.

In Hawai'i, for example, the wholesale cost of electricity generation is ≈ 60% of the rate charged to residential consumers by the utility (40% accounts for transmission & distribution infrastructure, maintenance, and profit). The June 2023 retail charge was \$0.35/kWh such that the current target for an OTEC plant as an Independent Power Producer is 60% of the retail or \$0.21/kWh. This target changes based on the situation at each site.

Another reference point is that for utilities that use primarily liquid petroleum fuels, given an \$80 barrel price, the fuel cost per kilowatt is about \$0.12/kWh. In remote locations such as SIDS and military bases, transportation and other costs are such that the fuel component cost alone is often \$0.25/kWh. The commercialization target for OTEC LCOE (\$/kWh) can, therefore, be taken as ≤ 0.25 \$/kWh once we progress beyond the first generation of commercial OTEC plants.

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

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

The Levelized Cost of Electricity Generation (LCOE) is formally estimated as follows (with further details in Appendix 1):

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

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

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

- **C**apital **R**ecovery **F**actor (CRF): CRF = [I x(1 + I)N]/[(1+I)N -1]

- Levelized Investment Cost: Amount ($) required yearly to pay capital loan: CC x CRF;
- Fixed Capital Cost Component of Cost of Electricity ($/kWh): Levelized Investment Cost/Annual Electricity Production. This is the amount that must be collected per kWh produced to pay the loan;
- **P**resent **W**orth **F**actor (PWF): PWF = $[(1+ER)/(I-ER)]/[1-\{(1+ER)/(1+I)\}N]$
- Annual **E**scalation (Inflation) **R**ate (ER): 3% constant for this study*(Over the last 20-years, for example, the average USA Manufacturing-Price-Index was 2.65 %);*
- **E**xpenses **L**evelizing **F**actor (ELF): ELF = PWF x CRF
- Levelized Expenses Cost: The fixed amount that must be collected yearly to cover all OMR&R costs accounting for inflation. This is equal to the amount estimated for the first year (as given above) times the ELF;
- Levelized OMR&R Component of COE ($/kWh): The levelized expenses cost ($) divided the annual production of electricity (kWh);
- Total Levelized Cost of Electricity ($/kWh): This is the sum of COECC and COE OMR&R; The value given here excludes environmental credits, tax credits and profit.

Table 19 and Table 20 provide the current estimates for first-generation plants. Levelized costs were estimated under two loan scenarios: 8%, 15-year commercial loan (Table 19); and 2.5%, 20-year concessionary loan (Table 20) from a development bank (e.g., ADB, WB), as a reference for future OTEC projects. All cases considered a fixed inflation rate of 3%. Based on this and previous work and because a generic site is considered the first year OMR&R is defined as 5.5% of the capital cost for plantships.

Under the specified commercial loan, excluding profits and credits, the breakeven point (defined as: levelized annual costs = annual revenue) for the 50 MW class closed cycle OTEC plants is given by a 15-year power-purchase-agreement for at least $0.26/kWh where HXC-B is used and as much as $0.38/kWh for HXC-A in Table 21.

In the case of the 50MW class open cycle OTEC plant the breakeven point, with relatively high credit of $1.5/m^3 for desalinated water, is given by a 15-year power-purchase-agreement for at least $0.36/kWh (Table 22).

Table 19 – Current LCOE Estimates with 8% - 15 years Commercial Loan

Class	Capital Cost ($/kW)	OMR&R (% CC)	LCOE ($/kWh)
10 MW Closed Cycle (w/ HXC-A)	27,012	5.5 %	**0.615** *(CC0.390 + OMR&R 0.225)*
10 MW Closed Cycle (w/ HXC-B)	21,606	5.5%	**0.492** *(CC0.312 + OMR&R0.180)*
10MW Closed Cycle 1st in Class Japan Data	32,169	$2.75 M/y	**.506**
10MW Closed Cycle Commercial Japan Data	27,700	$2.24 M/y	**.356**
10 MW Open Cycle*	33,962	5.5%	**0.618**
50 MW Closed Cycle (w/ HXC-A)	16,578	5.5%	**0.378** *(CC0.240 + OMR&R0.138)*
50 MW Closed Cycle (w/ HXC-B)	11,223	5.5%	**0.256** *(CC0.162 + OMR&R0.093)*
50 MW Open Cycle*	22,722	5.5%	**0.362**
100 MW Closed Cycle (w/ HXC-A)	13,023	5.5%	**0.297** *(CC0.188 +OMR&R 0.108)*
100 MW Closed Cycle (w/ HXC-B)	8,817	5.5%	**0.201** *(CC0.127 + OMR&R0.073)*

*Open Cycle plants include credit for desalinated water sales at $1.5\$/\text{m}^3$ with 23,690 m3/day for 10 MW and 118,450 m3/day for 50 MW. Abbreviations: CC (capital cost), OMR&R (levelized operation, maintenance, repair, and replacement)

Estimates for closed cycle OTEC 100 MW-class are included with “off-the-shelf” HXs and seawater pumps. Figures calculated from data from Japan[Okinawa Prefectural Government, 2019] with alternative designs are included as a reference.

Table 20 – OTEC LCOE Estimates with 2.5% - 20 years Concessionary Loan

Class	CC ($/kW)	OMR&R (% CC)	LCOE ($/kWh)
10 MW Closed Cycle (w/ HXC-A)	27,012	5.5 %	**0.462** *(CC0.214 + OMR&R0.248)*
10 MW Closed Cycle (w/ HXC-B)	21,606	5.5 %	**0.370** *(CC0.171 + OMR&R0.199)*
10MW Closed Cycle 1st in Class Japan Data	32,169	$2.75 M/y	**.301**
10MW Closed Cycle Commercial Japan Data	27,700	$2.24 M/y	**.214**
10 MW Open Cycle*	33,962	5.5 %	**0.424**
50 MW Closed Cycle (w/ HXC-A)	16,578	5.5 %	**0.284** *(CC0.132 + OMR&R0.152)*
50 MW Closed Cycle (w/ HXC-B)	11,223	5.5 %	**0.192** *(CC0.089 + OMR&R0.103)*
50 MW Open Cycle*	22,722	5.5 %	**0.233**

*Open Cycle plants include desalinated water credits at 1.5$/$m^3$ with 23,690 m3/day for 10 MW and 118,450 m3/day for 50 MW. Abbreviations: CC (capital cost), OMR&R (levelized operation, maintenance, repair, and replacement)

Previous work identified two distinct markets: (i) industrialized nations; and (ii) small island developing states with modest needs for power and fresh water. For example, although the first-generation plants are not currently cost competitive, which is expected as a part of any technology development program, Open Cycle OTEC plants could be sized at 1 MW to 10 MW, providing 450,000 to 9.2 million gallons of fresh water per day (1,700 to 35,000 m^3/day) to meet the needs of developing communities with populations ranging from 4,500 to 100,000 residents. This range encompasses the majority of SIDS throughout the world.

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

While OTEC–based mariculture operations and air-conditioning systems are attractive, the scale of water used by an OTEC system limits practical application of onshore OTEC to small plants ≤ 5 MW.

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

Presently, the external costs of energy production and consumption are not included in the determination of the charges to the consumer. Considering all stages of generation, from initial fuel extraction to plant decommissioning, it has been determined that no energy technology is completely environmentally benign. The net social costs of the different methods of energy production continue to be a topic under study. Estimates of costs due to corrosion, health impacts, crop losses, radioactive waste, military expenditures, employment loss, subsidies (tax credits and research funding for present technologies) are found in the literature. In the USA, for example, the range of all estimates is equivalent to adding from $80/barrel to over $400/barrel (equivalent to adding from $0.12 to $0.6/kWh). Accounting for these externalities is not the modus operandi but might eventually help the development and expand the applicability of OTEC. In the interim the scenarios discussed here should be considered as the market entry point.

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

Table 21–- First Generation 50 MW-class Closed Cycle OTEC Plantship

Current-Dollar Levelization (constant annual cost)

Inputs in Blue **Output Red**

System Net Name Plate:	**53.5 MW**	*SOA Components*
System Availability:	**92.3%**	*4-weeks downtime/module*
Site Annual Average Capacity Factor:	**100.0%**	*Design Selection*
Annual Electricity Production:	**432,609 MWh**	
Daily Desalinated Water Production	**0.00 MGD**	
	0 m^3/day	
Installed Cost (CC):	$886.92 M	**16578 $/kW**
1st Year OMR&R:	**$48.78 M**	*5.5% of CC*
I, interest (current-dollar discount rate):	**8.00%**	
ER, annual escalation (inflation) rate for entire period:	**3.00%**	*All elements*
N, system Life:	**15 years**	

