

# Are We There Yet?

## A Developer's Roadmap to OTEC Commercialization

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**Abstract**—Ocean thermal energy is a vast, untapped renewable energy resource that can provide baseload power. However, no commercial OTEC plants exist today and an OTEC industry remains nascent. The path toward commercialization is discussed from the perspective of one OTEC developer.

**Keywords:** OTEC, Ocean Thermal Energy Conversion, Commercialization

### I. WHERE ARE WE GOING?

Ocean thermal energy is a large, to-date untapped renewable energy resource that can potentially provide a conservatively estimated 5 terawatts of power for human consumption [1]. This thermal energy comes from an existing, vast energy storage mechanism, the tropical oceans. Ocean Thermal Energy Conversion (OTEC) is a technology that harnesses the temperature difference between warm surface water and cold deep water in a Rankine thermodynamic cycle to produce electricity. Because the ocean itself is the energy storage mechanism, OTEC is a baseload technology, i.e. provides power 24/7. This power can be connected directly to a local grid via undersea cable or be used to produce energy carriers and other products that can be shipped to shore.

*Lockheed Martin and our team members envisions a future where OTEC plants provide safe, secure, reliable, environmentally friendly power around the globe; where local economies use their own energy resources rather than export their wealth; where hundreds of thousands of new jobs in a new marine-industrial sector are created to design, build, install, operate, maintain, and improve these plants; where fossil fuels no longer have to be burned for their energy content but rather can be better utilized in value-add products; and where energy is produced in concert with nature rather than in opposition.*

But that future is still a dream, though OTEC was imagined by Jules Verne and investigated by Jacques Arsene d'Arsonval in the 1800s. That future is still a dream, though OTEC technology was demonstrated in the 1900s, first by Georges Claude, then by many others. That future is still a dream, though we are now cautiously optimistic that OTEC can finally be implemented in the 2000s, hopefully not too far into this new century.

*That future is still a dream, but it is a dream that can change our world.*

### II. HOW WILL WE GET THERE?

Development of new ideas and technologies follow typical business development stages. According to a Bloom New Energy Finance report [2], one example describing the stages is shown here:

Stage 1 – Research & Development – generate ideas and generate intellectual property

Stage 2 – Demonstration / Proof of Concept – Design and test prototypes, improve technology

Stage 3 – Deployment / Pilot Facility – Prove technology validity in the field, market technology

Stage 4 – Diffusion / Commercialization - Prove manufacture process can be scaled economically & prove technology is viable at scale

Stage 5 – Commercial Maturity – Proven technology is sold and distributed

Practical business barriers exist to move from early stages to commercialization. According to [2], it's not easy to move from stages 1 & 2 to commercialization because of the "Valley of Death," that is, projects need high levels of funding but no obvious sources exist.

Bloomberg [2] goes on to say,

"The problems posed by this funding valley represent fundamental, structural market shortcomings that most respondents, along with CEG and BNEF, believe cannot be resolved by the private sector acting on its own. Even in good times, when lending standards are most flexible, banks and other financial institutions are simply not structurally positioned to back large-scale projects deploying new technologies."

and,

“This is not a problem caused by a lack of interest by the various parties involved. In fact, no private funder has the mandate to deploy capital addressed at this particularly challenging point in the risk/reward spectrum. Venture capital firms have high technology risk tolerance but relatively limited capital, and they demand short-to-medium returns. Project finance funders and bank lenders typically have high levels of capital and can commit to longer-term investments, but they have little or no technology risk tolerance. No existing class of financing institutions is effectively positioned to address this particular risk/return category.”

This Valley-of-Death issue is particularly acute with OTEC because (1) affordable OTEC plants need to be big; (2) no power purchase agreement (PPA) revenue is available until essentially the entire plant is on-line; and (3) a smaller plant serving as a pilot facility is still expensive and doesn't generate sufficient PPA revenue to recoup costs. Also, unlike many renewable energy technologies, OTEC remains at the beginning of its learning curve. No commercial OTEC plants exist today.

