PNNL- 37320

Feasibility of Multi-Use Ocean Thermal Energy Conversion (OTEC) Platforms

Final Report

June 2025

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U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
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Pacific Northwest National Laboratory
Richland, Washington 99354

Executive Summary

Tropical islands and coastal communities in the United States and internationally suffer from high energy costs, unreliable electrical supplies, poverty, and underemployment. Multi-use Ocean Thermal Energy Conversion (OTEC) systems could align with the goals and values of these underserved and remote communities as scalable platforms that can provide baseload power, freshwater, and food, as well as potentially support new industries. The cold, nutrient-rich deep seawater needed for OTEC's power cycles has many promising byproduct applications such as seawater air conditioning (SWAC) for residential and industrial cooling, enhancing aquaculture farms (e.g., cooling and nutrients for seaweed, shellfish, finfish), producing freshwater through desalination, and generating efuels such as ammonia and hydrogen.

OTEC generates power from the temperature differential between deep cold ocean water and warm surface water, through a heat exchange process. A minimum 20^{o}C temperature differential is needed for OTEC power to be generated. Deep ocean water worldwide ranges from 2-4^{o}C, restricting OTEC power generation to the tropical and subtropical areas.

With support from the U.S. Department of Energy's (DOE) Water Power Technologies Office (WPTO), the Pacific Northwest National Laboratory (PNNL) assessed the feasibility and design considerations for developing the first U.S. multi-use OTEC platform based upon the existing onshore OTEC system run by the Natural Energy Laboratory of Hawaii Authority (NELHA) in Kona, Hawaii. The project team examined the multiple uses of OTEC water by conducting an OTEC resource characterization around Kona, exploring design considerations for OTEC when paired with various additional uses, examining OTEC's potential environmental effects and modeling the cold water return, engaging with the local community to educate and gather feedback, and considering tradeoffs among multiple uses.

The outcomes of the analyses indicate that there is ample thermal differential between the warm surface water off Kona to operate an OTEC plant. The major environmental concern for the development of an OTEC plant revolves around the need to discharge the cold water to an appropriate depth after the OTEC heat exchange process. To address this need, a new open source OTEC discharge water model was developed and linked to the resource characterization model to demonstrate the depth and location where the discharge should be sited. The project team partnered with Hawaii Sea Grant to engage with community leaders and the public and trained a group of outreach and engagement professionals in the topic area and visited and engaged with many of the tenants and management of the NELHA site, gauging their knowledge, interest, and long-term vision for the existing (and possible future) OTEC plant at NELHA.

Following the analysis of each potential use of OTEC process water, the challenges of combining each use and the tradeoffs required were examined. The results show that there are several viable pathways to combine onshore OTEC power production with other uses, most notably SWAC and industrial cooling, including cooling for aquaculture operations in warm climates. Seawater desalination also shows promise in collaboration with open cycle OTEC power production. Other future uses that have promise for offshore OTEC power production include the extraction of critical minerals from seawater and production of efuels. The report

concludes with several recommendations for future work to address the most pressing data and information needs around OTEC development, as well as the project team's next steps.

Acknowledgments

The authors would like to acknowledge the assistance of Richard Angell and others at Makai Ocean Engineering and Neil Sims at Ocean Era, as well as the many proponents and experts around Ocean Thermal Energy Conversion globally for sharing their expertise and knowledge with us. We also thank the administration and tenants at the Natural Energy Laboratory of Hawaii Authority for sharing their experiences with us.

Acronyms and Abbreviations

AEP	Annual Energy Production
CFSv2	Coupled Forecast System Model version 2
CME	Critical mineral extraction
CMEMS	Copernicus Marine Environment Monitoring Service
COP	Construction and Operations Plan
DOE	U.S. Department of Energy
ENSO	El Niño-Southern Oscillation
HOST	Hawaii Ocean Science & Technology
LCOE	Levelized cost of energy
NCEP	National Center for Environmental Prediction
NELHA	Natural Energy Laboratory of Hawaii Authority
NOAA	National Oceanic and Atmospheric Administration
NPGO	North Pacific Gyre Oscillation
OES	Ocean Energy Systems
OTEC	Ocean Thermal Energy Conversion
PDO	Pacific Decadal Oscillation
PNNL	Pacific Northwest National Laboratory
RMSE	Root-Mean-Square-Error
SCHISM	Semi-implicit Cross-scale Hydroscience Integrated System
SST	Sea Surface Temperature
SWAC	Seawater air conditioning
WPTO	Water Power Technologies Office