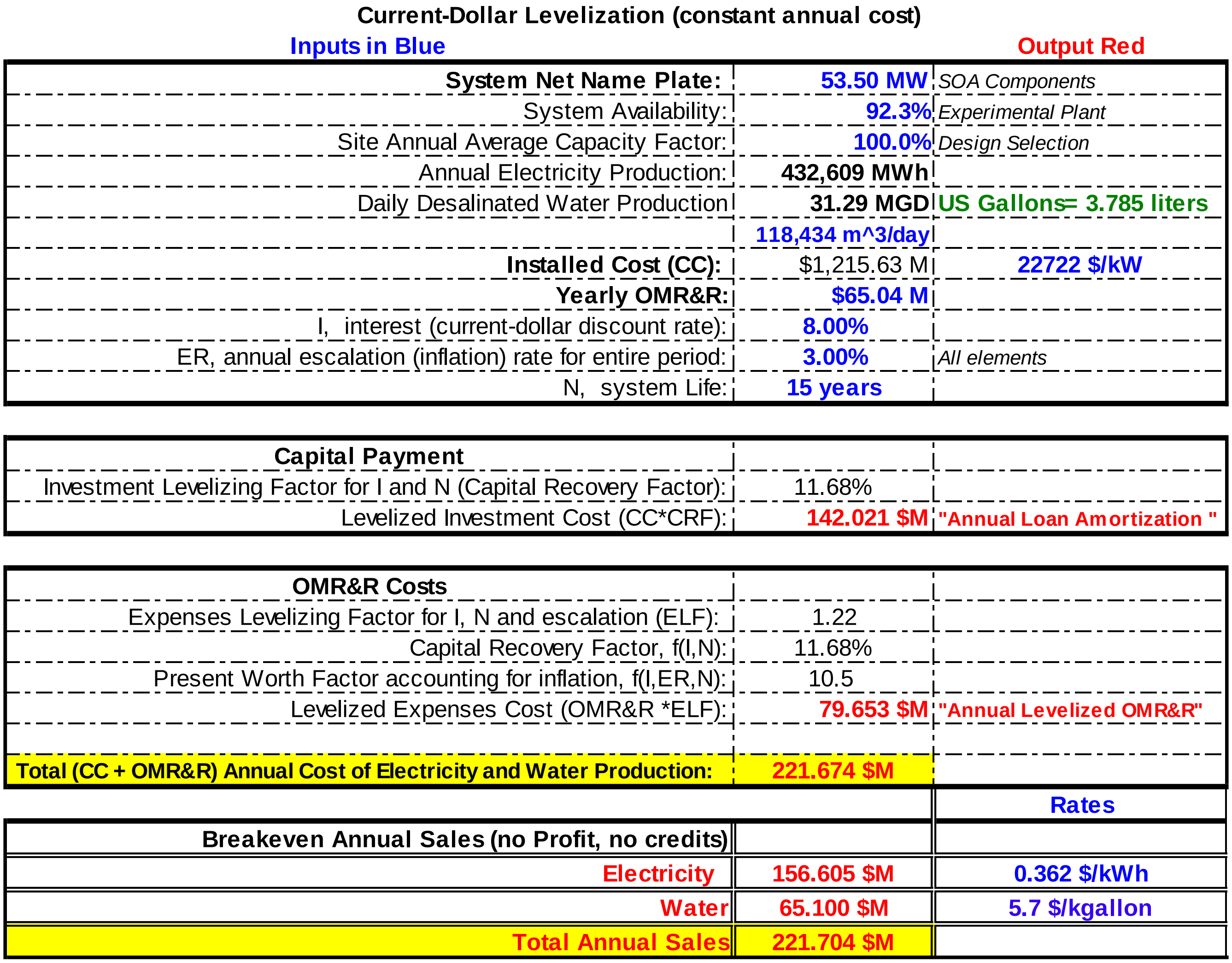
Capital Payment		
Investment Levelizing Factor for I and N (Capital Recovery Factor):	11.68%	
Levelized Investment Cost (CC*CRF):	**103.619 $M**	**"Annual Amortization"**
COE_{CC} : Fixed CC Component of COE	**0.240 $/kWh**	

OMR&R Costs		
Expenses Levelizing Factor for I, N and escalation (ELF):	1.22	
Capital Recovery Factor, f(I,N):	11.68%	
Present Worth Factor accounting for inflation, f(I,ER,N):	10.5	
Levelized Expenses Cost (OMR&R *ELF):	**59.740 $M**	**"Annual Levelized OMR&R "**
$COE_{OMR\&R}$: Levelized OMR&R Component of COE	**0.138 $/kWh**	
Total (CC + OMR&R) Levelized Annual Cost of Electricity Production:	**163.359 $M**	

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

The 2023 Levelized Cost of Electricity Production with commercial loans yield an upper limit of $0.378/kWh. With less expensive HXs the LCOE could be $0.256/kWh.

Table 22–- First Generation 50 MW-class Open Cycle OTEC Plantship



Current-Dollar Levelization (constant annual cost)

Inputs in Blue **Output Red**

System Net Name Plate:	**53.50 MW**	*SOA Components*
System Availability:	**92.3%**	*Experimental Plant*
Site Annual Average Capacity Factor:	**100.0%**	*Design Selection*
Annual Electricity Production:	**432,609 MWh**	
Daily Desalinated Water Production	**31.29 MGD**	**US Gallons= 3.785 liters**
	118,434 m^3/day	
Installed Cost (CC):	$1,215.63 M	**22722 $/kW**
Yearly OMR&R:	**$65.04 M**	
I, interest (current-dollar discount rate):	**8.00%**	
ER, annual escalation (inflation) rate for entire period:	**3.00%**	*All elements*
N, system Life:	**15 years**	

Capital Payment		
Investment Levelizing Factor for I and N (Capital Recovery Factor):	11.68%	
Levelized Investment Cost (CC*CRF):	**142.021 $M**	**"Annual Loan Amortization "**

OMR&R Costs		
Expenses Levelizing Factor for I, N and escalation (ELF):	1.22	
Capital Recovery Factor, f(I,N):	11.68%	
Present Worth Factor accounting for inflation, f(I,ER,N):	10.5	
Levelized Expenses Cost (OMR&R *ELF):	**79.653 $M**	**"Annual Levelized OMR&R"**
Total (CC + OMR&R) Annual Cost of Electricity and Water Production:	**221.674 $M**	

		Rates
Breakeven Annual Sales (no Profit, no credits)		
Electricity	**156.605 $M**	**0.362 $/kWh**
Water	**65.100 $M**	**5.7 $/kgallon**
Total Annual Sales	**221.704 $M**	

The 2023 breakeven electricity and water rates required with commercial loan for a 50 MW Open Cycle OTEC plantship would be $0.362/kWh and $1.5/m^3 ($5.7/kgallon).

Impact of Interest Rates on LCOE

Interest rates play an important role in determining the LCOE. Figure 8 depicts LCOE calculated for a 1.5 MW barge-based floating platform across multiple interest rates. For example, increasing the interest rate from 2.5% to 8% results in a 23% increase in LCOE under a 15-year term and 25% increase under a 20-year term.

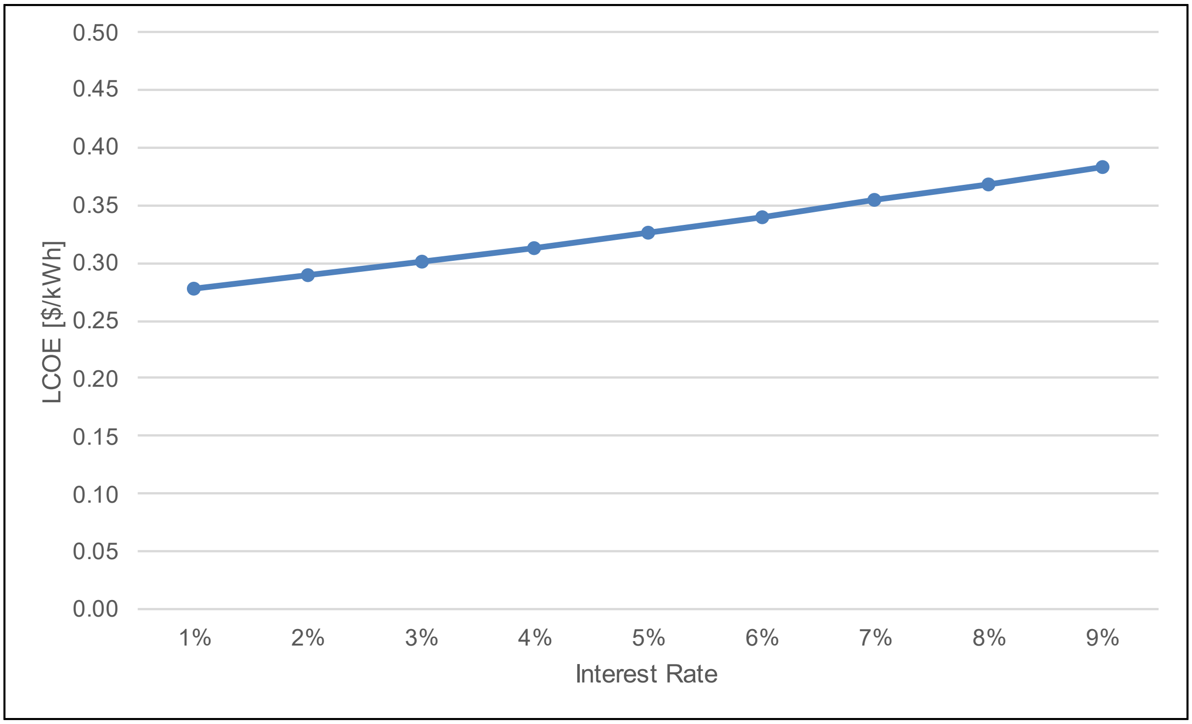


Figure 8–- Relationship Between Interest Rate and LCOE

Figure 8 shows the relationship between interest rates and LCOE. In this case for figures calculated for a 1.5 MW floating platform described below.

Additional Perspective

While this study focuses on off-the-shelf OTEC plantships, there are multiple methods of implementing OTEC. Japan's calculations for spar-type semi-submersible were provided as a reference. Here, we will also introduce figures from Global OTEC, a UK-based OTEC developer working to reduce costs through modular barge-mounted deployments. A barge was the platform hosting the successful 1 MW-scale OTEC test performed by KRISO in 2019. While low-cost, barge platforms are limited to benign weather environments, though as the numbers below indicate, they may provide for cost-effective application in some situations. In addition, the company proposed a modular approach to scaling similar to wind-farms, so that multiple identical units can achieve cost reduction through replicability.

