Hawaii Renewable Energy Development Venture
Technology Assessment

Ocean Thermal Energy Conversion (OTEC)

1. Overview

Ocean thermal energy conversion (OTEC) indirectly converts solar energy to electricity. From a thermodynamic perspective, OTEC power cycles operate as continuous heat engines driven by the transfer of energy between a thermal source and sink. Since OTEC expends renewable solar energy, recurring costs to generate electrical power are minimal; however, the fixed (capital) costs of OTEC systems per kilowatt of installed generating capacity are very high. This is a consequence of the low theoretical efficiency of OTEC--typically around 8%--that demands large components (e.g., heat exchangers; pipelines) to accommodate the thermal energy transfers necessary to produce small amounts of electricity. The high fixed costs dominate the economics of OTEC to the extent that it generally cannot compete with conventional power systems unless other benefits, such as reducing greenhouse gas emissions, energy security, or co-products are taken into consideration.

Warm surface waters of tropical oceans comprise the thermal resource utilized by OTEC. The oceans, which cover over 70% of the Earth's surface, intercept solar radiation passing through the atmosphere. While a portion of this energy is re-radiated directly back to space, a significant fraction is retained by seawater at lower latitudes, heating the upper mixed layer of tropical oceans to an average year-round temperature of approximately 28°C. The amount of solar radiation retained by the oceans is enormous: each day, energy equivalent to approximately 250 billion barrels of oil is absorbed over the 60 million km^2 of tropical seas. This is more than three orders of magnitude greater than the current daily energy consumption of all humanity.

Since the second law of thermodynamics dictates that only a fraction of the energy extracted from warm seawater can be converted to usable work by a power cycle, a thermal sink must be available to accept waste heat. The oceans provide such a sink in the form of a bottom layer of cold water lying beneath the warm surface zone. The warm surface layer, which can extend to depths of 100 m, is separated from the deep cold water by a thermocline. The vertical gradient in temperature below the mixed layer is usually substantial. The temperature difference between the surface and 1000 m depth ranges from 10° to 25°C, with larger differences occurring in equatorial and tropical waters.

The performance of OTEC power cycles depends ultimately on the available difference in the temperatures of the warm and cold seawater, ΔT. The rule -of-thumb is that a ΔT of about 20°C is necessary to sustain viable operation of an OTEC power station. This requirement limits the number of candidate OTEC sites, primarily to the lower latitudes. One of the principal technical challenges of recent years, therefore, has been to devise strategies to export the benefits of the renewable OTEC resource to locations outside the tropics, possibly via the production of energy carriers (e.g., methanol; ammonia; hydrogen via electrolysis).

OTEC power systems may be configured as closed or open cycles. Closed cycle OTEC systems use a pressurized working fluid that boils at low temperatures, such as ammonia or other refrigerants. The working fluid circulates through a closed loop, passing through an evaporator where it is vaporized by heat transfer from warm seawater, expanding through a turbine to generate power, before being condensed in a heat exchanger by heat transfer to cold seawater.

Open cycle OTEC (OC-OTEC) does not use a separate working fluid. Warm seawater is evaporated in a partial vacuum (typically less than 0.1 atmosphere) and the low-pressure steam is used directly to spin a turbine before being condensed by heat transfer to cold seawater and discharged. Since dissolved salts are left behind when the seawater evaporates, the condensate is fresh water, which can be marketed as a co-product along with electricity.

The relatively high density of the pressurized working fluids used in closed cycle OTEC systems allows the use of more compact components than OC-OTEC, where heat exchangers and turbines need to accommodate large volumetric flow rates of low pressure steam. Furthermore, maintaining the partial vacuum conditions of OC-OTEC is challenging and associated parasitic power losses to remove non-condensable gases can be significant. In consideration of these factors, closed cycle OTEC probably is the better candidate for power generation scenarios where desalinated water production is not necessary.

The primary practical advantage of OTEC over other renewable energy options such as direct solar, wind, or wave, is that it is a baseload system that can deliver steady power continuously, like fossil fuel or nuclear power stations.

Although OTEC appears to enjoy a favorable carbon footprint and is generally touted as a “green” alternative to conventional energy systems, it can pose environmental problems associated with the displacement of large volumes of surface and deep seawater. For megawatt-scale plants operating over a ΔT of 20°C, about 3.5 m^3/s of warm surface water must be supplied per megawatt of electricity generated by the turbine. Studies suggest that net power output is optimized when warm-water:cold-water ratios lie between 1.8:1 and 2:1. To place this in context, a 100 MWe (gross; about 70 MWe net after subtracting power consumed by the seawater pumps, etc.) OTEC plant which could service around 70,000 households, would require 350 m^3/s of warm seawater and 175 m^3/s of cold seawater, for a total flow rate of 525 m^3/s—about the size of the Colorado River, which is a primary source of water for a number of western states. The seawater effluent from the OTEC plant will consist of either separate or mixed streams of slightly cooled surface seawater and slightly warmed deep seawater. This effluent will, in general, have a different composition and temperature from the ambient seawater at the point of discharge back into the ocean, which could impact the marine ecology. Recent modeling studies have also suggested that the thermal OTEC resource, ΔT, may degrade over time if too much water is extracted and replaced too quickly, changing the local temperature profile of the ocean.