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1.0 Introduction

Ocean Thermal Energy Conversion (OTEC) is a unique marine energy technology with a long history of development onshore and offshore (OES 2021). OTEC generates power from a heat exchange process using the temperature differential between warm tropical surface water and cold, deep ocean water. OTEC provides a more significant baseline power potential than any other offshore renewable technology. Pathways to widespread OTEC production indicate the potential to bring its levelized cost of energy down to levels that rival solar and wind energy on land, with 24/7 production (OES 2021).

OTEC is a low-efficiency heat exchange process (as compared to other thermal engines), with efficiencies ranging from 4.7% for open-cycle OTEC systems (Liu et al. 2020) to 6.7% for closed-cycle systems (Kim et al. 2006). These low efficiencies require the pumping of extremely large quantities of seawater from depth and a sizable plant, resulting in high capital costs for OTEC projects. These capital requirements have prevented OTEC from becoming established as a commercial energy source to date, with commercial-scale development of the first OTEC plants ranging from 500M USD to 800M USD (OES 2024). Recent estimates for the levelized cost of energy range from 0.94 USD $kW^{-1}hr$ to 0.50 USD $kW^{-1}hr$ for small onshore plants, while larger offshore plants are likely to be in the range of 0.44 to 0.18 USD $kW^{-1}hr$ (Vega 2010; IEA-OES 2024). OTEC's use of seawater and infrastructure allows for additional value streams that could help to reduce the cost of power generation and provide much needed services and products in the tropical islands and coastal regions where the process is viable.

With support from the U.S. Department of Energy's (DOE) Water Power Technologies Office (WPTO), Pacific Northwest National Laboratory (PNNL) explored the potential for incorporating other value streams with OTEC, assessed the tradeoffs of adding those additional products or services, and determined which combinations of uses are feasible for end users. A series of use cases were developed to examine the potential uses and tradeoffs.

The project focused on a theoretical OTEC plant placed at the site of the existing 100 kW onshore OTEC plant at the National Energy Laboratory of Hawaii Authority's (NELHA) Hawaii Ocean Science & Technology (HOST) Park, located north of Kona, Hawaii. The multiple uses of OTEC water were examined through a series of tasks:

- Conducting OTEC resource characterization around Kona (Section 2)
- Exploring design considerations for OTEC and additional uses (Section 3)
- Examining environmental effects and modeling the cold water return (Section 4)
- Engaging with the community to educate and gather input (Section 5)
- Considering tradeoffs among multiple uses (Section 6)

2.0 Resource Characterization

Under this task, PNNL developed a high-resolution numerical model to estimate the available OTEC resources offshore around Kona and validated the model with existing data. PNNL used the Semi-implicit Cross-scale Hydroscience Integrated System (SCHISM; Zhang et al. 2016) model to demonstrate the spatial and temporal variability of the thermal gradients in the area. This high-resolution numerical model can better resolve and highlight oceanographic patterns and hydrodynamics that may vary across locations and time, which cannot be found in lower-resolution models. Factors that need to be considered in siting and operating OTEC plants include the temperature differential between the warm surface water and the cold deep water, as well as the bathymetry of the region, atmospheric forcing, prevailing currents in the area, and the proximity of deep water to the coast.

2.1 Methods

SCHISM is a 3D baroclinic model that uses unstructured grids and advanced numerical methods to simulate ocean dynamics, such as temperature and salinity, incorporating atmospheric and tidal forces. The model's domain covers the west coast of the Big Island of Hawaii, extending to a depth of 4800 m (Figure 1). The computational grid has high horizontal and vertical resolution, adapted to the bathymetry without smoothing. This unsmoothed bathymetry ensures accurate representations of ocean dynamics and geographic details around potential OTEC locations. The model domain consists of 3,161 nodes and 6,133 elements, with a high-resolution of 350 m around the Kona coast, where potential deployment of OTEC plants may be considered.