Global OTEC is also experimenting with cylindrical float hulls for severe weather environments. Designing to withstand weather during of a 100-year storm, they will deploy a structural test in the Canary Islands in 2024 funded by Horizon Europe.

The company is working directly with existing component manufacturers to build out their financial models, and while the details are proprietary, they have included their costs for comparison. For a 1.5 MW plant in Sao Tome and Principe, a first-generation barge-mounted OTEC plant is expected to cost roughly $42 M including 25% contingency. Replication and commercialization is expected to bring the cost down to roughly $26 M when 3 or more barges are deployed.

For operation and management costs, Global OTEC bases their estimates on conservative offshore energy industry practices, including significant percentage for insurance.

Utilizing the same LCOE calculation method as above, this equates to $0.30/kWh for first-generation at a 2.5% rate with 20-year terms. A 50% subsidy would reduce the first-generation LCOE to $0.19/kWh. Global OTEC proposes a longer 25-year term is possible, which would result in $0.18/kWh first-generation with subsidy.

Sensitivity of LCOE to Change in Component Costs

Each component estimated and evaluated in the previous section will be subject to future changes in cost based on material availability, changes in technology, or other concerns. The items with the larger percentage of overall cost will impact the LCOE the most in terms of increase or decrease. Table 23 provides a range in capital costs and resulting LCOE when varying each component between a reduction of 30% to an increase of 30%. Figure 9 shows the ratio of newly calculated LCOE compared to the baseline when changing the capital cost between the same range. From this graph it is easy to see that Assembly, as the largest single capital cost will have the most impact on overall LCOE, followed by the platform and heat exchangers.

Table 23- Comparison of Changes in Component Capital Cost on LCOE

		Change in Component Capital Cost (%)						
Component		-30%	-20%	-10%	0%	10%	20%	30%
Plantship	Component Capital Cost ($M)	19.81	22.64	25.47	28.30	31.13	33.96	36.79
	Total Capital Cost ($M)	219.56	222.39	225.22	228.05	230.88	233.71	236.54
	Calculated LCOE ($/kWh)	0.355	0.359	0.364	0.368	0.373	0.377	0.382
	Calc. LCOE / Baseline LCOE	0.965	0.976	0.989	1.000	1.014	1.024	1.038
Mooring	Component Capital Cost ($M)	15.40	17.60	19.80	22.00	24.20	26.40	28.60
	Total Capital Cost ($M)	221.45	223.65	225.85	228.05	230.25	232.45	234.65
	Calculated LCOE ($/kWh)	0.358	0.361	0.365	0.368	0.372	0.376	0.379
	Calc. LCOE / Baseline LCOE	0.973	0.981	0.992	1.000	1.011	1.022	1.030
Power Cable	Component Capital Cost ($M)	2.59	2.96	3.33	3.70	4.07	4.44	4.81
	Total Capital Cost ($M)	226.94	227.31	227.68	228.05	228.42	228.79	229.16
	Calculated LCOE ($/kWh)	0.366	0.367	0.368	0.368	0.369	0.370	0.370
	Calc. LCOE / Baseline LCOE	0.995	0.997	1.000	1.000	1.003	1.005	1.005
Pipes	Component Capital Cost ($M)	7.63	8.72	9.81	10.90	11.99	13.08	14.17
	Total Capital Cost ($M)	224.78	225.87	226.96	228.05	229.14	230.23	231.32
	Calculated LCOE ($/kWh)	0.363	0.365	0.367	0.368	0.370	0.372	0.374
	Calc. LCOE / Baseline LCOE	0.986	0.992	0.997	1.000	1.005	1.011	1.016
Water Pumps	Component Capital Cost ($M)	8.05	9.20	10.35	11.50	12.65	13.80	14.95
	Total Capital Cost ($M)	224.60	225.75	226.90	228.05	229.20	230.35	231.50
	Calculated LCOE ($/kWh)	0.363	0.365	0.366	0.368	0.370	0.372	0.374
	Calc. LCOE / Baseline LCOE	0.986	0.992	0.995	1.000	1.005	1.011	1.016
NH3 Pumps	Component Capital Cost ($M)	0.46	0.52	0.59	0.65	0.72	0.78	0.85
	Total Capital Cost ($M)	227.86	227.92	227.99	228.05	228.12	228.18	228.25
	Calculated LCOE ($/kWh)	0.368	0.368	0.368	0.368	0.368	0.369	0.369
	Calc. LCOE / Baseline LCOE	1.000	1.000	1.000	1.000	1.000	1.003	1.003
XHs	Component Capital Cost ($M)	18.69	21.36	24.03	26.70	29.37	32.04	34.71
	Total Capital Cost ($M)	220.04	222.71	225.38	228.05	230.72	233.39	236.06
	Calculated LCOE ($/kWh)	0.355	0.360	0.364	0.368	0.373	0.377	0.381
	Calc. LCOE / Baseline LCOE	0.965	0.978	0.989	1.000	1.014	1.024	1.035
TG	Component Capital Cost ($M)	8.75	10.00	11.25	12.50	13.75	15.00	16.25
	Total Capital Cost ($M)	224.30	225.55	226.80	228.05	229.30	230.55	231.80
	Calculated LCOE ($/kWh)	0.362	0.364	0.366	0.368	0.370	0.372	0.374
	Calc. LCOE / Baseline LCOE	0.984	0.989	0.995	1.000	1.005	1.011	1.016
Assembly	Component Capital Cost ($M)	78.26	89.44	100.62	111.80	122.98	134.16	145.34
	Total Capital Cost ($M)	194.51	205.69	216.87	228.05	239.23	250.41	261.59
	Calculated LCOE ($/kWh)	0.314	0.332	0.350	0.368	0.386	0.404	0.423
	Calc. LCOE / Baseline LCOE	0.853	0.902	0.951	1.000	1.049	1.098	1.149

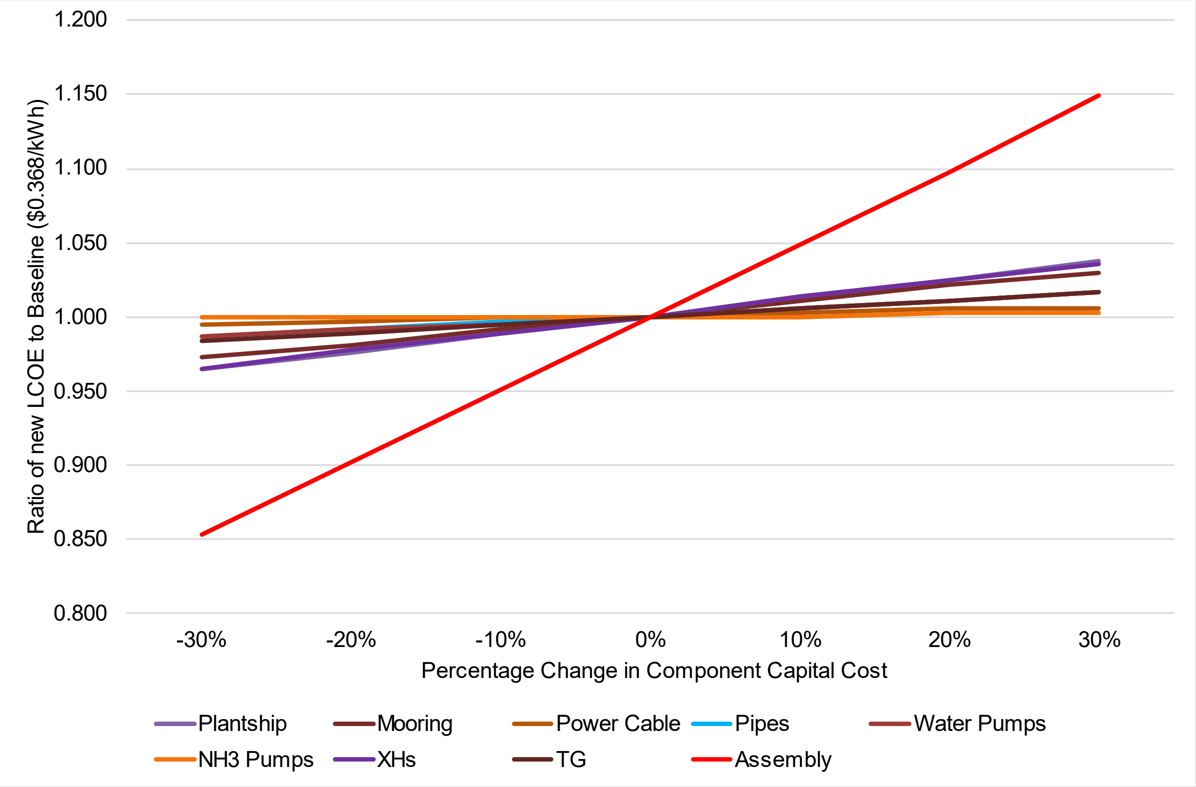


Figure 9-Change in LCOE by Varying Component Cost

5. Onshore OTEC

As of 2023, while short-term demonstrations have taken place offshore, there are only onshore OTEC facilities. OTEC relies on the availability of seawater intake infrastructure to bring water from offshore to the desired location. In both Hawaii, USA at the Natural Energy Laboratory Authority of Hawai'i (NELHA) and Kumejima, Japan at the Okinawa Deep Ocean Water Research Center (ODRC) the seawater infrastructures were provided as government owned and operated projects which provide seawater for research and industry development. These resources enabled the successful implementation of 100kW-scale OTEC demonstration in both locations.

