Pacific Northwest NATIONAL LABORATORY

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Feasibility, Environmental Effects, and Social Acceptance of Ocean Thermal Energy Conversion

Final Report

February 2023

Andrea Copping
Hayley Farr

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Summary

Ocean Thermal Energy Conversion (OTEC) uses the temperature differential between warm surface ocean water and deep cold ocean water to generate power through a heat exchanger process. Deep ocean water is generally between 2^{o} and 4^{o}C; the temperature differential of 20^{o}C needed for OTEC is found only in tropical waters. In the United States, OTEC is feasible year round only in Hawaii and island territories in the Caribbean and the Pacific. In addition to power from OTEC, cold ocean water can be used in place of traditional air conditioning, through a process known as SWAC (seawater air conditioning) that runs cold water through buildings and exchanges the heat, much like a heat pump. The deep OTEC water pumped to the surface may also be advantageous for other uses such as aquaculture. There is no established method of determining potential environmental effects of OTEC and SWAC. In general, the greatest risk to the marine environment from OTEC will be the return of large volumes of deep ocean water to the surface of the ocean where the temperature shock may kill organisms and potentially affect the stability of the water column. The deep cold water can be defused at depth to prevent these effects. There is little information about potential concerns from local communities where OTEC might be developed. There is a need for a broad education and outreach program to ensure that communities and local officials are well informed of the benefits and risk of OTEC.

Four use cases for developing OTEC are outlined for U.S. waters in Hawaii, Puerto Rico, St. Croix, and Guam. A simple education and outreach program is also outlined.

Abbreviations and Acronyms

APPA	American Public Power Association
DEDC	Department of Economic Development and Commerce
DOC	Department of Commerce
HOST	Hawaii Ocean Science and Technology
IRENA	International Renewable Energy Agency
NELHA	Natural Energy Laboratory of Hawaii Authority
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NREL	National Renewable Energy Laboratory
OES	Ocean Energy Systems
OTEA	Ocean Thermal Energy Association
OTEC	Ocean Thermal Energy Conversion
SWAC	Seawater Air Conditioning

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1.0 Introduction

To determine whether Ocean Thermal Energy Conversion (OTEC) is well suited for development in the United States, the project examined the technical feasibility, potential environmental effects, and social acceptance of both onshore and offshore OTEC, focused particularly at the 10 MW scale or less.

The research team at Pacific Northwest National Laboratory (PNNL) reviewed the available scientific and industry literature and conducted 15 interviews with OTEC experts around the world. Many of those interviewed have been trying to establish OTEC as an industry for decades, while others are new entrants into the field. The unexpected generosity of those interviewed in providing their time and expertise to discuss their history with OTEC, technical challenges to establishing OTEC, and their visions of how OTEC might become commercialized, provided the research team with essential information, and also highlighted the pent-up desire for and belief that OTEC is ready for deployment at the commercial scale.

This report summarizes what the team has learned about the status of OTEC internationally and provides an evaluation of the challenges and opportunities for this marine energy sector.

The following sections describe the various OTEC technologies and the potential environmental and social effects that should be examined to support smooth and responsible development. Four use cases are presented that span the U.S. exclusive economic zone, as a means of initially assessing the path forward for OTEC in the United States. The report also includes a simplified education and outreach plan for deployment to a variety of audiences that have a stake in OTEC, and it concludes with recommendations for next steps in this process. Appendix A includes the list of experts the research team interviewed and brief descriptions of those discussions.

2.0 Thermal Gradients in the Oceans

Thermal gradients exist in the oceans due to a circulatory pattern known as the "ocean conveyor belt" (Losier 2010). At the poles, ice formation creates seawater that is high in salinity and low in temperature. Global-scale oceanographic processes then move these high-density water bodies throughout the oceans, slowly mixing and surfacing them in the tropics where they are warmed by heat from the sun (Figure 1). This circulatory pattern creates temperature gradients in tropical and subtropical waters with warm surface water and deep cold water. The potential energy between these two water masses can be used to generate power through OTEC in areas where the temperature differential is at least 20°C (National Research Council 2013; Takahashi 1999; Vega 1995).

The overall technical resource potential for OTEC in the U.S., Pacific territories, and freely associated states is roughly 4,600 terawatt hours per year (Kilcher et al. 2021). Within the U.S. exclusive economic zone, areas where there is sufficient warming of surface ocean waters to allow for OTEC include the Hawaiian Islands, territories in the Caribbean Sea (e.g., Puerto Rico and the U.S. Virgin Islands), and island territories in the North and South Pacific (e.g., Guam, the Northern Marianas Islands, and American Samoa). The Gulf of Mexico and Atlantic coast of Florida also have some potential for OTEC. The worldwide potential for OTEC resources is approximately 3 terawatts, or 26,280 terawatt hours per year (Nihous 2005).

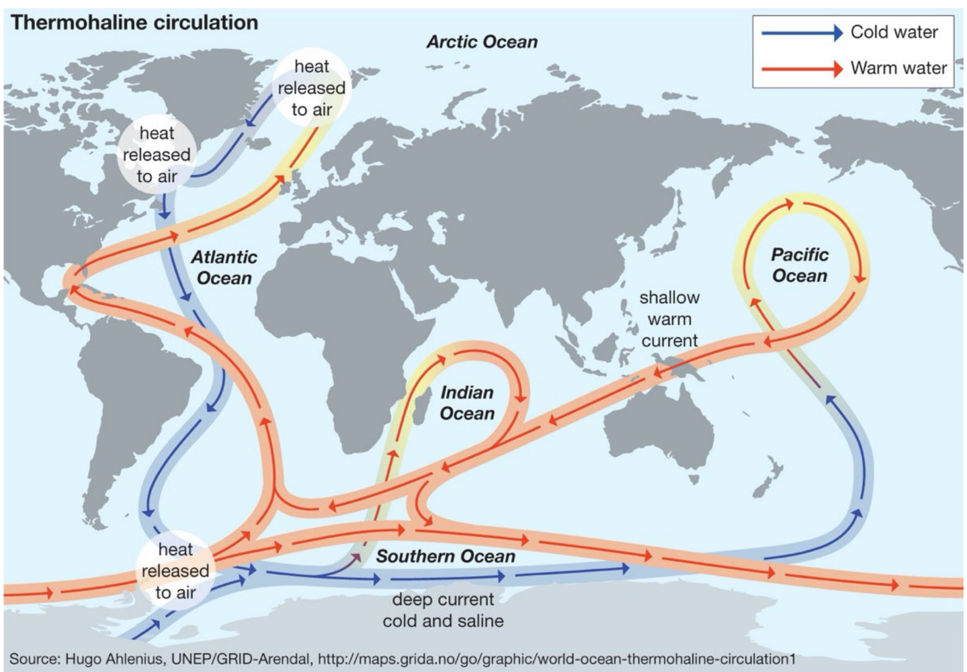

Figure 1. Circulation throughout the world's oceans due to changes in temperature and salinity, also known as the Ocean Conveyor Belt. Seawater exposed to cold temperatures at the poles sinks and later surfaces in the tropics where the sun's rays heat the surface water, flowing toward the poles, sinking as it goes. (Source: UNEP/GRID-Arendal)

3.0 OTEC Technologies

In a process analogous to a heat exchanger or heat pump operating on a commercial or residential property, OTEC works by exchanging heat between a working fluid and cooler water (Avery and Wu 1994). Specifically, the process consists of bringing deep cold ocean water to the surface and exchanging heat with the warm surface water.

3.1 Onshore and Offshore Plants

OTEC plants are designed as two major types: onshore and offshore. Onshore plants locate components including heat exchangers, turbines, and pumps on land, with the intake (warm surface and cold deep water) and discharge pipes running from the plant to the appropriate depths in the ocean. Construction of onshore plants follows that of other industrial facilities, with the intake and discharge pipes laid from shore through the intertidal areas (Avery and Wu 1994). Maintenance of onshore plants is simplified by their location and is treated as routine, as with other infrastructure (Coastal Response Research Center 2010b).

Offshore plants are mounted on a floating platform at sea with the infrastructure (heat exchangers, turbines, and necessary maintenance facilities) located onboard. The intake and discharge pipes are typically attached to the platform with a flexible attachment to manage movement of the platform and to allow for disconnecting from the platform during severe storms. The pumps for drawing water to the platform are most often mounted on the platform, but newer designs mount the cold water pump at the end of the pipe. Offshore platforms are designed to be moored to the seabed with a power export cable to shore (Coastal Response Research Center 2010b).

New offshore OTEC designs envision free-floating or motorized vessels that can be used to move the plant to different locations. These platforms could be deployed far from land and, rather than connecting to shore via an export cable, would likely produce electrofuels for export, such as ammonia and hydrogen (Lockheed Martin 2012). While maintenance of the platforms and OTEC systems should be minimal, maintenance crews would be deployed from land because the platforms are not likely to be crewed.