Oceanographic data used in the model included tides, salinity, temperature, currents, and sea surface height, which are derived from Finite Element Solution (FES) 2014 tide model and Copernicus Marine Environment Monitoring Service (Lellouche et al 2018), while atmospheric data such as wind speed, atmospheric pressure and heat flux come from National Oceanic and Atmospheric Administration's (NOAA) National Center for Environmental Prediction (NCEP) Coupled Forecast System Model version 2 (CFSv2) (Saha et al. 2014). The model simulated ten years of temperature data (2012–2021) and considers climate variability (e.g., El Niño-Southern Oscillation [ENSO]) and its effect on the thermal gradient potential for OTEC power generation.

The results of the model were validated with vertical temperature and salinity profiles from Argo floats deployed in the vicinity, as well as satellite data. Additional details on the model configuration and validation methodology can be found in Park et al. (*in review*).

The available net OTEC power was calculated, considering the power needed for operation ("parasitic power") (Grandelli et al. 2012). The power was calculated for a 100 MW plant, with a turbogenerator efficiency of 0.75 (Du et al. 2022).

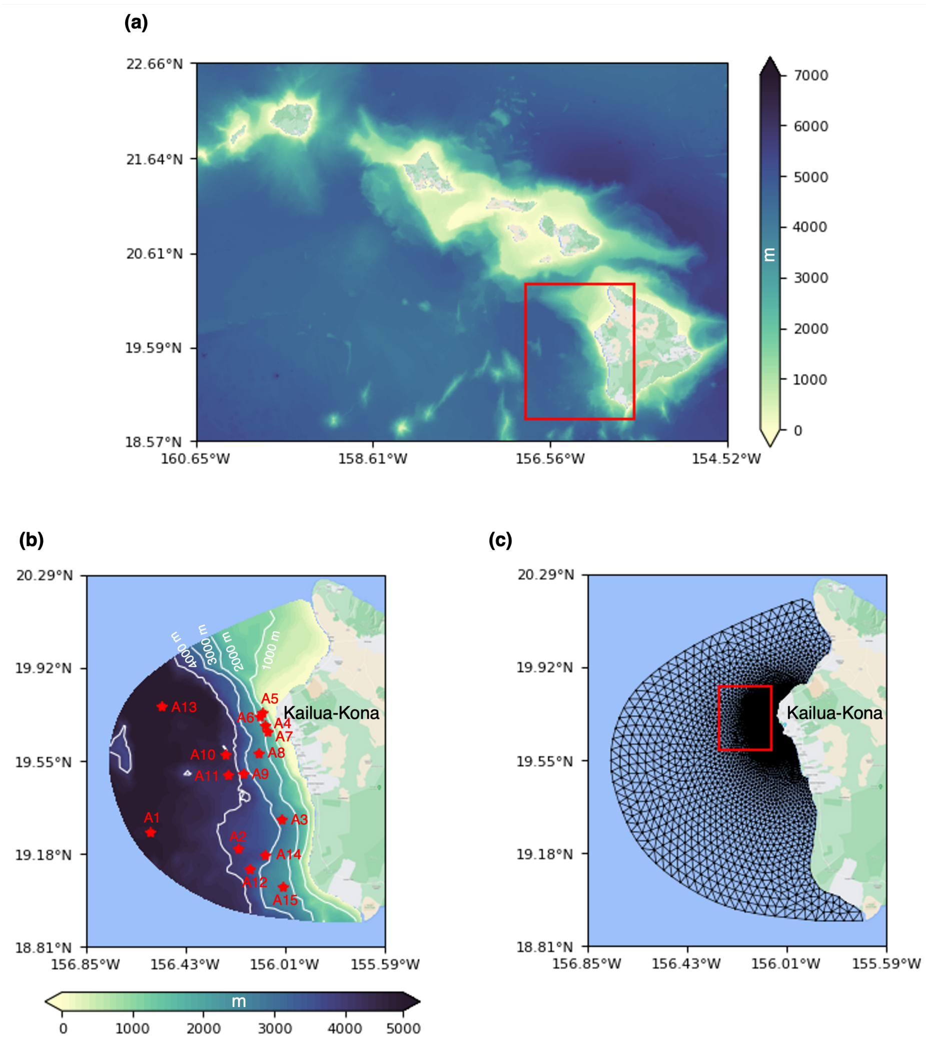

Figure 1. (a) Hawaii island archipelago; the red box indicates the targeted area for the model development. (b) View of the model domain around Kona, with interpolated bathymetry. The red stars indicate the locations of the Argo float observations used in Figure 2. The white lines represent the bathymetric contour lines from 1000 m to 4000 m. (c) The computational mesh; the red box indicates the area used to calculate the spatial-averaged sea surface temperature.