For a MW-scale OTEC facility, roughly ten-times the seawater capacity is required compared to a 100kW OTEC facility. Capacity is a factor of intake pipe diameter, with larger sizes providing access to more water, while also costing more in terms of capital cost. This is true for larger scales of OTEC, however, at the multi-megawatt-scale, offshore implementation allows for significant cost reduction through shortening the intake pipe length, though additional costs are incurred from the offshore platform, power cables, etcetera. As shown previously in Figure 3, OTEC benefits from economies of scale, yet one of the major inhibitors to OTEC's widespread adoption is a belief that onshore OTEC is too expensive.

In the onshore application, if considering all costs of seawater intake and power generation equipment, the cost for power generation is of course high. This is because onshore, among other factors such as limited economies of scale, the long intake significantly increases the capital cost. This high cost at small or pre-commercial scale is common in technology development and a major hurdle for development. Thus, in this section we will consider options for overcoming these challenges and provide evidence from actual implementation experience.

As data is readily available, we will introduce the specifications of a 1 MW OTEC facility for Kumejima, Okinawa, Japan. Since Kumejima is located at a relatively high latitude (26°20'), locations around the world closer to the equator will generally find higher energy output for the given equipment and/or reduced costs. For comparison with other technologies and the offshore scenarios, we define the case as follows.

1 MW OTEC Case Specifications

Annual Average Surface Seawater Temperature (15m): 26.7°C
    Surface Seawater Flow Rate: 305,000m3/d
Annual Average Deep Ocean Water Temperature (800m): 5.7°C
    Deep Ocean Water Flow Rate: 232,000m3/d
Annual Average Temperature Difference: 21°C
Gross Output Maximum: 1,880kW
Gross Output (Annual Average): 1,660kW
Capacity Rate: 85.6%
Parasitic/Internal Loss: 39.8%
Net Power Supply (Annual Average): 1,000kW

Onshore OTEC Capital Costs

Commercial onshore 1 MW OTEC facility costs were calculated in a New Energy and Industrial Technology Development Organization (NEDO)-backed project by IHI Plant Construction company, a major Japanese construction company. The cost for each component was tallied along with the design, building, and other related costs. The total was 2.7 billion in FY2013JPY or $22 million accounting for inflation and an exchange rate of 135JPY to USD. The costs generally align with expectations from other sources.

Onshore OTEC Operational Costs

Operation and maintenance costs for OTEC are limited in that no fuel is required, operation can be mostly automated, and many of the materials used can be rated for long operational life. In Okinawa, the Okinawa Prefecture OTEC Demonstration Facility is a useful reference for determining the actual expected costs for operating an OTEC plant. In the offshore cases, the selected approach includes replacement as a major factor. In Okinawa, titanium heat exchangers have been selected, which do not require frequent replacement. Thus, costs are simplified into periodic and irregular inspection and repair.

In 2017, as part of the Okinawa Prefecture "Demonstration Project of Power Generation Used for Advanced Deep Ocean Water Utilization" Project, operation and maintenance costs for a 1 MW facility were updated based on the actual experience of operating an onshore OTEC demonstration long-term. The Okinawa OTEC facility has been in operation for more than ten years. Table 24 includes figures updated to 2022 USD [Okinawa Prefectural Government, 2019], resulting in an expected annual operation and maintenance cost of $145,200 per year in the 1 MW onshore case. Another major difference is that in the Japan design and demonstration, the system is mostly autonomous, allowing for reduced personnel costs, especially when compared to a plantship configuration.

Table 24 - Updated Onshore OTEC Operation Costs

Item	1MW Class Estimate (Kumejima USD 2022)
Periodic Inspection/ Repair	$71,100
Turbine Generator	$11,000
Working Fluid System Equipment	$13,900
Electrical Equipment and Instrumentation	$46,000
Irregular Inspection / Repair	$24,600
Corrosion Response	$10,900
Other	$13,700
Daily Inspection, etc.	$23,600
Other Expenses	$9,000
General and Administrative Expenses	$16,900
Total	$145,200

Implementing Onshore OTEC

Around the world there are now at least 38 sites with 45 pipes to a depth of 200 m or more used for seawater intake. These intakes are not for OTEC, but for various Deep Ocean Water (DOW) Industrial uses. As an infrastructure similar to waste management, roads, or freshwater, the intakes operate a beneficial service, providing raw resources (warm and cold seawater) that can be used in useful industries.

Looking at options for expanding deep ocean water intake in Kumejima, a study proposed the “Kumejima Model” or advanced use of seawater, combining OTEC and DOW industries to improve the economic efficiency and benefits of both through multi-use of the water. In a practical sense, seawater intake is separated as an independent infrastructure project. While powered by OTEC, it receives its own operation and maintenance funding through sales of water, allowing OTEC to act as an independent power producer. This section will consider multiple scenarios under which onshore OTEC power generation can achieve competitive power generation costs, while DOW intake also provides resources for food, water, and economic security.

This application also allows us to compare OTEC as a power producer more directly to other renewable energies for consideration in achieving environmental goals when transitioning island grids. This is similar to applying wave power to existing breakwaters or other related existing infrastructure.

Seawater Intake

There are many factors in determining the exact intake size, design, and deployment method, The length of the pipe is driven by the proximity of the desired depth, which may be as shallow as 600 m and as deep as 1000 m. Deeper water provides colder water, which in turn increases opportunities for multiple use and higher power generation output from OTEC. Ideal locations will have as short a pipe as possible. The pipeline size may be in the range of 1.1 m to 1.7 m diameter, depending on local seawater conditions and plant optimization.

From previous studies and implementation, the cost of onshore seawater intake capable of supporting 1 MW OTEC is expected to be between $40 to $90 M if made from HDPE. A 2017 study “Investigation of Regional Activation Potential Using Deep Seawater in Remote Island Regions” conducted by the Okinawa General Bureau on the economics of seawater intake for Kumejima, identified the cost of intake construction on Kumejima at $65.2 M in 2022 USD[Okinawa General Bureau Cabinet Office, Departiment of Economy, Trade, and Industry, 2017]. This figure is for a 3.7 km intake of 1. 5m diameter HDPE. A presentation at the 7th Hawaii Okinawa Ocean Energy Workshop indicated $46.6 M in 2021 USD could be possible[Makai Ocean Engineering, 2016].

In the Okinawa General Bureau Study, a cost per year for DOW intake and maintenance was also calculated, including a significant fund for disaster recovery and large-scale equipment replacement. The expected annual cost was $1,500,000/year adjusted to 2022 USD. This operational cost equates to raw seawater sales of 15 million m^3/year if the seawater is sold at $0.1/$m^3$. As the total maximum capacity of the intake is roughly 131 million m^3/year, 11.5% of the water capacity needs to be sold to cover operational costs. If seawater sale price is reduced to $0.05/$m^3$, then 23% of the water capacity need be sold.

The minimum production volume can be reduced by varying the seawater sale price based on use, with larger capacity operations such as aquaculture having lower prices, and increased prices for lowquantity productive uses such as desalination or cosmetics. In some scenarios, OTEC may also provide significant funding to the intake operation business.

Seawater Industries

Professor Emeritus Masahiro Takahashi, former chair of the Deep Ocean Water Applications Society has summarized use of deep ocean water applications as in Table 25[Takahashi, 2019]. Deep Ocean Water has three major useful properties when compared to surface water: temperature (low-temperatures available year-round), nutrients (DOW has higher concentrations of nitrates, phosphates, silicates, etc that can be useful as fertilizer for aquaculture), and cleanliness (very low bacteria concentrations compared to the surface). With these and other properties, in addition to OTEC, DOW can be used in desalination (reverse osmosis or low temperature thermal desalination), seawater air conditioning (SWAC), cosmetics, water production, aquaculture, agriculture, mineral extraction, and other fields.

Table 25 - Productive Seawater Applications

	1. Low Temperature	2. Nutrients	3. Fresh Water	4. Minerals/Salts	5. Metals	6. Dissolved Organic Matter	7. Microorganisms	8. Cleanliness	9. Consistency	10. Anti-Aging	11. Renewability
1. Fermented Foods				●				●		●	
2. Food and Drink				●				●		●	
3. Drinking Water			●	●				●			
4. Bittern and Salt				●				●		●	
5. Bathing Goods				●				●		●	
6. Cosmetics				●				●		●	
7. Medical Care				●		●	●			●	
8. Agriculture	●			●							●
9. Sea Plant Culture		●								●	●
10. Aquaculture	●							●		●	●
11. Fish Stocking	●							●		●	
12. Metals					●			●			●
13. Power Generation	●							●	●		●
14. Refrigeration	●							●	●		●
15. Cooling Water	●							●	●		●

Scope of Consideration for OTEC Business

Figure 10 summarizes the separation of roles between onshore intake and DOW industries including OTEC. The intake infrastructure supplies water for a fee which covers its operation and maintenance. In the case of private sector implementation, it may also be able to recover capital cost expenditure.

The OTEC facility provides power for intake, and post-OTEC water is also available for use by DOW Industries and may be managed by the intake operation business.