3.2 Open, Closed, and Hybrid Cycles

OTEC technologies exist as three major types: closed-cycle, open-cycle, and hybrids of the two. All types of systems are at a high technology readiness level, although there have been relatively few deployments worldwide. The individual components of the systems are all well-known engineering capabilities and have been deployed both on- and offshore for many years (OES 2021).

Closed-cycle OTEC systems use a working fluid with a low boiling point, most commonly ammonia. Although other working fluids are also used, many are toxic (e.g., hydrocarbons) or of environmental concern (e.g., chlorofluorohydrocarbons). The working fluid is heated to a gas by passing warm surface seawater through a heat exchanger, and is used to power an air turbine to produce electricity. Cold deep seawater is pumped through a second heat exchanger to condense the working fluid back to a liquid (Vega 1995; Avery and Wu 1994). The working fluid exists in a closed system and is reused throughout the life of the plant (Figure 2).

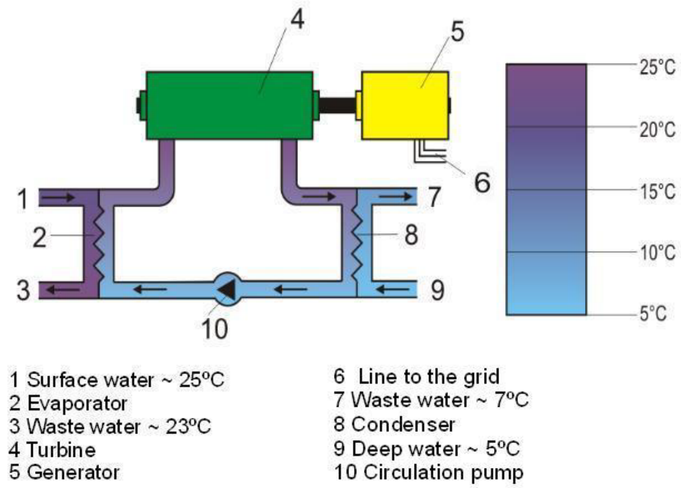

Figure 2. Diagram of a closed-cycle OTEC process. (Illustration from Kraftwerks, Germany, altered to include English notations)

Open-cycle OTEC plants use seawater directly, rather than a working fluid, to generate electricity. Warm surface water is placed under low pressure, distilling the water to a freshwater vapor that can be used to drive an electrical generator. The water vapor is condensed through heat exchangers with the cold deep ocean water, creating freshwater that is suitable for drinking and other uses (Vega 1995; Avery and Wu 1994) (Figure 3). There are alternate open-cycle processes that do not result in desalination as well.

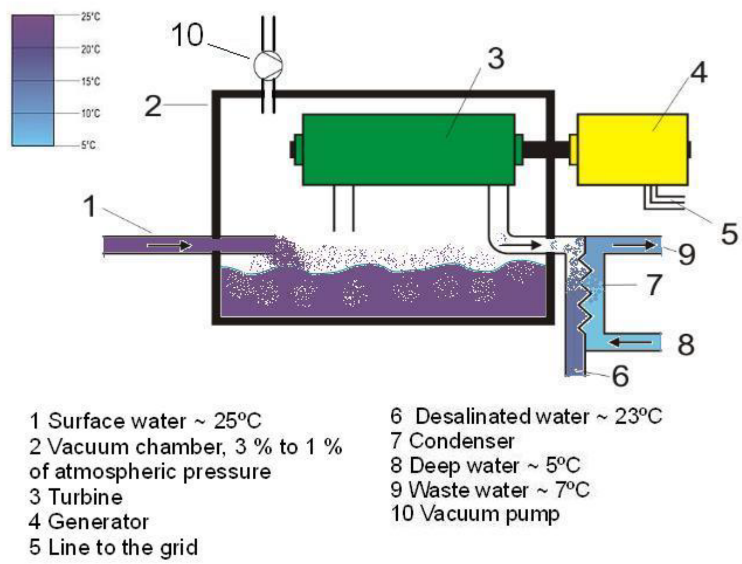

Figure 3. Diagram of an open-cycle OTEC process. (Illustration from Kraftwerks, Germany, altered to include English notations)

Hybrid OTEC systems combine the closed and open-cycle systems, with warm seawater evaporating to steam. The steam is used to heat the working fluid (ammonia) in a closed loop cycle, and is then cooled with the cold ocean water (Vega 1995). This type of system can also produce freshwater.

3.3 Ancillary Services

In addition to generating power from temperature gradients, OTEC processes that bring deep cold water to the surface can support a number of other ancillary services, including seawater air conditioning (SWAC), support for aquaculture power needs, and desalination (National Research Council 2013; Comfort et al. 2015), as well as the potential to produce ammonia or hydrogen at sea for transport as a liquid fuel.

SWAC provides cooling directly for facilities from cool ocean water. SWAC is a specialized case of using cold source water for pre-cooling that is carried out in many industrial uses in proximity to the ocean and other large bodies of water. The same deep pipes that provide cold water for OTEC can bring water to onshore or offshore facilities, augmenting or replacing electrically generated air conditioning (Figure 4) or for other pre-cooling uses (Kempener and Neumann 2014). For many tropical areas, particularly tourist resorts, air conditioning can account for up to half the electrical load. SWAC does not require as large a seawater temperature differential as OTEC, so SWAC can be used in many more coastal locations throughout the world, with shorter intake pipes, and much less infrastructure cost than OTEC, opening up temperate and even boreal regions to the use of SWAC and other pre-cooling capabilities.

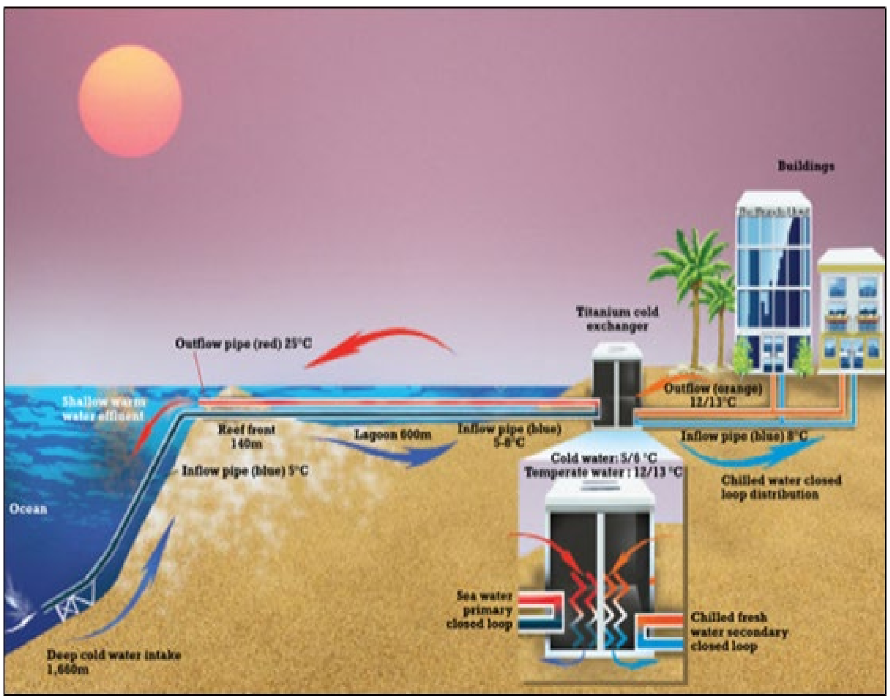

Figure 4. SWAC diagram showing intake of cool water, circulation through buildings, and return of warm water to the ocean. (Illustration from Kempener and Neumann 2014)

Open-cycle OTEC plants can be used to desalinate seawater to obtain potable freshwater, because the seawater is used as the heat exchange fluid. In most designs, a desalination plant is placed on top of the OTEC heat exchangers, and a portion of the condensed water is rerouted for further deionization through reverse osmosis filters. There is a practical limit to the size of closed-cycle plants (generally considered to be 5–10 MW) because the turbines greatly increase in size with the increased output, more so than with closed-cycle plants (Hunt et al. 2020). Thus, desalination of seawater in conjunction with OTEC is feasible at the small island or coastal scale but becomes less attractive at larger scales.

4.0 OTEC and SWAC Development Around the World

The history of OTEC development around the world started with deployments as early as the 1930s in Cuba, and the earliest SWAC deployments occurred in the 1980s in Canada and other nations. OTEC and SWAC deployments have continued to the present with pilot, demonstration, and very small commercial projects that have been deployed and/or are under development in many countries including the United States. Studies from a number of nations have underscored the viability, economic needs, and potential for baseload power (Asian Development Bank 2014). These projects include studies for OTEC in developing countries (Figure 5) and include areas such as:

- Nigeria in west Africa (Adesanya et al. 2020);
- Martinique in the Caribbean (Auvray et al. 2015);
- Columbia's Pacific and Caribbean Sea areas (Herrera et al. 2022; Osorio et al. 2016; Devis-Morales et al. 2014; Osorio et al. 2011);
- Mauritius in east Africa (Doorga et al. 2018);
- Malaysia (Fahmie et al. 2018);
- Pacific coast of Mexico (Garduño-Ruiz et al. 2021; Hernández-Fontes et al. 2020);
- Islands of Indonesia (Negara and Koto 2017; Koto 2016; Siahaya and Salam 2010);
- Kiribati in the south Pacific (Petterson and Kim 2020; Lee et al. 2016).