#### A. Past

Our OTEC journey started in 1974 when Lockheed Missiles & Space Company, Inc., a subsidiary of Lockheed Aircraft Corporation, supported by Bechtel Corp and T.Y. Lin International, began a “9-month study of the practicality of generating electrical power at competitive bus bar prices by using the solar energy that is stored as a thermal gradient in the world's oceans.” That study was performed for the National Science Foundation's Research Applied to National Needs program partly in response to the increase in fossil-fuel costs (notably oil) in late 1973, (Fig. 1).

Government direction of the program moved to the Energy Research and Development Administration (ERDA) when that organization was activated in January 1975. After that study effort, federal OTEC programs moved to the new Department of Energy (DoE), created in 1977.

Lockheed followed the NSF study with a self-funded 3-month demonstration called Mini-OTEC in 1979, with engineering and material support from the US Navy, Makai Ocean Engineering, Dillingham Construction, and other firms (Fig. 2).

The 50 kilowatt (gross) Mini-OTEC plant was successful and today still remains the only floating, net-power producing OTEC plant ever built. Mini-OTEC was operated by the Lockheed team for three months off the Natural Energy Laboratory Hawaii Authority (NELHA) on the Big Island of Hawaii to gather technical data on the operation of the system as well as to prove the feasibility of clean electricity production using ocean temperature differences in an environmentally benign way. (Mini-OTEC would be classified as a business development Stage 2 demonstration.)

During the 1970s, studies and tests by many industry, academic, and government institutions were conducted. The way seemed open to transition OTEC technology to



Figure 1. Lockheed Design Concept for Ocean Thermal Energy Conversion Power Plant, Circa 1975.

deployment / pilot facility (Stage 3). DoE was ready to award a contract in 1982 to build a 40 MW pilot plant. Unfortunately, that award never happened as the new federal administration began to seriously reduce funding for renewable energy in general and ocean energy in particular (Fig. 3)[2]. The ensuing reduction in federal support and the return of fossil fuel prices to low levels curtailed most industry support for OTEC development, though a number of significant activities, including the OTEC-1 heat exchangers, FRP cold water pipe (CWP), and the NELHA open cycle plant and corrosion tests continued through the 1990s. Lockheed's journey was interrupted.

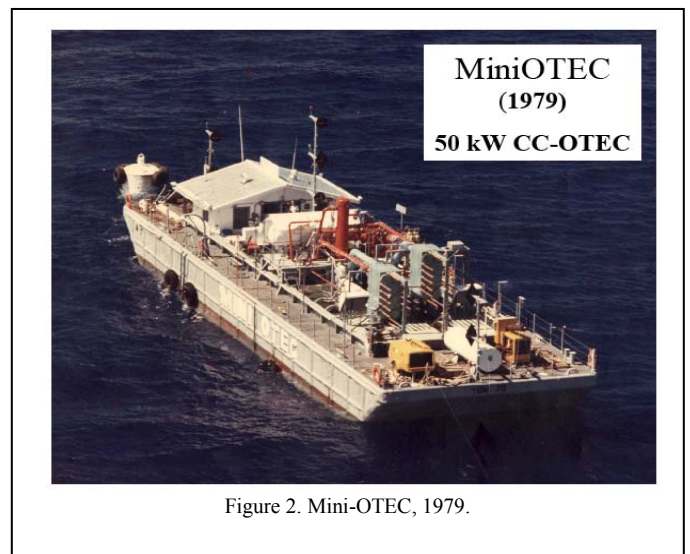
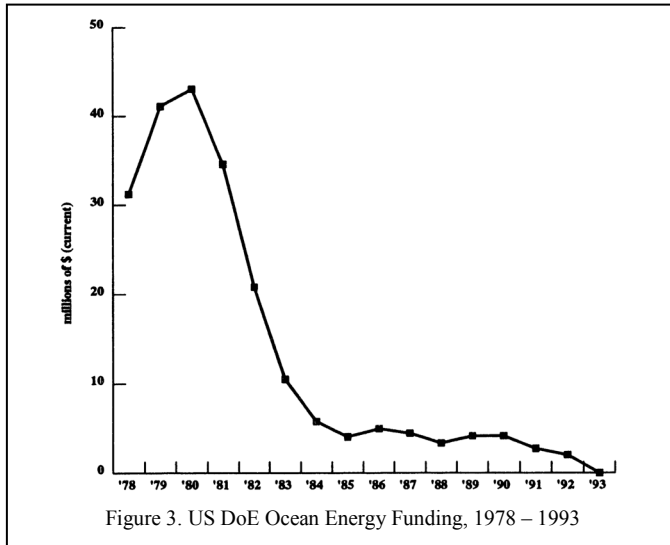