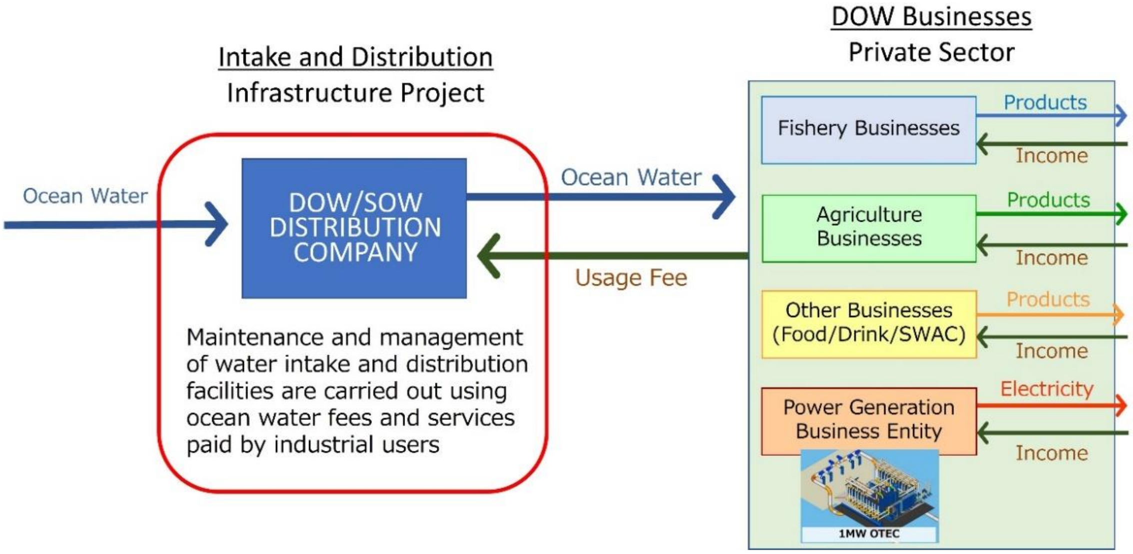


Figure 10 - Relationship between Seawater Intake and Private Sector Businesses

Scenarios for Onshore OTEC Implementation

Given capital and operating costs, it is possible to calculate various LCOE depending on interest rates, etc. which is a useful tool for evaluating and comparing OTEC as an investor or business. It may be less useful in terms of evaluating cost and benefits for end users, especially in certain unique situations. This section will provide a variety of scenarios in which onshore OTEC may be effectively applied.

Scenario 1 – Official Development Assistance (ODA)

OTEC is uniquely suited to supporting island and coastal communities most in need of assistance in transitioning from fossil fuels. In the Pacific and other tropical areas, many communities at the forefront of climate change do not have adequate access to other renewable energies such as solar (land use issues), wind (resource availability), geothermal, etcetera. Conversely, many of these communities have very good thermal gradients at relatively close proximity.

Although there are many forms of ODA, we will describe a multi-country approach based on the Kumejima Model. In this scenario, seawater intake, OTEC, and support of industry will be carried out as coordinated but distinct projects.

Seawater Intake

Once installed, the intake can be run by a local company, government, or partnership that will receive operating budget from selling water. A build-up phase may be required to support operations until sufficient income is achieved to cover expenses. This phase may be covered by a separate support project in order to facilitate new businesses as noted below, or through the original development project. Anchor tenants, such as OTEC will de-risk and accelerate regenerative impact. The need for support may be further reduced by establishing a contingency fund as part of the intake construction, which would reduce intake operation and maintenance costs to essentially personnel fees and basic maintenance.

Support for New Industries

There are a wide variety of productive use applications available when seawater resources are available. As productivity from aquaculture increases compared to wild-caught fish, the demand for fishery resources also increases. In many island communities, there are already efforts underway to increase sustainable food production through aquaculture and related initiatives. Transitioning existing operations to include deep ocean water can improve the business case and reduce risk. Some companies may be able to transition effectively on their own through innovation, while others may require additional support in terms of research, development, or training. For ODA, these are smaller projects that may be integral or separate from the seawater intake development. In addition, SWAC and desalination provide opportunities to add value and more quickly realize overall benefits.

Essentially, achieving a minimum production volume will be an important step to ensuring long-term viability. User diversity in terms of scale and sector adds to reliability. As projects increase their seawater use prices can be adjusted to encourage further development. For this scenario, OTEC can also provide significant funding support.

OTEC

Although there are many types of ODA, in the case of a grant, the capital cost of the OTEC facility no longer plays a significant figure in calculating the cost and benefit to local communities. Rather, the power generation price, what the utility will, and after their addons, the local people, will pay for power. Reducing this cost through renewable energy will then have the largest benefit in terms of the local people. Thus, if the capital cost is removed as a function of the grant, then only two costs remain. The operational cost is well understood from Table 24. This equates to $0.03127/kWh. This low cost provides a major benefit for significantly reducing power generation costs for island communities. It also provides an opportunity for financially supporting intake operations.

While it is expected water will be sold to users by volume, OTEC will provide operational benefits to the intake in terms of decreasing the head necessary for downstream industries and renewably supplying power. In addition, in this scenario the OTEC Facility can supply a fixed annual payment, which can help guarantee operational success and reduce the need or burden of productive support. In order to fully fund seawater intake and OTEC operations and maintenance with no other productive uses, a power purchase price of $0.28/kWh would be required, calculated by combining the levelized intake ($0.25/kWh) and OTEC ($0.03/kWh) operation and management costs in the LCOE calculation. While high, in some locations this may be lower than the cost of power produced. With the many benefits of deep ocean water use, even small-scale applications and an anchor use such as desalination can help achieve a much lower power generation cost.

Given an expected annual production of 4,642,857 kWh/year, every $100,000 paid to the seawater distribution operator will increase the OTEC operational costs by $0.0215/kWh. This means that the needs of the power supply (reducing costs) can be balanced with economic development through seawater utilization. In the case of a 16 cent-per-kilowatt-hour power purchase price, OTEC can contribute $600,000 per year to intake operations. Over time, as productive uses increase, the power generation cost can be reduced for greater impact to energy bills. Surplus revenue can also be used to fund incubation activities, finance new projects, or expand infrastructure.

Scenario 2 – Public Private Partnership

This scenario assumes seawater intake is approached as either ODA or public infrastructure, with OTEC implemented as a joint partnership between the private sector and government. Within this scenario, there are several possible approaches to supporting implementation of OTEC.

1.Power Purchase Agreement

The simple approach is to provide a private sector company with a fixed-term power purchase agreement (PPA) guaranteeing repayment of the capital invested. For OTEC, the challenge is that the initial cost is high, and while operational life may be 40 years, most PPA are fixed to 15 to 20 years.

In the Kumejima case, using the LCOE calculation method described earlier in this paper, with capital cost of $22 million, operational costs of $145,200 per year, inflation at 2% and rate of 5% (in the Japan case) this would equate to:

- $0.229/kWh over 20 years
- $0.191/kWh over 30 years
- $0.175/kWh over 40 years

As indicated in the comparison of OTEC scales, at small scale, it is still difficult to achieve a profitable business model through traditional PPA, however, a long-term approach could allow successful implementation with no public sector upfront cost, however, even in the best case, in most regions, this would equate to similar costs to current fossil fuel technologies. Locations with high power generation costs would benefit most.

2.Feed-in Tariff

A common method of supporting early implementation of renewable energy projects are feed-in tariffs (FIT), where a purchase price over fixed term is set high enough to encourage private sector investment. Similar to a power purchase agreement, a FIT scheme would allow shorter term financing which would offset private sector investment risk and improve options for project finance. In Japan a FIT of 40 JPY/kWh ($0.29/kWh) was established for geothermal using binary power generation, a process similar to OTEC.

3.Direct Subsidy

Another method of public private cooperation would be direct subsidy towards the capital cost of the installation. In some cases, this could be in-kind support such as land use, permitting, or other efforts that reduce capital cost.

For example, a 30% subsidy to capital cost would result in the following LCOEs (a decrease in the power generation cost):

- $0.167/kWh over 20 years
- $0.141/kWh over 30 years
- $0.130/kWh over 40 years

A 2/3rds subsidy would result in the following LCOEs:

- $0.091/kWh over 20 years
- $0.079/kWh over 30 years
- $0.074/kWh over 40 years

In the case of the latter subsidy group, this would provide a competitive cost even at shorter terms, albeit with higher upfront cost burden on the public. The offset is the effect on power generation cost, and subsequent price paid by consumers, while also replacing fossil fuel production.

4.Contracted Operation

Another option for implementation is as a public demonstration project, where a company or JV is contracted to build and operate a facility through public project. In this case, an open procurement process can solicit proposals to build out the facility for a fixed sum. Follow-on operation and maintenance could also be on a fixed-term basis. This approach allows the public to fully own the power generation equipment and set the amount charged to consumers irrespective of the actual power generation cost. This decoupled approach has the highest burden on the state with potentially the highest benefit to reducing power generation costs. In addition, it supports the development and deployment of OTEC in the local market. Similar to an ODA approach but for a domestic market, this would allow power generation costs as low as about $0.03/kWh if only operation and maintenance costs are to be recovered.

Scenario 3 – Certificates, Offsets, and Credits

There is yet no internationally agreed standard for accounting for the positive impact of renewable energy projects such as an OTEC facility, however, there are various schemes emerging in national and private sector markets that may be of use.

Renewable Energy Certificates

A simple approach is to allow grid customers to allocate the renewable energy on the grid to their demand for a fee that can help offset the cost of integrating more renewable energy projects. An example is The Okinawa Electric Power Company’s “Uchina CO_2 Free Menu” which allocates renewable energy production to participants in the program[The Okinawa Electric Power Company, Inc., 2021]. While the final energy used by the customer is still a mix of the power on the grid, it allows customers to “own” a portion of the renewable energy capacity and provides the utility additional funds for further investment. The US EPA notes the premium in US markets is about $0.02/kWh[US Environmental Protection Agency, 2023]. It would be expected such a premium could not be fully allocated to a single renewable energy project, however, a targeted approach could potentially allocate a portion of such benefit for an OTEC project, such as if a local utility is the OTEC project owner.