In addition, OTEC and SWAC planning and initial deployments have continued at a slow pace in developed countries including the Hawaiian Islands in the United States (Cross 2020; Havens et al. 2010; Nihous 2010).

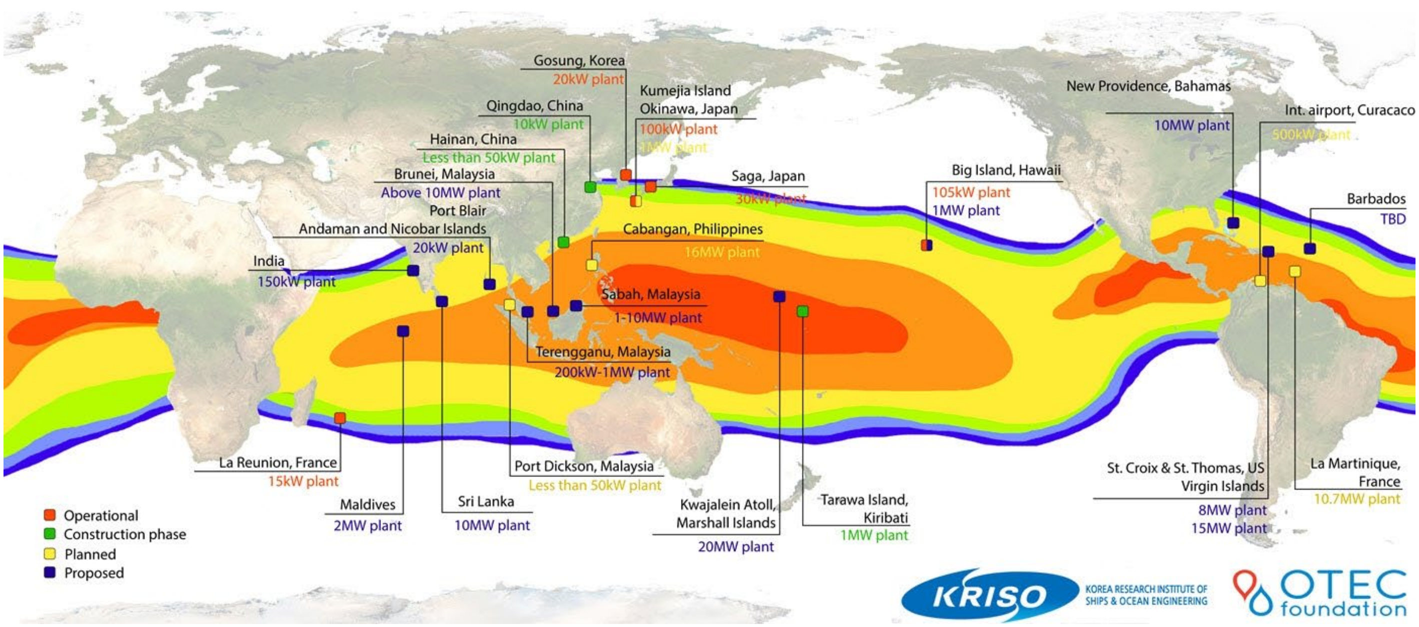

Figure 5. Some of the areas where OTEC plants are proposed or are under development. (Courtesy of KRISO, South Korea)

5.0 Potential Environmental Effects

Studies and environmental assessments for preliminary regulatory approval of OTEC plants have examined a range of potential environmental effects that include the following:

- changes in oceanographic conditions including thermal effects on organisms and water column stability in deep water (Hua et al. 2020; Jia et al. 2018; Giraud et al. 2019; Wang and Tabeta 2017; Jia et al. 2012; Grandelli et al. 2012; Comfort and Vega 2011);
- effects on oceanography and marine biota in shallow water (Oshimi et al. 2021);
- effects of noise from OTEC plants on marine life (Auvray et al. 2015);
- destruction of intertidal and shallow subtidal habitats (Harrison 1987);
- effects on macroalgae (Thorhaug and Marcus 1981);
- artificial reef effects (Chan et al. 2020);
- effects of OTEC system biofouling on marine biodiversity (Auvray et al. 2015);
- effects on ichthyoplankton (Hogan et al. 2013);
- effects on life stages of tropical fish (Yeakub 2021; Lamadrid-Rose and Boehlert 1988); and
- effects on fisheries (Myers et al. 1986).

In addition, some studies suggest potential environmentally conscious solutions for development of OTEC, including criteria for sustainable OTEC development (Zhang et al. 2019) and use of existing offshore structures for OTEC development (Zukifli et al. 2019)

The U.S. National Oceanic and Atmospheric Administration (NOAA) originally addressed the potential for OTEC development in the United States with an environmental impact assessment in 1981 (NOAA 1981). In 2010, NOAA's Coastal Response Research Center hosted a series of workshops on OTEC (e.g., Coastal Response Research Center 2010a, 2010b). Based on studies and papers written during a prior period of focus on OTEC in the 1970–1990s, the results of the NOAA workshops, and more recent literature, the research team assessed of the potential environmental effects of OTEC for both floating (offshore) and coastal (onshore) OTEC.

There are three potentially important environmental effects of OTEC, as well as some other speculative effects. Each effect needs to be examined in more depth, but none of them appear to be overly challenging and can most likely be avoided or mitigated. The three effects that need particular scrutiny are cold water return, entrainment of marine life in cold water pipes, and chemical discharges (detailed below). Other potential effects include effects on habitats, reefing, displacement, entanglement, and pathways for invasive species (Table 1).

The cold deep ocean water brought to the surface for heat exchange in the OTEC process must be returned to the ocean. However, this water could be up to 20^{o}C colder than ambient surface water, creating a thermal shock to organisms if discharged in the surface or shallow subsurface waters, and thereby potentially destabilizing the stratification of ocean water that maintains warm water at the surface (Giraud et al. 2019). To mitigate these effects, the cold water must be discharged at an intermediate depth (which can be determined by numerical modeling) in such a manner that it is rapidly diluted to match ambient water temperatures. Discharges of this type are used for wastewater and industrial discharges into the ocean and are regulated under the

National Pollutant Discharge Elimination System permitting process; designing these discharges is a well-established field of environmental engineering. The cold deep water will also contain higher levels of dissolved nutrients and lower levels of dissolved oxygen, which will also reach background levels in the subsurface ocean if the discharge is managed correctly.

Table 1. Framework for examining the potential environmental effects of OTEC development.

	Cold water return	Entrainment	Chemical discharges	Effects on habitats	Reefing	Displacement	Entanglement	Pathway for invasives
Offshore (floating) OTEC	Potential risk	Potential risk	Potential risk	Unlikely risk	Some possible risk	Some possible risk	Some possible risk	Some possible risk
Onshore OTEC	Potential risk	Potential risk	Potential risk	Potential risk	Some possible risk	Unlikely risk	Unlikely risk	Some possible risk

Potential risk | Some possible risk | Unlikely risk

The cold water pipe that pumps ocean water from 800–1000 m or more in most OTEC operations has the potential to entrain fish or other marine organisms, bringing them up to the surface where they are unlikely to survive the change in pressure. The presence of marine life in the deep sea is sparse because there is little food at these depths to sustain a complex food web. Evidence from the operational OTEC plant in Okinawa province in Japan over 8 years indicates that this event is very rare—less than one fish is seen a year (pers. comm. B. Martin). Similarly, evidence from the Natural Energy Laboratory of Hawaii Authority (NELHA) plant in Hawaii indicates that this event is so rare it has never been recorded. While regrettable that deep marine life might be lost, this event is certain to remain below detection in targeted monitoring programs. Special consideration would be given to threatened and endangered species that might come into contact with an OTEC platform or pipes.

OTEC platforms, particularly large plants at sea, will have some harmful chemicals on board, notably petroleum products for lubricating turbines (although biobased oils may be substituted). Closed-cycle OTEC systems use ammonia or other chemicals as the heat exchange medium. Leakage of these chemicals in gaseous form could be harmful to human and marine life. As part of any permitting process, a hazards analysis and a hazardous waste mitigation plan will be required. This plan will also address the potential loss of portions of the platform, moorings, pipes, and other hardware that might occur during a storm.

Other environmental effects that may be raised by stakeholders or regulators are likely to be manageable and can be informed by other development and offshore industries. These effects include the following:

- **Effects on habitats:** Cold and warm water pipes crossing coral and other valuable habitats for onshore OTEC plants may have an effect on intertidal habitats. Careful siting and mitigation will be needed.