Figure 2. Mini-OTEC, 1979.



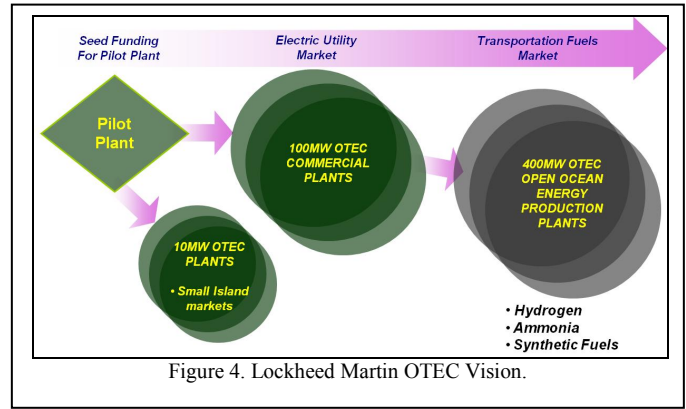
**B. Present**

In 2006, Makai Ocean Engineering was awarded a small business innovative research (SBIR) contract from the Office of Naval Research (ONR) to investigate the potential for OTEC to produce nationally-significant quantities of hydrogen in at-sea floating plants located in warm, tropical waters. Realizing the need for larger partners to actually commercialize OTEC, Makai approached Lockheed Martin to renew their previous relationship and determine if the time was ready for OTEC. And so in 2007, Lockheed Martin resumed our OTEC journey and became a subcontractor to Makai to support their SBIR.

Lockheed Martin separately began to engage with Makai Ocean Engineering and others to collectively review the work that was done over the decades to commercialize OTEC, a dream kept alive by Joe Van Ryzin, Luis Vega, CB Panchal, Bob Cohen, Jim Anderson, Hans Krock, and others. Developing the envisioned vast marine-industrial sector supporting affordable commercial OTEC applications (Stage 5) required conducting Stage 2 proofs of concepts for any new technology, deploying a pilot facility (Stage 3), and building the first commercial plant (Stage 4). We developed a vision, commercialization roadmap, and technology strategy focused on what we saw as the primary risks and hurdles to scaling OTEC to utility applications.

Our vision (Fig. 4) began with the need to field an integrated pilot plant to enable our move to Stage 4 - commercial market entrée to electric utilities in locations with existing high costs of electricity. We expect that as more plants are fielded, we will move down the learning curve and see decreasing unit costs, eventually enabling entrée to lower cost electricity markets. Initial market entrée requires larger plants due to OTEC economics. Smaller plants may eventually become affordable, but in the near future, small plants will need to be subsidized.

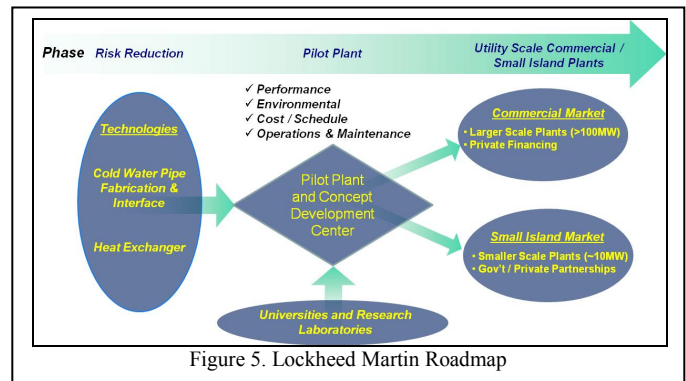
As electricity generation becomes established and progress is made toward Stage 5, larger OTEC plants “grazing” in the open oceans will be developed to produce energy carriers and/or synthetic fuels. These plants will have the potential to begin to offset transportation fluids.