Carbon Offsets

A carbon offset promotes renewable energy implementation by allocating the carbon reduction to a sponsoring agency. Japan’s Joint Crediting Mechanism is an example where Japan is able to offset its own emissions by supporting carbon reducing projects internationally. Japan partners with twenty-seven countries to provide financial support in reducing emissions and receiving part of the overall JCM credit created by the program[Government of Japan, 2023].

These programs, rather than providing a direct reduction in cost of power, are an additional incentive for government support as noted in scenario 1 or 2 above. Thus, programs like JCM can incentivize subsidy or ODA support for OTEC.

Carbon Credits and Pricing

International agreements since the Kyoto Protocols have supported the establishment of various national and international carbon pricing markets. The World Bank lists a variety of markets with general price ranges. As a reference, a selection are quoted below[The World Bank, 2023]:

2021 Prices

- American Carbon Registry (USA): US$11.37/tCO2e
- Australia EFE (Australia): (US$11.94-12.66/tCO2e
- J-Scheme (Japan) 2021 Price: US$12.42-20.75/tCO2e
- Gold Standard (International): US$3.94/tCO2e
- Verified Carbon Standard (International): US$4.17/tCO2e

In the Japan-based 1 MW onshore OTEC facility, annual electricity production is expected to equal 8,487,000 kWh per year. As petroleum power production produced 0.00122 tCO2e/kWh, the annual carbon reduction for a 1 MW OTEC plant will be on the order of 10,300 tCO2e/kWh. This equates to a range of $0.0048/kWh to $0.025/kWh given the examples above. Follow-on industrial uses such as SWAC and desalination would increase carbon reduction.

It should be noted that such credits may not be available for use in tandem with government subsidy or ODA as the credit may be reserved in part or full by the sponsoring agency.

Table 26 compares various scenarios and the resulting effect on LCOE. In these approaches, economic benefit is derived from reducing the power generation cost. In particular, we find that with some level of public support, OTEC can achieve very attractive power generation costs in addition to the other technical and economic benefits of stable baseload supply, inertia, and ease of use.

Table 26 - Comparison of Scenarios and Resulting LCOE

Scenario	**NEDO Estimate Updated with OTEC Demonstration Results**	**ODA/ Contracted Operation**	**ODA (with intake support)**	**2/3 Direct Subsidy**	**2/3 Direct Subsidy (with intake support)**	**Carbon Credit**
Capital Cost (Construction Cost, etc)	$22 million	$0	$0	$7.3 M	$7.3 M	$22 M
Operation/ Management/ Maintenance Costs	$145,200/year					
Ocean Water Costs	Not Paid	Not Paid	$600,000/year	Not Paid	$600,000/year	Not Paid
Power Generation Cost (per kWh unit power generation)						
Capital Cost (Investment Recovery)	$0.158/kWh	$0	$0	$0.05/kWh	$0.05/kWh	$0.158/kWh
Operation / Maintenance Costs	$0.031/kWh	$0.031/kWh	0.031+0.129= $0.16/kWh	$0.031/kWh	0.031+0.129= $0.16/kWh	0.031-0.015**= $0.012/kWh
Interest Rate	5%					
Inflation Rate	2%					
Term	30 years					
Cost of Energy	**$0.19**/kWh	**$0.03**/kWh	**$0.16**/kWh	**$0.08**/kWh	**$0.18**/kWh	**$0.17**/kWh

*1USD = 135JPY

**A carbon credit of $0.015/kWh, the average from a range of international cases, is assumed as an example.

NEDO: New Energy and Industrial Development Organization of Japan

Calculated based on the environmental conditions in Kumejima, Japan

6. Conclusions

This study examined the current cost of OTEC equipment and found that advances in technology and offshore infrastructure have altered the situation compared to previous study. At the same time, inflation continues to increase costs.

Clearly, first generation LCOEs are challenging. A 10MW first-of-a-kind off-the-shelf closed cycle OTEC plantship is expected in the range of \$0.37~0.46/kWh with concessionary loans. Based on the implementation of similar technologies, later generation designs are expected to have reduced costs. Alternative platform and designs have indicated offshore OTEC can obtain first-generation LCOE of \$0.30/kWh without subsidy, or \$0.18/kWh with subsidy and longer (25-year) term. Establishment of an offshore pre-commercial demonstration of 5 MW scale is identified as a stepping-stone to larger offshore implementation.

Sites with higher ΔT are advantageous for initial plants as the net output increases such that for a location with ΔT of 24.5 ºC will yield ≈ 40% higher outputs such that the LCOE would be about 30% lower or \$0.19/kWh in the case of a 50MW commercial plantship with concessionary financing.

For onshore OTEC, implementation is most realistically approached with deep ocean water intake as a separate infrastructure project that supports energy, water, and food applications. OTEC can provide services, such as renewable energy production for the intake facilities, while de-risking initial development of DOW industries by acting as an anchor tenant. This method accounts for the benefits of various DOW industries, which are otherwise difficult to account for in power generation costs under a combined OTEC and DOW intake project structure. Several scenarios were examined based on demonstration data from Japan. In all scenarios, favorable LCOE (under \$0.20/kWh) can be achieved for government or private sector implementation at rates lower than current diesel fuel power prices.

Perhaps a lesson can be learned from the successful commercialization of wind energy, which has been achieved due to consistent government funding of pre-commercial projects (with first generation LCOEs much higher than the rates estimated herein for OTEC) that led to appropriate and realistic determination of technical requirements and operational costs in Germany, Denmark and Spain. In a similar fashion, expanding OTEC implementation is expected to create new markets for component suppliers that will lead to further cost reductions through improved efficiency in production and design.

As the world looks to the oceans for solutions to energy, food, and water challenges, OTEC provides a potential answer. This study has shown that while in general, historic estimates are still relevant, technology development in offshore technologies has created opportunity for cost reduction, while small-scale demonstrations provide long-term operational evidence previously lacking. Various methods have been identified for implementation of cost-effective onshore implementation where deep water infrastructure is also established.

In May 2023, the Japan International Cooperation Agency (JICA) took the first step towards implementing OTEC and DOW industry by beginning a study on implementation for Palau. If actual implementation is successful, this approach may lay the foundation for future economical OTEC deployment.

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List of Figures

List of Tables

Appendix 1

Levelized Cost of Electricity (LCOE: $/kWh)

Luis A. Vega, Ph.D.

Conventional Production of Electricity

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

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

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

$COE_{fuel} = 1.6 \times 10^{-3} \times CB$,

CB is the Cost of a (42 U.S. gallons) Barrel of fuel.

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

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

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

To estimate the total cost of electricity production the COE_{fuel} must be added to the capital cost as well as costs associated with Operations, Maintenance, Repair and Replacement(OMR&R.)

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

Conventional Production of Desalinated Water from Seawater

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

RO plants require energy solely as shaft power from, for example, an electric motor. Current, freshwater production by RO costs **1 ± 0.5 $/m^3** (3.8 ± 1.9 $/kgallon).

OTEC Levelized Cost of Electricity: Methodology

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

Referring to Appendix 5, for example, the following terms are defined:

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

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

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

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

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

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

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

Interest (I): From the loan terms

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

System Life (N): As a conservative assumption, this is defined as the loan term (15 years for the commercial loan; and 20-years for the bonds or concessionary loans) although the OTEC system is designed for a 30-year useful life. Some components are replaced in 15-year intervals (e.g., pumps; Turbines) others require 30-year intervals (e.g., Titanium heat exchangers);

Under Capital Payment (loan amortization):

Capital Recovery Factor (CRF):

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

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

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

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

Under OMR&R Costs (levelized costs):

Present Worth Factor (PWF):

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

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

Expenses Levelizing Factor (ELF):

ELF = PWF x CRF

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

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

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

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

Appendix 2

OTEC Stakeholder Snapshot

Ocean Thermal Energy Conversion is a specialized application that utilizes various techniques and equipment also employed in other industries, thus there is wide variety in terms of the depth of involvement between research, academia, government, and industry. Below we have listed organizations actively involved in ocean thermal applications such as OTEC. This will not be comprehensive as only organizations who have consented to inclusion are provided below.

Organizations will be listed by region (where applicable) alphabetically. Note: Inclusion in this list does not indicate endorsement or validation by the authors or OES. Request for information was sent broadly through ocean energy related networks. Responses have been edited for format and clarity.

Ocean Thermal Energy Association (OTEA)

The Ocean Thermal Energy Association (OTEA) is a volunteer organization providing a means for collection, coordination, and dissemination of information for Ocean Thermal Energy Conversion (OTEC) stakeholders. The Association is transnational, non-political, and dedicated to the realization and future growth of commercial OTEC deployment.

Type
Industry- Association

Location
International

Primary Area of Research, Responsibility, or Business
Networking, Public Awareness, and Events

Areas of Specialty
OTEA provides resources for stakeholders and the public to better understand OTEC and related technologies, while also supporting member initiatives.

Previous Ocean Thermal-related Experience
OTEA's Executive Committee consists of elected delegates from 50 countries and regions representing the leaders in OTEC academia, business, and government.

Website
www.ocean-thermal.org

Contact
admin@ocean-thermal.org

Americas

CEMIE-Oceano

CEMIE Oceano is a multidisciplinary nucleus of organizations combined as an ocean research center in charge of generating innovative products, techniques, and technologies that exploit the diversity of ocean energy resources.

Type
Academia

Location
Mexico City, Mexico

Primary Area of Research, Responsibility, or Business
OTEC Feasibility, System Design, Thermodynamics

Areas of Specialty
Interdisciplinary approach to research and development

Previous Ocean Thermal-related Experience
Five years of research on OTEC as part of a broader national initiative on ocean energy culminating in the development of Central America's first OTEC lab.