- **Reefing:** Fish and other organisms may reef or congregate around an offshore floating OTEC plant and/or the intake pipes. However, it is difficult to find a pathway for harm to the organisms or the environment. Similarly, biofouling organisms will grow on all submerged parts of an OTEC plant. This becomes a maintenance issue to ensure that the growth does not impede operations and does not affect the surrounding environment.
- **Displacement:** Interference with migratory routes of marine mammals, sea turtles, and large fish may occur if many large floating OTEC plants are deployed in a key migratory pathway for marine organisms; some displacement could occur. Careful siting and spacing between the floating structures could assure sufficient room for the organisms to reach their intended habitats.
- **Entanglement:** Mooring lines from floating offshore OTEC plants, like those of floating offshore wind, wave, or tidal devices, have been postulated to pose risk of entanglement to large marine animals swimming nearby. To date there is no evidence of this risk; some additional studies may be needed around OTEC plants offshore.
- **Pathway for invasive species:** It has been postulated that the presence of offshore structures such as OTEC platforms, as well as the cold and warm water pipes, could provide a pathway for non-native invasive species to gain a foothold and enter a new environment. To date studies that have addressed this question have been unable to show that invasive species found on offshore structures were not already present in the area before the structures were deployed.

Each of these effects is evaluated qualitatively to provide an estimate of how they might play a role in permitting OTEC plants (Table 1).

6.0 Potential Social Concerns

Little information available in the literature documents or addresses societal concerns of OTEC development for onshore or offshore plants, partially due to the lack of deployments to date. Additionally, the experts interviewed had limited insight into potential concerns. For small islands, there is often sufficient interest in developing a secure, independent energy source that the local officials and the community are favorably disposed toward developing OTEC. Some residual issues may remain among community members where OTEC had been proposed in the past, particularly in Guam and Hawaii. The local experts with whom we discussed the likely community interest felt that the times had changed sufficiently and that OTEC technologies and the need for secure locally sourced renewable energy were likely to be met with more favorable community support than they had been in the past (pers. comms. R. Argall, L. Vega, B. Bentlage).

For island nations, U.S. and European tropical territories, and India, there was a general consensus among the experts that the need for power as well as SWAC and desalinated water as means to improve the lives and livelihoods of the people provides strong incentives to encourage local leaders and industrial partners to seriously consider investments in OTEC. In every case, the experts felt that overcoming the financial hurdles of high capital expenditures (CAPEX) seem to be more difficult than overcoming local opposition. Although there are few studies of the benefits or effects of OTEC on communities, anecdotally communities that have obtained OTEC plants with desalination systems have reported a significant increase in public health and individual well-being (pers. comm. P. Jalihal).

To date, discussions with local communities, as reported by the experts, have involved questions about the siting of the cold and warm water piping (for onshore plants) crossing the intertidal and shallow subtidal areas, because these areas are important economically to support fishing, aquaculture, and tourism. Careful siting of these infrastructure components in collaboration with local communities will be needed. Clearly, health and safety issues will need to be addressed as well, including the potential for release of ammonia or other toxic gases near communities from closed-cycle systems, potential leaks of other hazardous materials, and worker safety.

The potential for an OTEC plant to create conflicts with fisheries in the nearshore region will need to be investigated, although to date few documented issues have been raised.

7.0 Use Cases

Based on the current understanding of the readiness level of OTEC technologies for deployment, an exploration of use cases will allow further insight into how onshore and offshore OTEC plants might be established in U.S. waters. Four use cases were chosen to span the space of U.S. tropical and semi-tropical waters where OTEC is feasible, and to meet the variety of needs for power and ancillary services needed by different communities. All four use cases are island states (Hawaii) or territories (Puerto Rico, St. Croix, Guam). These cases are reasonably representative of the U.S. waters that have sufficient ocean temperature gradients to generate power.

Each use case is described, including the oceanographic setting, specific communities and needs that could be met by an OTEC plant, and the potential environmental and social concerns that would need to be addressed.

The settings, communities, ancillary benefits of the OTEC plant, and potential environmental and social concerns have many commonalities among the four use cases. These commonalities have been described in previous sections of this report, while the individual use cases focus on additional opportunities or challenges specific to each area.

7.1 Use Case 1: Puerto Rico

7.1.1 Setting and Description

Puerto Rico is a tropical U.S. island territory located in the Caribbean Sea due east of the island of Hispaniola (Figure 6). Running roughly east–west, Puerto Rico has a land mass of 8870 km^2 with a south-central ridge of mountains along the east–west line. Most of the coastline consists of beaches and fringing marshes sloping inland.

Figure 6. Map of Caribbean Islands, noting Puerto Rico (in red).

Puerto Rico lies south of a deep ocean trench and is highly seismically active. Depths up to 1000 m occur close to land off the western end of the island, and up to 2000 m off the southeast corner of the island (Figures 7 and 8).

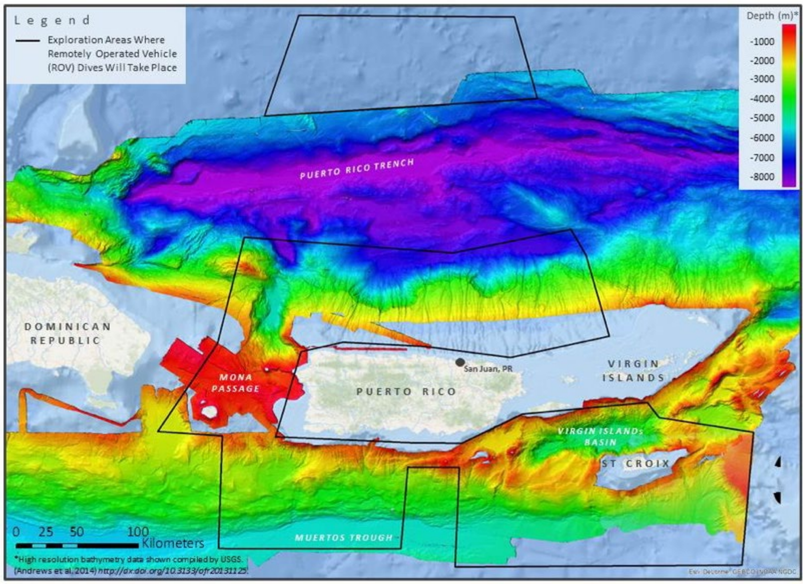

Figure 7. Bathymetry of the ocean in the vicinity of Puerto Rico and the U.S. Virgin Islands, mapped by the NOAA Ship Okeanos Explorer using remote operating vehicles during 2014. (Illustration from the NOAA Office of Ocean Exploration and Research)

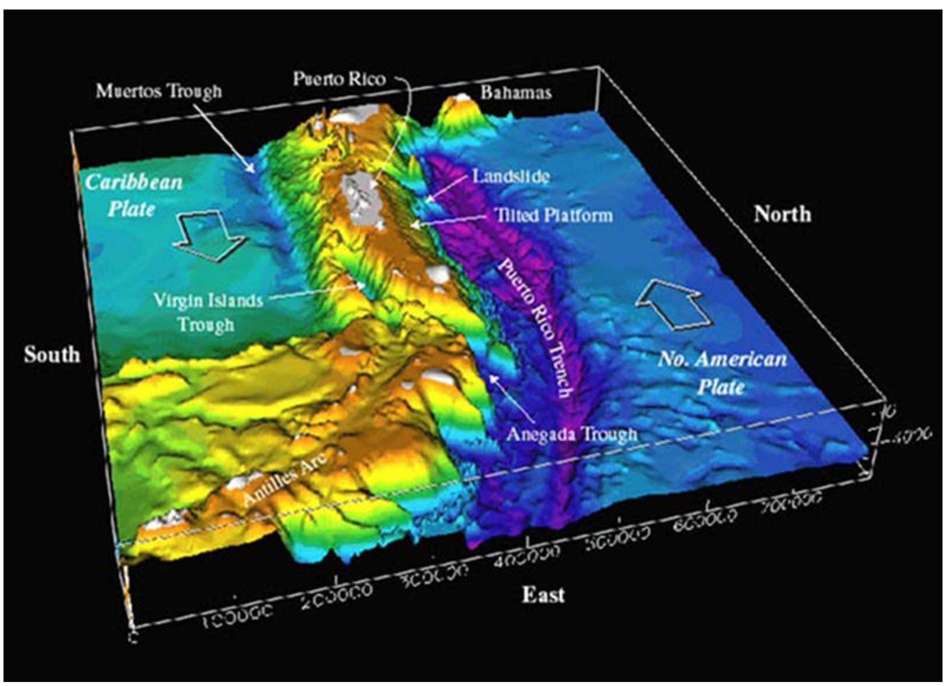

Figure 8. Detailed bathymetry of the Puerto Rico Trench. (Illustration from the United States Geological Survey)

Puerto Rico and two small islands to the east (Vieques and Culebra) support a population of approximately 3.2 million people. Power for the islands is dominated by oil and natural gas plants, with some hydroelectric energy supplied from mountainous areas. Peak power demand in Puerto Rico is estimated to be 3685 MW (U.S. Energy Administration 2021). In 2021, generation and delivery of power for residential and commercial use was taken over from the Puerto Rico Electric Power Authority by a private company (Luma Energy), after the destruction of most of the power grid by Hurricane Maria in 2017. That delivery company has also failed in recent months and responsibility for the generation and delivery of power has been taken back over by the Puerto Rican government.