Achieving our vision required us to understand technology solutions and develop realistic cost and schedule estimates to determine whether OTEC commercialization could yet be realized. Based on assessments, we developed our commercialization roadmap to provide another view of our commercialization plan (Fig. 5). Though much technology and system work exists, much has also changed since the 1970s. We identified a number of technology development/ demonstration tasks to reduce remaining risk.

However, successful risk reduction is not the only barrier for commercialization. We needed to address the Valley-of-Death, finding funds to build a pilot facility large enough to convince investors and Lockheed Martin management we could be successful at commercial utility scales. We believe an integrated megawatt scale pilot plant is still needed to obtain the large amounts of private financing needed for commercial, utility scale OTEC plants. Our early focus was on a 10 megawatt (MW) floating design. We viewed scaling 10 MW up to an initial commercial 100 MW plant as a reasonable step with acceptable risk for the private financing requirements.

The pilot plant serves several purposes and addresses multiple stakeholder concerns. It provides an integrated system demonstration of the technology. When connected to a local grid, it provides the utility with the opportunity to ensure baseload OTEC power performs as expected. The pilot plant allows measurement of environmental parameters so the regulatory agencies can understand and assess how larger, commercial plants will operate. The pilot plant will also enable NOAA, the federal agency with OTEC licensing authority, to fine tune their regulatory process. The pilot project will validate cost and schedule plans so both industry and financial





communities can extrapolate results to commercial projects. Since no commercial OTEC plants are in operation today, the pilot plant will provide the opportunity to validate estimate of operations & maintenance (O&M) requirements. Finally, a pilot plant will provide public relations and community education opportunities about this new renewable resource.

We developed sufficient confidence and optimism to invest in tasks that would refine our design. Along the way, we “picked up new friends,” companies that provided key skills and credibility to make real progress. Complementing our Lockheed Martin / Makai Ocean Engineering team (Fig. 6), we’ve added companies with expertise in the offshore industry, naval architecture, ocean engineering, OTEC systems, composites, and the environment.

The primary technical challenges included heat exchanger optimization, affordable and survivable cold water pipes at 10m+ diameter and 1km length, stable and affordable ocean platform concepts, and affordable and efficient system designs.

We invested in heat exchanger design efforts to address performance, corrosion, and producibility (Fig. 7). A companion test program focused on understanding the behavior of candidate alloys in both warm and cold seawater was devised by Makai. Today we have over a year of exposure for hundreds of samples. To confirm performance estimates for our HX designs, we have conducted testing at both small scale (laboratory) (Fig. 8) and large scale at NELHA (Fig. 9) using multiple working fluids and a range of representative environmental operating conditions. A separate paper at this conference addresses more details.

We identified a survivable, lower cost composite cold water pipe solution that could be fabricated on the platform to reduce deployment challenges (Fig. 10). Teamed with the DoE, we validated the composite pipe fabrication approach and key elements of the composite tooling (Fig. 11). Teamed with the USN, our team addressed the challenging interfaces between that composite pipe and the steel platform structure (Fig. 12). Future plans include integration of the full pipe fabrication system for a full scale land based demonstration.