2.2 Results

The model validation showed good agreement with the Argo data for vertical profiles of temperature, with a mean Pearson correlation coefficient of R of 0.99, Root-Mean-Square-Error (RMSE) of 0.50ºC, and bias of -0.13ºC throughout different locations and times of the model runs. Similarly, the model results of predicted sea surface temperature (SST) were in close agreement with the satellite SST data (Figure 2).

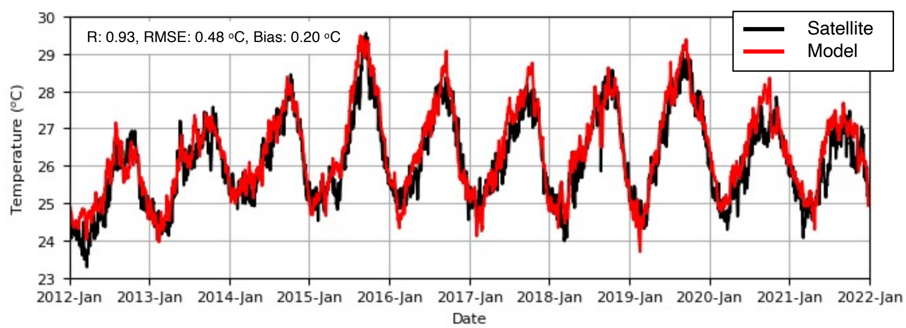

Figure 2. Seven-day running average spatial-mean sea surface temperature for the observation (black line) and model (red line) within the specific area indicated in Figure 1c.

The annual mean SST (Figure 3) highlights a noticeable increase from 25.4°C in 2012 to 26.84°C in 2015. Following 2015, SST values remained elevated, fluctuating between 26.46°C and 26.87°C until 2019, before decreasing to 26.19°C by 2021. These variations demonstrate considerable SST variability around Kailua-Kona across multiple time scales, influenced by local wind patterns and large-scale climate drivers such as the North Pacific Gyre Oscillation (NPGO), El Niño-Southern Oscillation (ENSO), and Pacific Decadal Oscillation (PDO; Gove et al. 2019).

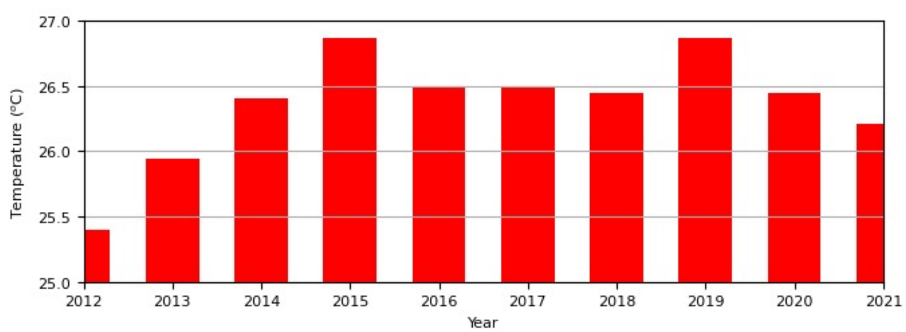

Figure 3. Annual mean sea surface temperature derived from the time-series data in Figure 2.