7.1.2 Potential for OTEC

The optimal area for OTEC generation for Puerto Rico lies off the southeast corner of the island near the port of Puerto Yabucoa (Figure 9). Deep ocean water, approximately 1045 m in depth, lies several kilometers offshore. This and other locations were explored by the Puerto Rico Ocean Technology Complex (PROtech) that seeks to develop a maritime industrial park in the vicinity of Yabucoa (DEDC 2020). Several locations were considered, and Puerto Yabucoa was deemed the most practical. With the availability of seawater of greater than 20^{o}C difference from surface to depth, cold water pipes would run approximately 4.7 km to an onshore OTEC system.

This use case proposes the development of a 10 MW offshore closed-cycle OTEC plant. The plant is planned to provide 24/7 baseload power to support critical infrastructure after a major disaster and would be designed as a low profile hurricane-proofed installation. The Port of Yabucoa is considered critical infrastructure because almost all of the island's transportation fuels come through the port; until renewables can replace all conventional fuels, this port is critical to keeping the island running. The port power load is approximately 2 MW, allowing for additional power for disaster recovery from a 10 MW OTEC plant that could be brought online within hours of the cessation of a hurricane, assuming the pipes and cables remain intact.

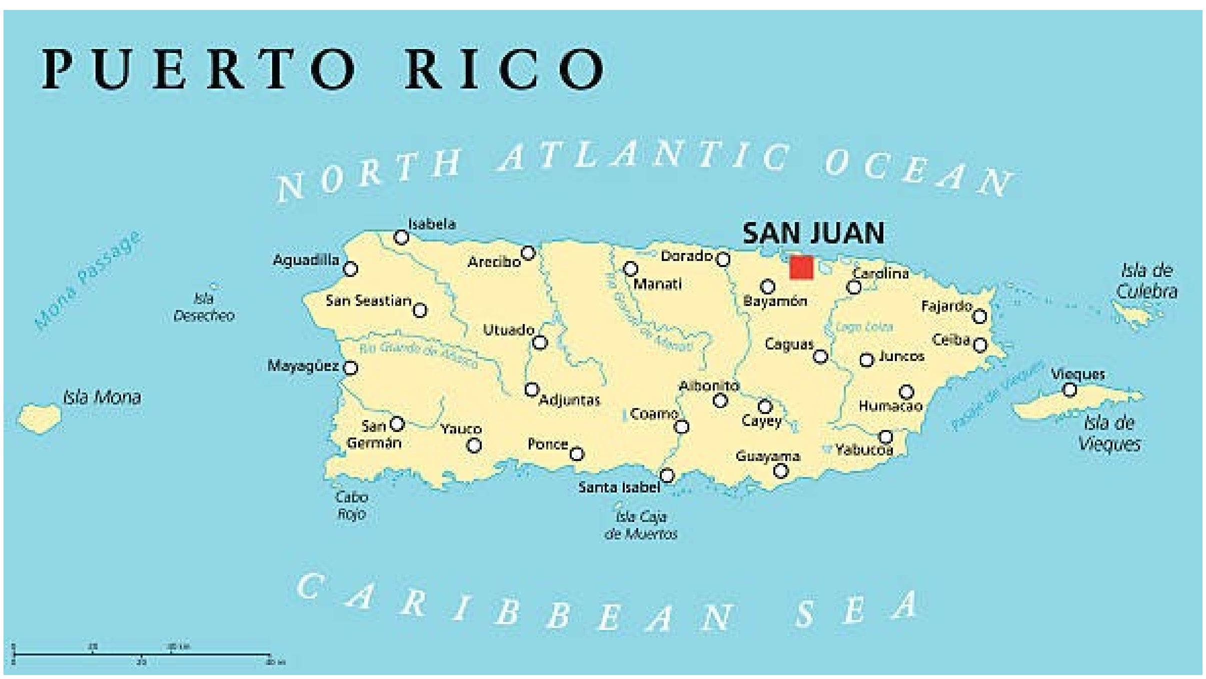

Figure 9. Map of Puerto Rico.

7.1.3 Ancillary Services

The cold deep water brought to the surface for OTEC will be used for cooling nearby industrial facilities and tourist resorts, before being returned to the ocean at the appropriate depth. Although many regions in Puerto Rico suffer from freshwater shortages, the need for power is greater and will drive this use case toward the larger more efficient closed-cycle system, rather than the open-cycle system with added desalination. However, after a natural disaster such as a major hurricane, there may be reason to consider a small desalination plant in conjunction with an open-cycle OTEC plant, to provide emergency amounts of potable water to hospitals and other high-risk institutions. Assuming the 10 MW offshore plant were developed, deep cold ocean water brought to the surface for OTEC would also become available for use in nearby aquaculture facilities, which are of great interest in that area of the island, including finfish growing, octopus and squid rearing, and potentially macroalgae for extraction of food processing chemicals and other industrial uses.

7.1.4 Potential Hazards

Puerto Rico lies in the hurricane zone of the Atlantic Ocean and is frequently hit directly by strong storms and hurricanes, and has suffered from the storm surge and high winds of those weather events that miss the island but move through the Caribbean. An onshore OTEC plant and intertidal piping (as well as any future proposed offshore floating plants) would have to be protected from high winds and waves. Seismic activity in the area would also have to be accounted for in any onshore plant.

7.1.5 Potential Environmental Effects

Construction of the shore-based plant and installation of the cold and warm water piping across the intertidal area has the potential to affect coastal, intertidal, and shallow subtidal species and habitats.

7.1.6 Community Benefits and Concerns

Puerto Rico has suffered from chronic power shortages and challenges associated with providing electricity to the residents. A combination of management and financial issues, and vulnerable grid infrastructure that has been destroyed or severely damaged by hurricanes, has left the island in need of reliable power sources and new energy generation that is less susceptible to damage and diesel supply chain issues. Investigation by a Puerto Rico government-directed study has indicated the potential for OTEC generation in conjunction with other industrial development, including aquaculture on the southeast corner of the island. Power and the ability to bring cooling and freshwater to the island residents is such an important need that to date there has been no clear indication that Puerto Rico residents would oppose such a development.

7.2 Use Case 2: St. Croix

7.2.1 Setting and Description

St. Croix is a tropical U.S. island territory located in the Caribbean Sea east of Puerto Rico, part of the U.S. Virgin Islands, within the Virgin Island archipelago (Figure 10). The eastern-most Virgin Islands include the U.S. Virgin Islands of St. Thomas, St. John, and St. Croix. Like Puerto Rico, St. Croix lies to the south of the Puerto Rico trench (Figures 7 and 8).

Figure 10. Map of the Caribbean Islands, noting St. Croix (in red).

St. Croix is 35 km long and 9 km wide and has a land mass of just over 200 km^2. The western end of the island is rocky and dry while the eastern end has lush growth. A single mountain peak rises 355 m. Like Puerto Rico, St. Croix is seismically active.

In 2010, the population of St. Croix was approximately 50,000 but has since shrunk to approximately 40,000. Electricity on St. Croix and the other U.S. Virgin Islands is generated from approximately 80 percent imported petroleum products with the other 20 percent from industrial and community solar. Peak power availability on St. Croix is approximately 100 MW, while demand is roughly 48 million kWh (U.S. Energy Administration 2021).

7.2.2 Potential for OTEC

Areas north of the town of Christiansted on the north shore of St. Croix are within 6–7 km of 1000 m deep water that is ideal for OTEC development (see map) within 2 km. Plans to develop OTEC and SWAC off St. Croix were put in place in 2016–2018 by the Ocean Thermal Energy Corporation to build a floating nearshore plant, but the development never occurred. Installation and maintenance could be partially handled from Gallows Bay, a small port in Christiansted that largely supports passenger service. Larger installation activities could be supported out of Krause Bay, a larger commercial port on the south coast, approximately 35 nm from Christiansted. The local jurisdiction for development is the Territory of the U.S. Virgin Islands, District of St. Croix.

This use case proposes the development of a land-based open-cycle 3 MW OTEC plant with the potential to upgrade to 5 MW, fitted with a desalination system.

7.2.3 Ancillary Services

The cold deep OTEC water could be used for SWAC in nearby resorts and houses as well as in aquaculture facilities found on land west of Christiansted.

7.2.4 Potential Hazards

St. Croix, like Puerto Rico, lies in the hurricane zone and has suffered direct hits from severe storms and hurricanes, as well as the storm surge and high winds of those that miss the island but move through the Caribbean. An onshore OTEC plant and intertidal piping (as well as any future proposed offshore floating plants) would have to be protected from high winds and waves. Seismic activity in the area would also have to be accounted for in any shore-based plant and offshore pipes. An offshore plant would be less susceptible to seismic activity.