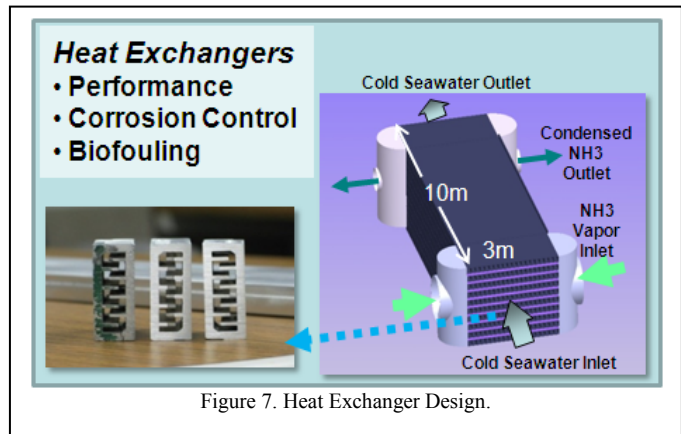


Figure 7. Heat Exchanger Design.

We surveyed the offshore industry to understand the state of the art in large stable floating structures for offshore deepwater applications (Fig. 13). As one might expect, because of the progress in the offshore oil and gas industry moving into deeper and deeper operational environments, many of what were challenges in the 1980s are no longer viewed by the industry as technology challenges today. However, these deepwater technologies have been exquisitely engineered to address oil and gas challenges which don’t necessarily plague OTEC and hence are not necessarily cost optimized for our application. Our team has worked hard to understand the applicability of existing offshore standards in the ultimate design of an OTEC system, and we have begun working with certification and classification experts focused on safety of operations as well as NOAA and environmental experts to ensure our design addresses key ecological concerns.



Figure 8. OTEC Thermodynamic Laboratory, Manassas, VA.



Figure 6. Lockheed Martin OTEC Team

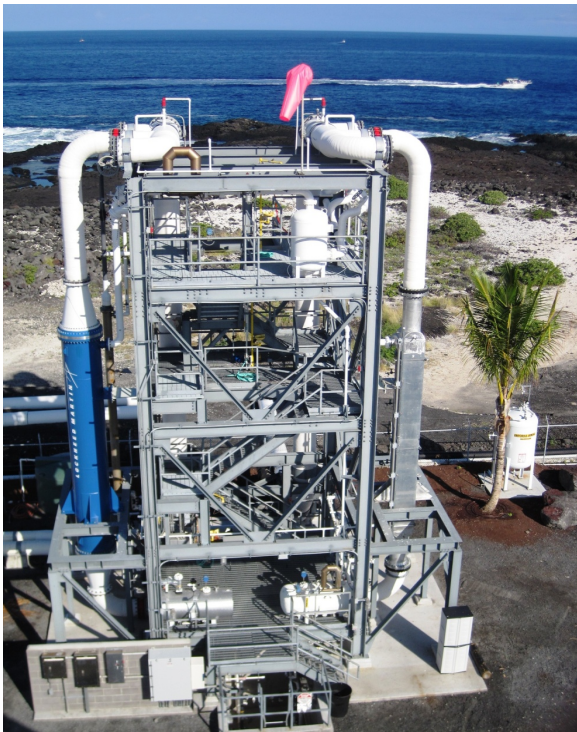


Figure 9. OTEC Heat Exchanger Test Facility, NELHA, HI

### III. ARE WE THERE YET?

We're making progress. Capital cost is the primary challenge. Since we believe private financing will require a substantial demonstration to show performance, validate environmental predictions, confirm cost and schedule estimates, and collect operational data our focus has been on a pilot plant. But we face a conundrum – a pilot plant will be a “small” OTEC plant; small OTEC plants aren't economic. We have therefore focused on federal support for a pilot plant program. Unfortunately, today's budget woes challenge the ability of the federal government to support a substantial demonstration.

Many demonstration options exist ranging from multiple megawatt systems that can be upgraded to commercial operation after the pilot phase to a set of subsystem tasks that collectively address every issue. The choice of demonstration