Website
https://www.cemieoceano.mx/

Contact
CEMIE-Oceano@iingen.unam.mx

Energy Harvesting Systems LLC

EHS is a Complete Solutions OTEC Developer

Type
Industry- Developer

Location
Honolulu, Hawaii, USA

Primary Area of Research, Responsibility, or Business
Commercial OTEC

Areas of Specialty
Financial analysis, power and marine systems integration, ocean science, naval architecture

Previous Ocean Thermal-related Experience

Website
www.energyharvestingsystems.com

Contact
Chipellis@energyharvestingsystems.com

Makai Ocean Engineering

Makai has been in business since 1973 providing a wide array of professional ocean engineering and software services. We have become a world-recognized leader in several areas of ocean technology and energy systems. Our clients have referred to us as a "think tank" for ocean and energy related problems, owing to our reputation for being innovative, fast, and thorough in our designs.

Type
Industry- Developer

Location
Waimanalo, Hawaii, USA

Primary Area of Research, Responsibility, or Business
Pipeline Engineering Services, cable lay software, heat exchanger manufacture, and engineering

Areas of Specialty
Intake, OTEC, Heat Exchangers, SWAC

Previous Ocean Thermal-related Experience
105kW OTEC Pilot Plant, multiple NELHA-related pipeline projects, 1979 Mini OTEC

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makai@makai.com

Natural Energy Laboratory Authority of Hawaii

NELHA, a self-sufficient State of Hawaii agency, administers Hawaii Ocean Science and Technology (HOST) Park, an innovative green economic development park to serve as an engine for economic development in Hawaii. HOST Park is a unique outdoor demonstration site for emerging renewable energy, aquaculture, and other ocean-based sustainable technologies. HOST Park has become the world's premier ocean science innovation hub and operates at the nexus of water, energy, and food. Three sets of pipelines deliver cold deep sea water from up to 3,000 ft. depth as well as warm pristine surface sea water. Current equipment and pipeline infrastructure is capable of pumping up to 100,000 gallons per minute of seawater throughout the 900-acre technology park.

Type
Government- Infrastructure

Location
Kailua-Kona, Hawaii, USA

Primary Area of Research, Responsibility, or Business
Science and technology park

Areas of Specialty
OTEC, renewable energy, ocean sciences, aquaculture, desalination.

Previous Ocean Thermal-related Experience
Home to OTEC R&D facility (owned and operated by Makai Ocean Engineering Inc.). Site of several OTEC pilot and proof of concept projects.

Website
www.nelha.org

Contact
nelha@nelha.org

OceanBit

Through a novel integrated cycle and business model OceanBit reduces costs, improves efficiency, and monetizes the stranded energy of grazing OTEC. OceanBit is designing, building, and demonstrating our innovation with a 10MW pre-commercial OTEC plantship to bootstrap OTEC into a leading global energy source.

Type
Industry- Developer

Location
Kailua-Kona, Hawaii, USA

Primary Area of Research, Responsibility, or Business
Grazing OTEC

Areas of Specialty
Integrated-cycle design, stranded energy monetization, educational outreach, engineering, operations, commercialization, business model development, and fundraising.

Previous Ocean Thermal-related Experience
Offshore research, offshore engineering, offshore energy, chemical method development, geochemistry, technology business development and management, financial modeling, grant writing, venture capital funding

Website
www.oceanbitenergy.com

Contact
nathaniel@oceanbitenergy.com

Pacific Northwest National Laboratory (PNNL)

PNNL is a multi-program US Department of Energy national laboratory. PNNL is the only Dept of Energy national lab with a marine station and over 90 marine scientists and engineers.

Type
Government - Research

Location
Seattle, Washington, USA

Primary Area of Research, Responsibility, or Business
Marine energy, including OTEC. Environmental effects, feasibility of location, deployment.

Areas of Specialty
Environmental effects, feasibility in US, social acceptance.

Previous Ocean Thermal-related Experience
PNNL has been working on preliminary feasibility projects for OTEC under sponsorship from the US Department of Energy

Website
www.pnnl.gov

Contact
andrea.copping@pnnl.gov

PCCI, Incorporated

PCCI's licensed Professional Engineers, engineering technicians, construction managers, and quality assurance personnel combine their education and experience with the latest design software tools to provide the best mix of equipment and materials for the job. Their hands-on experience in the field with marine facility installations, ship salvage, oil spill response operations, and underwater ship repairs translates back to the office and allows us to design and engineer systems to overcome difficult environmental and working conditions. PCCI's Alexandria, VA headquarters has 6,600 square feet of offices, meeting rooms, library space, computer aided drafting equipment, networked computers, reproduction facilities and graphics equipment. PCCI utilizes ANSYS, Rhino 3D, AutoCAD, Solid Edge, ESRI ArcGIS, Global Mapper, and MS Office 365, as well as specialized software for ship handling and mooring design analysis including GHS, HECSALV, OPTIMOOR and ORCAFLEX.

Type
Industry- Developer

Location
Alexandria, Virginia, USA

Primary Area of Research, Responsibility, or Business
Ocean Engineering, Naval Architecture, Moorings, Environmental Analysis

Areas of Specialty
OTEC plant engineering and design, economic analysis, large pipes, environmental analysis

Previous Ocean Thermal-related Experience
PCCI is performing OTEC modeling for Argonne National Laboratory and will be working on a USTDA-funded feasibility study with India's NIOT. Our chief ocean engineer Patrick Grandelli, P.E., was a certified operator of the 250 kW open-cycle OTEC plant (1996), operated the closed-cycle 100 kW plant (2000), specified the grid-connected 105 kW ammonia turbine generator (2015), served as system engineer for several Lockheed/US Navy design studies and was principal investigator for two OTEC bio-plume environmental studies. He currently serves on the International Electro-Technical Commission TC114 OTEC standards group.

Website
www.pccii.com

Contact
MSchubert@pccii.com

Strogen Strategic Sustainability, LLC

Strogen Strategic Sustainability supports innovative technology companies in evaluating and articulating their economic, environmental sustainability, and national security advantages to more expeditiously develop commercial partnerships and attain financial sponsorship from U.S. federal agencies.

Type
Industry - Consultancy

Location
Washington, DC, USA

Primary Area of Research, Responsibility, or Business
Life-cycle Assessment, Techno-economic analysis, US DoD energy policy and innovation programs

Areas of Specialty
Environmental effects, feasibility in US, social acceptance.

Previous Ocean Thermal-related Experience

Website
www.strogen.com

Contact
bret@strogen.com

University of Rio de Jeneiro

Academic research in ocean Engineering applied to OTEC

Type
Academia

Location
Rio de Jeneiro

Primary Area of Research, Responsibility, or Business
OTEC / Ocean Engineering / Oceanography

Areas of Specialty
Ocean Physics

Previous Ocean Thermal-related Experience
Oceanic and OTEC plant modeling / Ocean thermal resource mapping

Website
www.oceanica.ufrj.br

Contact
robertovalente@oceanica.ufrj.br

Asia

Institute of Ocean Energy Saga University (IOES)

IOES is a laboratory located in the Imari bay area, some 50km to the north from our administrative office in Saga City. The institute functions as a study center of fundamental and practical aspects of various ocean energy technologies.

Type
Academia

Location
Japan

Primary Area of Research, Responsibility, or Business
Ocean Thermal Energy, Ocean Hydraulic Energy, Offshore Wind, and Interdisciplinary Research

Areas of Specialty
OTEC, specifically enhancement of power generation efficiency and new OTEC system concepts, LTTD, and effective utilization of energy and energy substances to be obtained from an OTEC power plant.

Previous Ocean Thermal-related Experience
Saga University is a leader in OTEC R&D with over 50 years of experience. Through elemental technology development, IOES has supported progress towards the realization of commercial OTEC. In addition to developing patented technology, IOES has contributed to studies, papers, outreach, and actual implementation around the world.

Website
https://www.ioes.saga-u.ac.jp/en/

Contact
visit@ioes.saga-u.ac.jp

Japan International Cooperation Agency (JICA)

JICA, with its partners, will take the lead in forging bonds of trust across the world, aspiring for a free, peaceful and prosperous world where people can hope for a better future and explore their diverse potentials.

Type
Government Agency

Location
Japan

Primary Area of Research, Responsibility, or Business
Technical and financial support for developing countries, including OTEC.

Areas of Specialty
JICA is a donor with offices around the world contributing to the promotion of international cooperation

Previous Ocean Thermal-related Experience
Through a joint project framework with the Japan Science and Technology Agency, SATREPS, JICA has supported the joint research and establishment of a hybrid OTEC lab in Malaysia. From May 2023, JICA has begun considering support of establishment of the Kumejima Model in other countries such as Palau.

Website
https://www.jica.go.jp/english

Okinawa Prefecture Deep Ocean Water Research Center (ODRC)

ODRC is a prefectural government research center developing technologies related to deep ocean water utilization. It also sells water to the private sector for industrial use and hosts the Okinawa OTEC demonstration facility.

Type
Government- Infrastructure

Location
Japan

Primary Area of Research, Responsibility, or Business
Fisheries use of deep ocean water, seawater intake and management

Areas of Specialty
Prawn and sea plant technology development.

Previous Ocean Thermal-related Experience
The ODRC falls under the Fisheries and Forestry division of the prefectural government. Its buildings utilize deep seawater air conditioning (SWAC) and has allowed the Industrial Policy Division to operate a 100kW OTEC demonstration since 2013.