7.2.5 Potential Environmental Effects

As in Puerto Rico, construction of a shore-based plant and installation of the cold and warm water piping across the intertidal area has the potential to affect coastal, intertidal, and shallow subtidal species and habitats. A floating plant would have a lower footprint on nearshore waters.

7.2.6 Community Benefits and Concerns

The St. Croix Legislature has strong renewable energy goals and strives to increase the share of locally generated power. In addition, St. Croix is a dry island, in need of potable water and freshwater for agriculture. Although no formal assessment of local community needs and concerns about OTEC has been carried out, there is reason to expect that the addition of renewables and desalinated water would be welcomed. Attention paid to community needs and careful siting of the intake and discharge pipes should alleviate most concerns.

7.3 Use Case 3: Hawaii

7.3.1 Setting and Description

The island of Hawaii (the Big Island) is a tropical U.S. state island located in the central basin of the Pacific Ocean. As the most remote island chain in the world, the islands are located approximately 4000 km from a continent, rising above the seafloor from depths of 4000–5000 m. The archipelago was formed as a hot spot in the Earth's crust burned through thin areas of oceanic crust, creating the buildup of magma, and eventually the Hawaiian island chain as the oceanic plate moved northeast. In addition to the seven well-known Hawaiian Islands, there are 125 older islands and atolls that make up the chain. The Big Island is the southern-most, youngest, and largest island in the archipelago, with a land mass of approximately 10,000 km^2 (Figure 11). Two major volcanic peaks dominate the island (Mauna Kea and Mauna Loa), rising more than 4200 m above sea level. The island is made up of volcanic rock, and the western and northern areas are predominantly dry while the eastern side of the island receives more precipitation, supporting jungle and wetlands. The interior of the island is made of a high plateau between the peaks of Mauna Loa and Mauna Kea, supporting agriculture and other uses.

Figure 11. Hawaiian island chain with the island of Hawaii (Big Island) on the lower right.

Deep water is found close to all the Hawaiian Islands, including depths of 2000–3000 m off the west coast of the Big Island (Figure 12).

The Big Island supports a population of almost 190,000 and has an average power demand of 400,000 MWh. Electrical generation and other power needs in the State of Hawaii are 80 percent from imported petroleum products, and wind, solar, and geothermal make up the rest (U.S. Energy Administration 2021). Big Island services are provided by the Hawaii Electric Light Company.

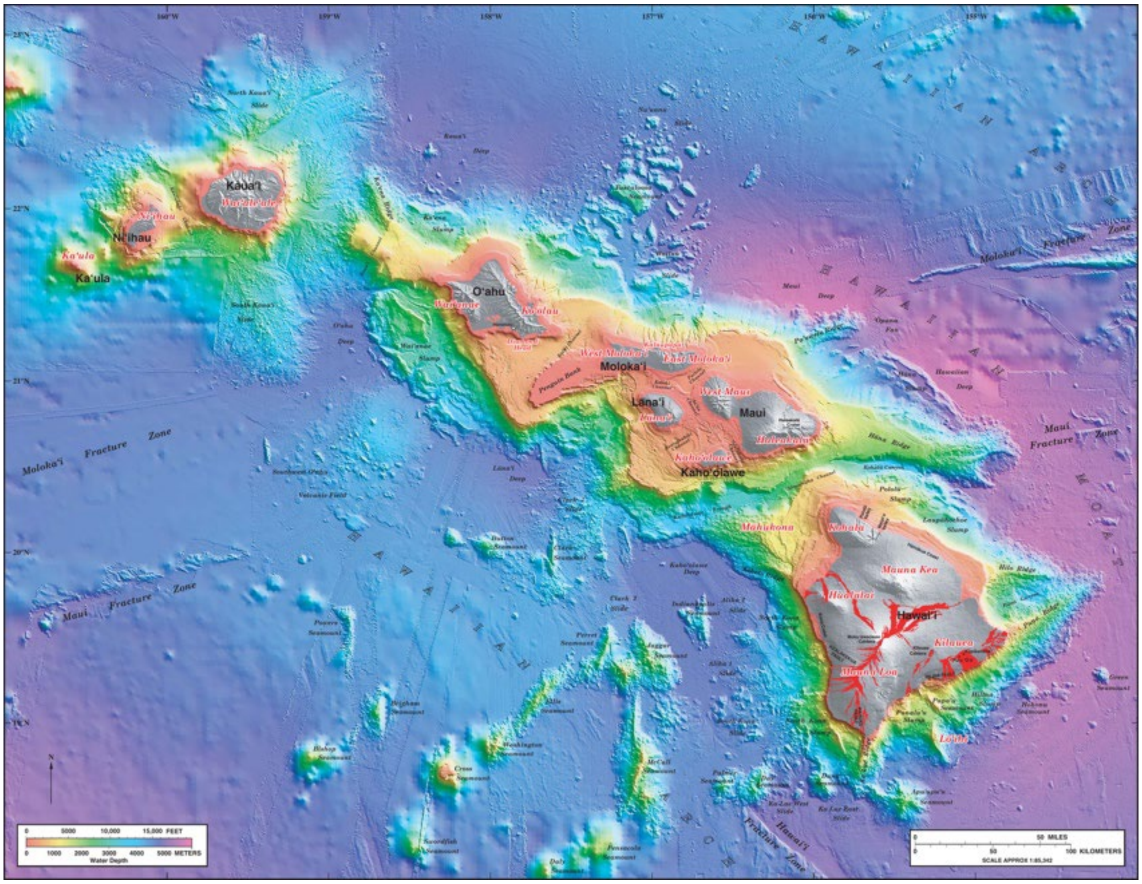

Figure 12. Bathymetric map of Hawaiian Islands.

7.3.2 Potential for OTEC

There are many potential areas on the Big Island (and other Hawaiian Islands) where OTEC might be developed. NELHA developed a pilot onshore OTEC plant within the Hawaii Ocean Science and Technology Park (HOST Park) in the Kailua-Kona district on the western shore of the Big Island, beginning in 1974. The plant was supported by NELHA through 1990. The plant continues to operate today under the guidance of Makai Engineering but does not generate electricity (Figure 13). The deep ocean water brought to the surface is instead used in nearby aquaculture and other industrial interactions as well as SWAC for the NELHA facility. The intake and discharge pipes for warm and cold water continue to function. The commercial port of Kawaihae is 37 km north of the NELHA site.

Figure 13. OTEC plant operating on the NELHA site, under management by Makai Engineering. (Courtesy of Renewable Energy World)

This use case proposes a 10 MW closed-cycle floating plant directly offshore of NELHA, using the same intake and discharge pipes.

7.3.3 Ancillary Services

This use case does not propose the addition of other uses, but expansion of the use of SWAC from the plant to nearby Kona resorts and communities could be achieved. Although portions of the Big Island are dry, there are significant precipitation patterns on the island to supply freshwater, so no seawater desalination is planned.

7.3.4 Potential Hazards

Hurricanes (generally called typhoons in the Pacific Ocean) are rare in the Hawaiian Islands, although more severe storms have been hitting the islands in recent years. The presence of active volcanoes on the younger Hawaiian Islands, particularly the Big Island, is a hazard that must be managed. Most active volcanic eruptions on the Big Island occur on the eastern and central portions of the island remote from Kailua-Kona, but all structures must be built to seismic specifications. The Hawaiian Islands are also at risk from tsunamis generated by sudden changes in seafloor elevation due to undersea seismic activity (earthquakes) that can originate as far away as Alaska and Japan. Portions of the Big Island have suffered immense damage and loss of life from tsunamis in the past, leading to a strong and sophisticated tsunami warning system and hazard management.

7.3.5 Potential Environmental Effects

The established intake and discharge pipes built by NELHA will relieve the need to construct new pipelines and infrastructure through the sensitive nearshore areas, although routine maintenance will still be needed in these areas. The floating plant should not cause additional risk to nearshore resources and is unlikely to adversely affect marine mammals or sea turtles that frequent the area. In addition to many fish species, these animals are likely to be attracted to the platform out of curiosity or for shelter, but no mechanism of harm is foreseen.

7.3.6 Community Benefits and Concerns

The presence of the NELHA site for many years on the Big Island is likely to pave the way for a small offshore plant with little community opposition. The local communities see NELHA (which addresses other renewables and research priorities at the site) as an asset and source of employment for the area. Similarly, it is unlikely that significant environmental concerns will be raised if the plant is sited and operated appropriately, because the most disruptive aspect of the development (installation of the intake and discharge pipes) has been in place for decades.