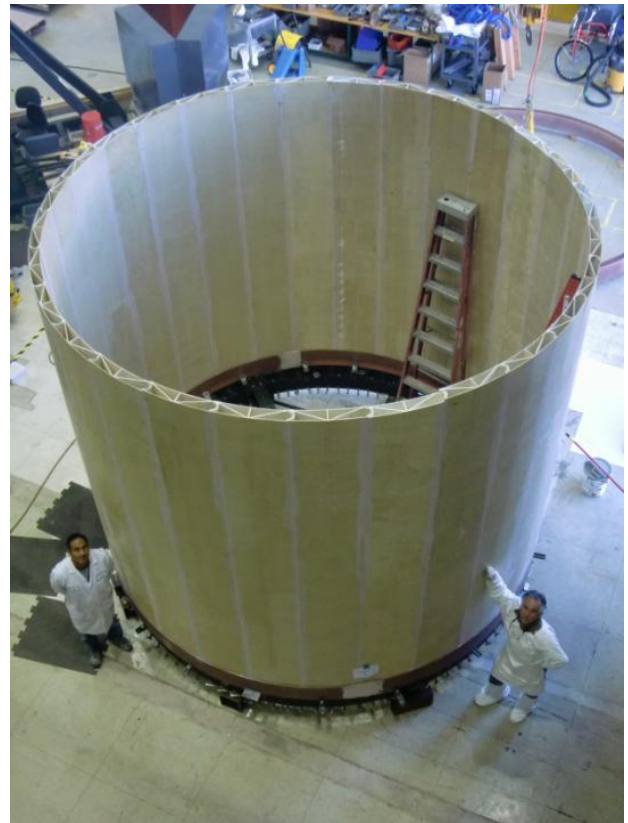


Figure 11. Four-Meter Cold Water Pipe Core.

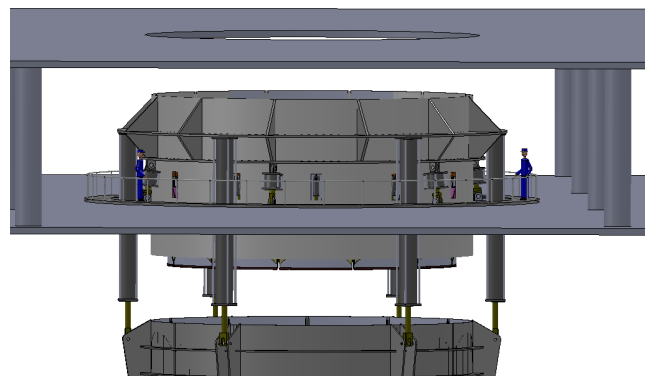


Figure 12. Cold Water Pipe Handling System (Gripper).

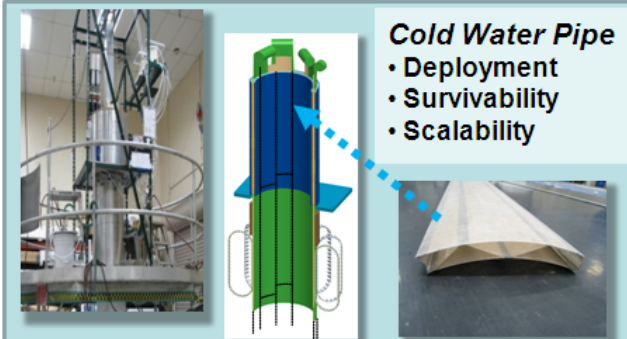


Figure 10. Cold Water Pipe Design.

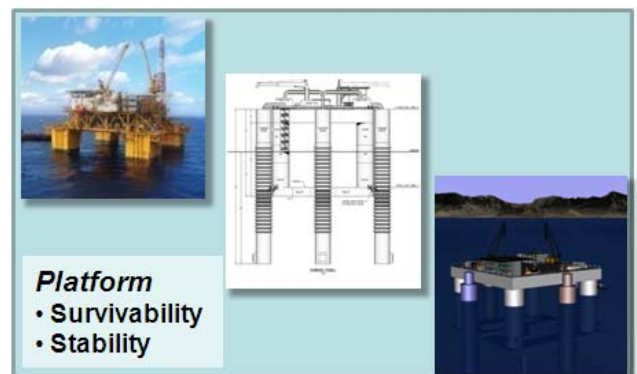


Figure 13. Platform Design.

will be decided by available funding and by the needs of those who will invest in commercial projects.

We continue to seek partners who will help us finish our road to OTEC commercialization.

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