Website
http://otecokinawa.com/en/index.html (OTEC Facility Website)
https://www.pref.okinawa.jp/site/norin/shinsosuiken/index.html (official site in Japanese only)

Contact
http://otecokinawa.com/en/Contact/index.html

LumareEnergi

LumareEnergi is an Indonesian start-up on a mission to market drinking water from Deep Sea Water (DSW), powered by ocean thermal energy.

Type
Industry - Developer

Location
Jakarta, Indonesia

Primary Area of Research, Responsibility, or Business
Onshore/offshore ocean thermal energy plants for Indonesian small islands

Areas of Specialty
Conceptual and detailed design, commercialization, project execution, process/mechanical engineering

Previous Ocean Thermal-related Experience
LUMARE’s team originated from the oil & gas industry and has built and operated all the equipment needed for an ocean thermal energy project.

Website
https://www.lumare-energi.com/

Contact
https://www.lumare-energi.com/contact-us

Mitsui O.S.K. Lines (MOL)

The Mitsui O.S.K. Lines Group ais to contribute to a sustainable society through its Blue Action MOL initiative including establishment of OTEC-related businesses.

Type
Industry

Location
Japan

Primary Area of Research, Responsibility, or Business
Shipping, Ocean Energy

Areas of Specialty
MOL has a long history and understanding of ocean-based project operation and management. We’re bringing our knowhow in ocean-centered business to OTEC.

Previous Ocean Thermal-related Experience
MOL has supported the operation of Okinawa’s OTEC Demonstration since April 2022. MOL is also working on adapting the Kumejima Model for Mauritius.

Website
https://www.mol.co.jp/en/

Contact
https://www.mol.co.jp/en/contact/

National Institute of Ocean Technology (NIOT)

The energy and fresh water group of National Institute of Ocean Technology, focuses on harnessing energy from the ocean in the form of waves, seawater currents and ocean thermal gradient to generate electricity and desalinate sea water. The mandate of the group is to develop cutting edge technologies which can produce fresh drinkable water and generate electricity from ocean.

Type
Government - Research

Location
Chennai, India

Primary Area of Research, Responsibility, or Business
Heat exchangers for LTTD and turbines for Ocean Thermal Energy Conversion (OTEC) are the focal areas of research.

Areas of Specialty
Low Temperature Thermal Desalination (LTTD), Open Cycle OTEC

Previous Ocean Thermal-related Experience
Establishment of LTTD plants in Kavaratti, Agatti and Minicoy Islands; Demonstration of barge mounted LTTD plant of 1 MLD capacity offshore in deep waters; Establishment of LTTD plant at NCTPS, Chennai using power plant condenser reject water; DPR preparation of 10 MLD offshore desalination plant; and establishment of OTEC and desalination laboratory.

Website
https://www.niot.res.in/niot_efwtech_en.php

Contact
postmaster@niot.res.in

Seawater Energy Plant Research Center (SEPRC)

SEPRC is one of the centers of Korea Research Institute of Ships and Ocean Engineering (KRISO) founded as stable securing of resources essential to survival and leading the creation of new maritime industry through the sustainable development and utilization of seawater resources (including deep seawater).

Type
Government – Research

Location
Korea

Primary Area of Research, Responsibility, or Business
Development of technology for basic and composite utilization of seawater energy and Development of technology for seawater resource plant and convergence system

Areas of Specialty
SEPRC has established seawater energy laboratory, desalination and extraction of useful minerals in deep seawater laboratory,20kW OTEC, seawater intake, and 60RT SWAC system.

Previous Ocean Thermal-related Experience
SEPRC has established and tested 20kW OTEC lab and 200kW hybrid-OTEC system. In 2019, SEPRC achieved the world’s largest power generation in an offshore 1MW-scale facility test. Continued research and development is supported including ODA support.

Website
https://www.kriso.re.kr/menu.es?mid=a20202010000

Contact
kriso@kriso.re.kr

Universiti Teknologi Malaysia (UTM) Ocean Thermal Energy Centre

UTM's Ocean Thermal Energy Centre carries out research and educational development centered on OTEC.

Type
Academia

Location
Kuala Lumpur, Malaysia

Primary Area of Research, Responsibility, or Business
OTEC System Optimization, Feasibility, OTEC Byproducts, Turbine Development, etc.

Areas of Specialty
OTEC, Deep Ocean Water Use, Collaborative Research and Development.

Previous Ocean Thermal-related Experience
OTEC Pre-Feasibility Study Off Pulau Layang-layang under DCNS-Naval Energies offset funding (2016 - 2017). UTM is in the process of establishing an OTEC lab in collaboration with multiple stakeholders under the SATREPS program framework. The lab is located in Port Dickson, Malaysia.

Website
https://research.utm.my/otec/

Contact
sathiabama@utm.my, utmotec@utm.my

Xenesys Inc.

Xenesys Inc. has focused on researching and developing ocean energy in order to realize and commercialize OTEC and its huge potential. Xenesys's core capabilities include the design and construction management of power generation systems utilizing small thermal differences and the manufacture of heat exchangers, the most important component of such systems. Their heat exchangers are a unique all-welded plate type, most suitable for temperature difference power generation due to their high efficiency and compactness.

Type
Industry- Developer/Manufacturer

Location
Japan

Primary Area of Research, Responsibility, or Business
Small Thermal Difference Engineering, Heat Exchanger Manufacturing

Areas of Specialty
OTEC, SWAC, LTTD, Multiple Use of Deep Ocean Water

Previous Ocean Thermal-related Experience
Xenesys contributed to the construction of the Okinawa OTEC Demonstration Facility in 2012-2013 and continues operation and management of it on behalf of the Okinawa Prefectural Government. Xenesys has a long track record of OTEC-related R&D including manufacturing equipment for the Institute of Ocean Energy Saga University (IOES), and UTM OTEC in Malaysia. Xenesys has also produced various studies such as feasibility studies for our clients.

Website
http://xenesys.com/english/index.html

Contact
info@xenesys.com

Europe

DEEPRUN

DEEPRUN is a start-up based on Reunion Island, composed with 3 engineers that work on the design of a disruptive cold-water pipe for OTEC.

Type
Industry- Developer

Location
La Reunion, France

Primary Area of Research, Responsibility, or Business
Research on cold-water pipe

Areas of Specialty
Naval Engineering : Hydrodynamics, Structure

Previous Ocean Thermal-related Experience

Website
www.deeprun.re

Contact
matthieu.hoarau@deeprun.re

Geocean SAS

GEOCEAN is an EPCI contractor specialized in Marine & Offshore works that is part of VINCI Construction Grands Projects as its marine works integrated business unit.

Type
Industry- Contractor

Location
France

Primary Area of Research, Responsibility, or Business
EPCI Contracting for Marine works

Areas of Specialty
Installation of deep water intake pipes

Previous Ocean Thermal-related Experience
Geocean was the main contractor for installation of SEWAC intake piping for Tetiaroa in French Polynesia. It completed the successful installation of SWAC intake for the French Polynesian Hospital in Papeete, Tahiti.

Website
https://www.geocean.com/en/geocean-home/

Contact
https://www.geocean.com/en/geocean-home/contact/

Global OTEC Resources Limited

Global OTEC was founded to provide clean, reliable and affordable energy for small island developing states which experience some of the highest energy costs in the world.

We have designed the first commercial Ocean Thermal Energy Conversion system to transform the energy landscape for tropical island nations. By commercializing ocean thermal energy, we aim to free Small Island Developing States and coastal cities from the need to import expensive and dirty fossil fuels and help them meet the Sustainable Development Goals (SDGs).

Type
Industry- Developer

Location
London, U.K.

Primary Area of Research, Responsibility, or Business
Floating OTEC Platform Development

Areas of Specialty
Commercialization of proven technology concepts; Sourcing applicable finance for scaling up; Innovating new floating OTEC solutions

Previous Ocean Thermal-related Experience
Technical Lead of Horizon Europe funded PLOTEC.eu project; Prefeasibility studies; Technoeconomic studies; Thermocline field studies

Website
www.globalotec.co

Contact
andreas.koall@globalotec.co

Ocean Energy Systems Limited (OESL)

OESL is a marine consultancy business based in the oil and gas capital of Aberdeen in the U.K. The company has been trading for 23 years. The company operates in both the renewables and oil and gas markets. As well as OTEC the company has worked on Floating Wind and model testing of a Wave Energy Converter. For several years, the majority of OESL's work was related to offshore oil and gas operations. This understanding of how conventional energy systems are designed, installed and operated is now applied to marine renewable energy sources.

Type
Industry- Consultancy

Location
Aberdeen, U.K.

Primary Area of Research, Responsibility, or Business
OESL provides specialist consultancy advice and project management services for energy projects on a worldwide basis. This can be desktop suitability studies through to detailed design, transportation and offshore installation.

Areas of Specialty
Investment appraisal and LCOE assessment, Methodology and cost estimation for Transportation and Installation of OTEC systems, Mooring & power cable design and integrity, Naval Architectural services – stability, motions etc., Marine Warranty Services (MWS), Project Management/Project Engineering of the above services including running Joint Industry Projects (JIPs).

Previous Ocean Thermal-related Experience
Study on Multiple Product OTEC for Taiwan, 2022; Principle author of IEA-OES's "White Paper on Ocean Thermal Energy Conversion OTEC," October 2021; Study into the suitability of converting a Drillship into a grazing OTEC Production Facility; Investigated application of FPSO Technology for OTEC; Investment appraisal for a Multiple Product OTEC complex on Grand Cayman Island in the Caribbean; Publication of seven technical papers on OTEC including presenting at Offshore Technology Conference (OTC) in Houston, Texas.

Website
www.oceanenergysystems.co.uk

Contact
martinbrown@oceanenergysystems.co.uk