7.4 Use Case 4: Guam

7.4.1 Setting and Description

The island of Guam is a tropical U.S. territory located in the equatorial region of the north Pacific Ocean, within the group of islands identified as Micronesia (Figure 14). The island is the western-most territory of the U.S., and sits in a roughly southwest to northeast configuration; it has a length of 50 km, a width varying from 6 to 19 km, and a land mass of approximately 550 km^2. Guam is the southern-most island in the Mariana chain within Micronesia. The Marianas islands were formed by the Pacific plate moving westward and plunging beneath the Marianas plate, to form the Marianas Trench. The Marianas Trench is the deepest ocean trench—its Challenger Deep was surveyed as the deepest point on Earth at almost 11,000 m below sea level. The northern portion of Guam is made up of older volcanic rock, which has been covered with coral reef-created limestone as sea levels have fluctuated in the past, while the southern portion is made up of newer volcanic rock. The island is mountainous and its highest peak (Mount Lamlam) reaches 407 m above sea level. Significant seismic and hydrothermal activities are found throughout the island. The deep ocean around Guam brings water of 1000 m or deeper close to land (Figure 15).

Figure 14. Map of Pacific Islands, with Guam highlighted (in red). (Figure courtesy of Crow Canyon Journal)

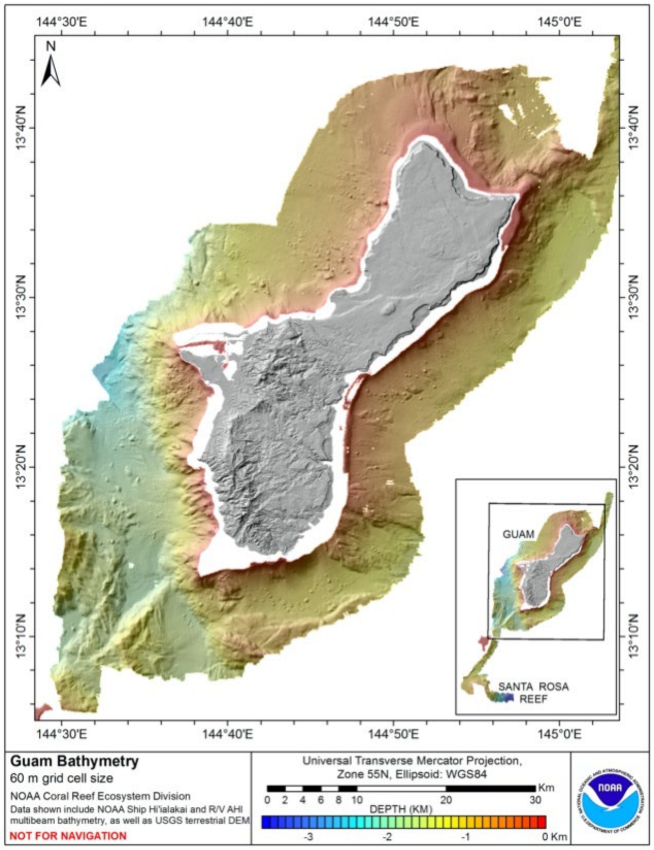

Figure 15. Bathymetric map of Guam, demonstrating the deep water close to shore, particularly along the eastern side of the island. (Illustration from NOAA Coral Reef Ecosystem Division)

The permanent population of Guam is approximately 168,000, with an additional 13,000 U.S. military personnel and their families. The Guam Power Authority delivers electricity to consumers and industry on the island, and most of the generation and fuels are derived from imported petroleum products, largely from Asia through the port of Apra. Until recently there was little renewable power on the island, though modest amounts of solar are finding their way into use. Electricity and fuel costs are typically two to three times the average U.S. prices. The power grid and reliability of delivery have been disrupted several times in recent years.

7.4.2 Potential for OTEC

OTEC was considered as a power source in Guam during the 1990s, but no serious proposal was put forward (pers. comm. T. Taitano). Its proximity to deep water, need for renewable and affordable local power, and significant U.S. military presence make Guam an obvious area for OTEC development. There are two potential favorable locations on Guam for siting an onshore closed-cycle 5 MW OTEC plant with the potential to upgrade to 10 MW or more:

- The closest deep water is directly off the west coast from Apra Harbor. Apra Harbor is a significant military and commercial port that could support installation and maintenance of an OTEC plant and has strong connection to the grid (Figure 16).
- Farther north on the island there is an existing marine laboratory and aquaculture center at Tanguisson, which would provide good access to the island grid.

A floating offshore plant in the vicinity of the harbor would also be reasonable.

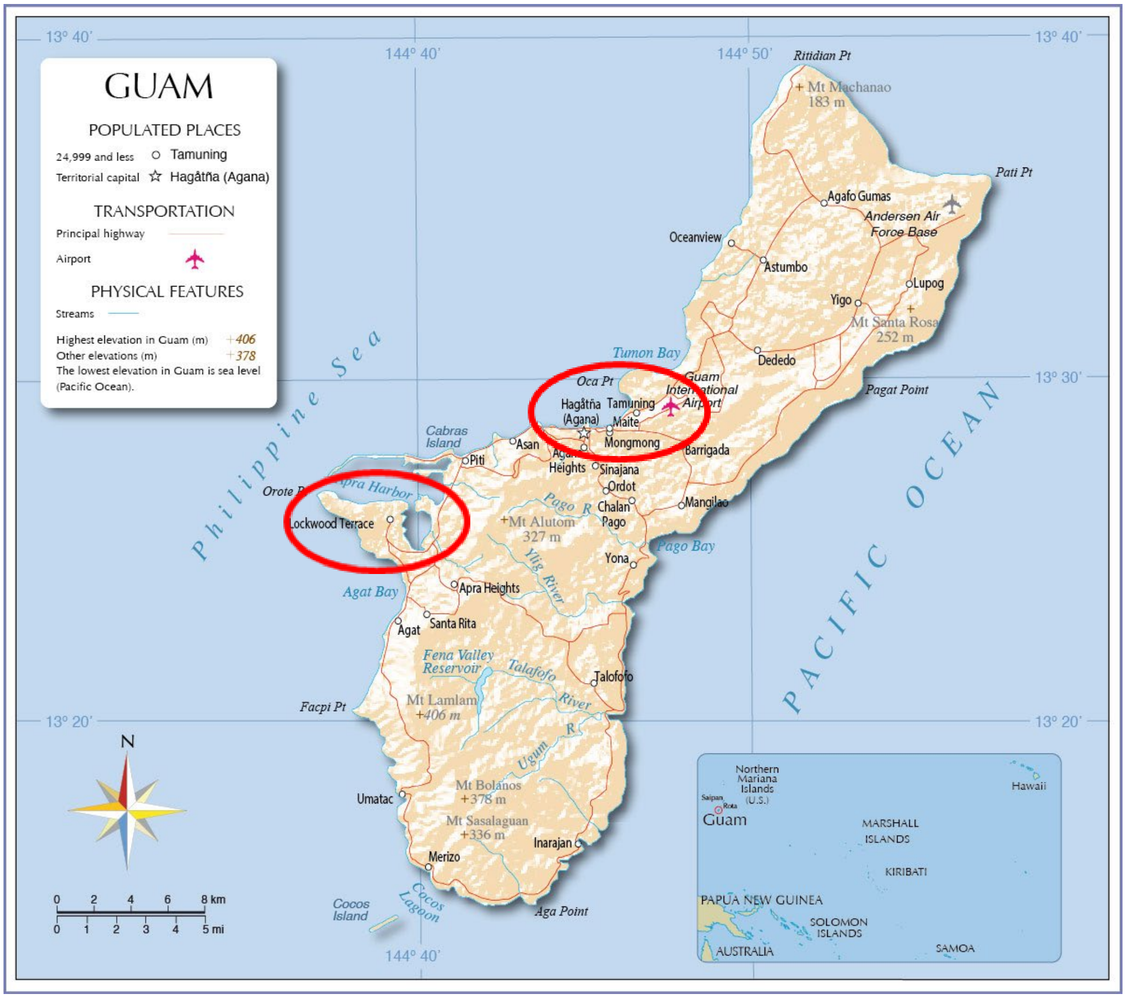

Figure 16. Map of Guam, showing Apra Harbor on the west (in red) and Tanguisson farther north (also in red). (Illustration from Nations Online Project)

7.4.3 Ancillary Services

SWAC has been examined for use on Guam's Naval Base, and was studied in 2006 and 2014 for use under a Guam Power Authority strategic plan, which estimated a potential reduction in the annual use of imported fossil fuels by more than 145,000 barrels (Guam Power Authority 2023). To date this plan has not been implemented. Under this use case, SWAC for residential, commercial, tourist, and military uses would be encouraged. In addition, there is interest in using the deep cold water associated with an OTEC plant to enhance and expand aquaculture resources on the island (pers. comm. T. Taitano).

7.4.4 Potential Hazards

Guam lies in the Pacific typhoon zone and is regularly hit by severe storms and typhoons, resulting in loss of property and life. The island is well prepared with requirements that power plants be constructed of concrete or prefabricated structures able to withstand 180 mph winds (APPA 2021) and by placing vital power transmission lines underground. To date, approximately

60 percent of the electrical system load is served through underground infrastructure. The island is also in a seismically active zone, and although earthquakes are infrequent, there is a strong correlation with tsunamis in the region because Guam lies at the southern end of the Marianas arc and at the edge of the Philippine Sea Plate.