As mentioned previously, various co-products have been explored that would generate revenue streams to offset the high capital costs of an OTEC power station. These include: desalinated water; air conditioning and refrigeration; and mariculture. Since a large percentage of the OTEC resource is located far away from land and major population centers, delivery of electricity via submarine cables to onshore power grids from floating OTEC plants may not always be practicable. It may be possible, instead, to use the generated power to produce high value energy carriers such as hydrogen or liquid fuels that could then be transported and sold on the world market.

2. Status of Commercial Readiness

The OTEC concept was first proposed in 1881 by the French engineer J.A. D'Arsonval. Fifty years later in 1930, G. Claude, D'Arsonval's former student, conducted the first field test of an OC-OTEC system in northern Cuba. Since that time there have been numerous laboratory, modeling, design, and field studies conducted of closed cycle OTEC and OC-OTEC. These studies have clearly demonstrated proof-of-concept. Existing technologies have been validated for use in OTEC power facilities, although further optimization of the heat exchangers and turbine could provide modest cost and performance gains. There remains some technical uncertainty about the cold water pipe for large OTEC power stations and this area also warrants additional R&D.

From a technical perspective, a general consensus exists among OTEC experts that a small to mid-size (i.e., with a generating capacity of the order of tens of megawatts) land-based or floating OTEC plant could be successfully constructed and operated today. There are no major technical showstoppers. Rather, the primary roadblock to widespread commercialization of OTEC is the lack of long-term operational data from a pilot-scale facility. This is essential to provide the level of confidence needed to secure financing to cover the substantial capital costs of OTEC, which for a first-generation ~10-50 MWe power station could exceed $30K per kW of installed generating capacity. This is an order of magnitude greater than the cost of a state-of-the-art coal power plant.

Since private investment in OTEC is unlikely to materialize until a pre-commercial facility is operated over several years to demonstrate reliability, substantial government support will probably be required to build such a facility.

3. Appropriateness to Hawaii

Hawaii is an ideal site for OTEC. Hawaii arguably has the best OTEC resource in the U.S. The islands rise sharply from the seafloor, resulting in bathymetry that provides excellent near-shore access to deep, cold seawater. Annual sea surface temperatures around Hawaii typically are in excess of 25°C, which is sufficient to provide the 20°C temperature differential required to ensure acceptable thermodynamic performance of an OTEC cycle.

Over the past 30 years almost all major U.S. OTEC studies have taken place in Hawaii. In 1979, Mini-OTEC, the first successful floating closed-cycle OTEC system, was tested offshore of Keahole Point on the west coast of the island of Hawaii. This project, a joint effort between the State of Hawaii, Lockheed Missiles and Space Company, Alfa Laval Thermal, and the Dillingham Corporation, produced up to approximately 50 kWe gross power (10-17 kWe net) during its three month operation. The following year, USDOE funded TRW, Inc. to test titanium shell-and-tube closed cycle OTEC heat exchangers on OTEC-1, a converted navy tanker that was again moored off the west coast of the island of Hawaii. In 1984, Ocean Thermal Company, under contract to USDOE, completed detailed plans for a 40 MWe OTEC plant that would be operated as a bottoming cycle for the Hawaiian Electric Company's 600 MWe (at that time) thermal power station located at Kahe point on the island of Oahu. Funding to construct the OTEC plant did not materialize, however, and the project was terminated.

Since the late 1980's, other OTEC demonstrations and studies have been conducted at the Natural Energy Laboratory of Hawaii Authority (NELHA) facility at Keahole Point. NELHA was established in 1974 by the State of Hawaii to pursue OTEC and other ventures utilizing deep ocean water. Between 1992 and 1998, NELHA hosted the USDOE's Net-Power Producing Experiment (NPPE) in which an open cycle OTEC system was constructed that produced a recorded maximum of 255 kWe of gross power (equivalent to >100 kWe net) as well as potable water from a second stage desalination unit.

Given the exceptional OTEC resource around Hawaii, the extensive history of OTEC development in the state, and the OTEC technical expertise that can be found at the University of Hawaii, in government, and in the local private sector, it is obvious that OTEC warrants serious consideration as a future energy option for Hawaii. By State law, 20% of the electricity supplied by the local utilities in 2020 must come from renewable resources and improvements in energy efficiency. Currently, renewables constitute about 8% of the approximately 2,400 MWe installed generating capacity, which means about 300 MWe must be added over the next decade. While wind, solar, wave, and biomass sources could probably make up this difference, the first three do not provide baseload power, which poses challenges regarding electrical grid stability, and questions have been raised about the availability of locally-produced biomass feedstocks. OTEC, on the other hand, could provide the entire 300 MWe in the form of baseload power using only a fraction of the available thermal resource. Environmental impacts of the seawater effluent will need to be addressed, however, and the required capital investment will be large—although good opportunities exist to extract additional value from cold water air conditioning and mariculture.