7.4.5 Potential Environmental Effects

Construction of an onshore plant and installation of the cold and warm water piping across the intertidal area has the potential to affect coastal, intertidal, and shallow subtidal species and habitats. A floating plant would have a lower footprint on nearshore waters.

7.4.6 Community Benefits and Concerns

The strong need for lower-cost and renewable power is likely to help the community in Guam to embrace alternatives such as OTEC. However, the addition of a community-scale solar photovoltaic plant proved to be a disappointment to many residents who expected a much quicker retreat from fossil fuel use. This speaks to the need to address the expectations and concerns of the community carefully, working with local leaders. The potential to enhance the aquaculture industry may help to interest local residents. The U.S. Navy and Air Force should also be engaged to determine their interest in a pilot OTEC plant.

8.0 Education and Outreach Program

There is a general lack of available material that discusses OTEC, its benefits and potential effects, or interactions with local communities around OTEC plants (OES 2021). During discussions with the experts, the need for educational materials and outreach programs was strongly endorsed; most experts stated that the lack of familiarity with OTEC appears to hinder discussions and development in many areas. With little focus on what issues might be raised by local communities, financial backers, or supply chain companies, it appears that development of a general and focused outreach and education program about OTEC would be the most appropriate step toward socializing the idea of the technology, gaining acceptance, and understanding what additional information stakeholders might need. Such a program should include basic background material that will be useful for multiple audiences as well as more focused material that will be most needed and accessible for specific audiences. A process and need for such a program is laid out below.

8.1 Content Outline

A general broad education program would allow for the development of presentations tailored to different audiences. The major audiences that have an interest in OTEC for a particular region might include government officials, policymakers, financial markets, and local communities. In addition, there is a need to educate the broader public about this marine energy source, because OTEC plants in the United States and other nations will require broad public support to ensure funding is available.

By starting with a broad education program, specifics that pertain to certain audiences can be included and become the focus of public engagement, as needed. Overall, the content of a broad education program should include the sections outlined in Table 2. A slide deck that reflects these topics is included with this report.

Specifics that might be stressed for certain audiences, and where more in-depth content would be needed or could be tailored to a specific location, are presented in Table 3.

Table 2. Content of model OTEC education and outreach program.

What is OTEC?	Environmental Effects
• Ocean Thermal Energy Conversion • Thermal Gradient in the Oceans • Ocean Thermal Resources • Onshore and Offshore Plants • Open, Closed, and Hybrid Systems	• Overview of Potential Effects • Colder Waster Discharge • Entrainment of Marine Life • Chemical Discharges • Other Potential Effects
History of OTEC	**Potential Benefits and Concerns**
• Past Deployments (e.g., OTEC-1) • Operational Plans (e.g., Makai, Okinawa) • Planned Deployments (e.g., Kiribati)	• Contribution to Climate Change • Additional Products and Services • Siting and Community Involvement
	Remaining Challenges
	• Technical Barriers to Development • Financial Barriers to Development • Regulatory Barrier to Development

Table 3. Content specific to particular audiences with an interest in OTEC.

	Broad Public Audiences	Local Communities	Policymakers & Financial Markets	Government officials
Fundamentals of OTEC	x	x		x
Potential benefits and concerns	x	x	x	x
Contribution to climate change needs	x			
Costs of systems and power		x		
Siting		x		
Regulatory regimes				x
Employment and financial effects		x		
Supply chain issues			x	
Economics of OTEC			x	

8.2 Vehicles for Delivery

Delivery of an OTEC education and outreach program requires a multi-pronged approach—the most important aspect being the identification of the appropriate audiences in a given location. Relying on local experts to identify the interested audiences and individuals is key. In the United States, the local Sea Grant advisory (extension) agents are likely to have the best access into the various audiences. Local university faculty and staff may also be deeply engrained in the ocean community and know the local thought leaders and those who have the influence and ability to bring together appropriate groups.

Depending on the delivery venue (e.g., in person, online, in large groups or small), the outreach methods and educational vehicles must be made personal and local in order to best connect with the audiences.

In preparation for specific outreach activities, a portfolio of materials is needed, which should include:

- factsheets
- slide presentation (model presentation included with this report)
- webinar materials
- videos.

In addition to preparing for and meeting with local officials, communities, and parties interested in promising OTEC locations, it is important to educate them more broadly about the benefits, costs, and uses of OTEC. The Ocean Thermal Energy Association (OTEA; http://www.ocean-thermal.org) is an international group of experts, researchers, companies, and others with an interest in OTEC, and supply chain personnel. In addition to an annual symposium, OTEA holds local events and encourages knowledge sharing about the technology and its advancement. Participating with OTEA (as have the authors of this report) can help broaden U.S. knowledge and capabilities, and signal the willingness of the U.S. to become a player in OTEC globally. OTEA membership is also an excellent vehicle for getting education and outreach materials disseminated.

In addition, providing presentations and interacting with practitioners at OTEC-oriented, marine energy, and offshore renewables conferences and workshops can help spread accurate information about OTEC.

9.0 Next Steps in OTEC

This work on the feasibility of developing OTEC as a power source and for ancillary services has discovered:

- There is a huge interest in the United States and worldwide in furthering development of onshore and offshore OTEC, and experts in the field are eager to have the United States engage.
- There are a number of areas in the United States (as shown in the use cases) that could be developed for onshore or very nearshore OTEC, with clear offtakers of the power and consumers of the ancillary services that OTEC can bring, particularly SWAC and disaster recovery power and desalination. There is also clearly an appetite to explore and augment the use of OTEC with aquaculture in several areas.
- The OTEC technology is relatively simple compared to many of the more emerging marine energy devices and systems; it consists mainly of pipes, pumps, heat exchangers, and turbines, all of which are well known and widely used technologies.
- There is a sense among the experts interviewed that the time for OTEC to launch as a mainstream marine energy resource has come, based on pilot projects being pursued internationally, some clear cost savings in moorings and other components, and the added incentive of climate change mitigation (and perhaps carbon dioxide removal) coming to the forefront of government policy around the world.
- Several of the U.S. experts interviewed suggested a need for a U.S.-based group of interested parties from the industry, supply chain, and research community that could assist in the development of the technology through information exchange and by expressing their common interests.

Considerable work remains to be done to fully understand how these studies might lead the United States toward engagement in OTEC. This work is a simple introduction to some of the issues, the potential for OTEC in the United States, and the role OTEC might play worldwide.

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Appendix A – Experts Interviewed for OTEC Seedling

Expert	Affiliation	Topics of Discussion
Bastian Bentlage	Professor, University of Guam	Potential for OTEC in Guam and ancillary applications
Benjamin Martin	Facility Manager of Okinawa OTEC plant in Japan (Xenesys) and Secretary General of OTEA	Description of Okinawa OTEC plant and ancillary applications
Diego Acevedo	Eneda Engineering, Aruba and Combined Region OTEA delegate	Development of OTEC in Bonaire
Ghouri Bhuyan	Consultant (formerly BC Hydro) and Canadian OTEA delegate	History of OTEC technology development globally
Gregory Navarre, Hans Krock, and Chip Ellis	Energy Harvesting Systems (Navarre is U.S. OTEA delegate)	History of OTEC in U.S. and potential for floating systems
Hyeon-Ju Kim	Korea Research Institute of Ships and Ocean Engineering	History of OTEC research and development in Korea and outreach/education efforts
Jeremy Feakins and Patrick Lyden	Ocean Thermal Energy Corporation and Lobbyist	Background of Ocean Thermal Energy Corporation, political will, and industry needs
Lars Golmen	Norwegian Institute for Water Research, Norwegian OTEA delegate	Development of OTEC, multi-use platforms, and electrofuels
Manuel Rivera Laboy, Manuel Carretero Cannella, and Jesus Cintron River	Government of Puerto Rico	Development of OTEC in Puerto Rico, disaster resilience and recovery, and working with FEMA
Martin Brown	Ocean Energy Systems Limited, OTEA Vice Chair and UK delegate	Development of OTEC, OES white paper, and electrofuels
Nadia Fabina	CEO, Lumare Energi, Consultant, and OTEA Vice Chair	Development of OTEC in Small Island Developing States
C.B. Panchal and Luis Vega	E3Tec Services, LLC and University of Hawaii	Background of OTEC, technical feasibility, and lessons learned
Petter Terenius	Lancaster University	Finances of the OTEC and developing nations
Purnima Jalihal	National Institute of Ocean Technology and Indian OTEA delegate	Background of OTEC globally, Indian efforts at floating OTEC, and success in small dry islands
Robert Varley	Lockheed Martin	History of OTEC in U.S. and plans for large floating systems
Dan Grech	Global OTEC	History of OTEC globally, progress on developing San Tao and Principle OTEC, other projects
Thomas Plocek	Offshore Infrastructure Associates	History of OTEC globally, use in algal growth, St. Croix

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