Figure 4 (a) shows the 10-year mean OTEC resources using temperature difference between surface waters (20 m depth) and deep water (1000 m depth). The OTEC resources are relatively low at depths less than 500 m and negligible near the coast. At depths greater than 500 m, there is a strong potential for OTEC generation, ranging from 100 MW to 140 MW. The probabilities of the mean net OTEC power exceeding 100 MW in Figure 4 (b) show that OTEC power over 100 MW could be generated more than 95% of the time during the 10-year period from 2012 to 2021. Using a 100 MW plant as an example, the Annual Energy Production (AEP) is estimated in Figure 4 (c). It is clear that there is ample OTEC resource with the maximum value of 1.2 TWh/year at depths greater than 500 m, as shown in Figure 4 (c). The AEP has the potential to power about 112,686 homes based on a yearly mean household electricity consumption of 10,649kW (Kilcher et al. 2021).

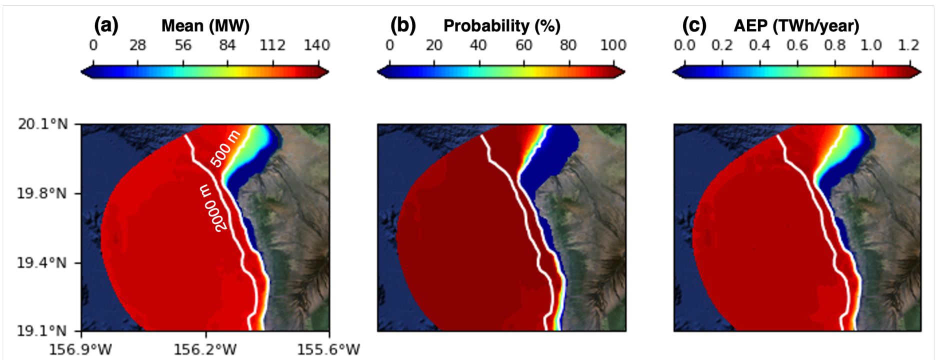

Figure 4. Mean power generated for a 100 MW OTEC plant including (a) the mean power; (b) the probability of exceeding 100 MW production; and (c) the annual energy production from a 100 MW OTEC operation.

Using a 100 MW OTEC plant as an example, there is some annual variation in the amount of power that can be produced from the available resource, as well as variation among years for the 10-year study period. An OTEC plant of a different capacity would yield different annual power. The temporal variations of the OTEC resource were evaluated at three specific locations (e.g., P1, P2, and P3) selected for their proximity to the coast (≤10 km) and a high probability (≥95%) of mean net OTEC power exceeding 100 MW, as shown in Figure 5.

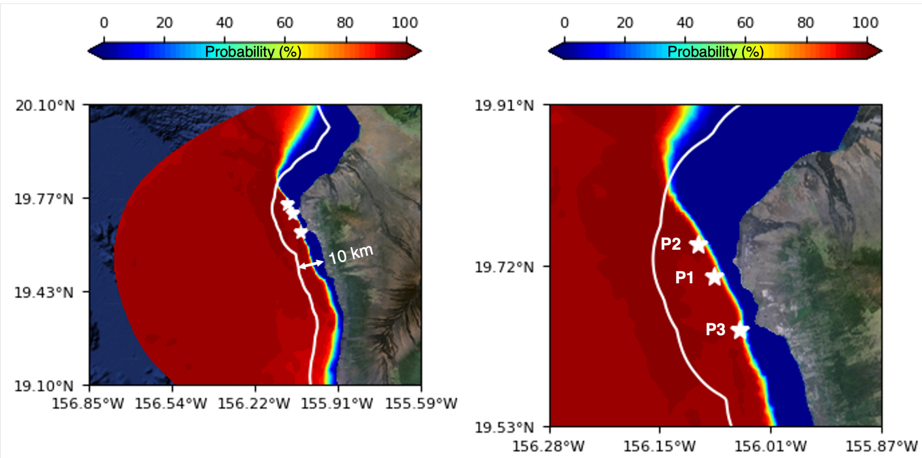

Figure 5. The three locations chosen for analysis, at two scales off the coast of Kona, with the white line indicating a 10 km distance off the coast.

Figure 6 presents the monthly climatology of net OTEC power at these locations, highlighting similar seasonal variations with peaks of 150 MW in September and lows of 112 MW in February. These seasonal fluctuations align with the energy demand of many small islands in tropical regions, making OTEC a promising renewable energy source. Figure 6 shows the annual variations of the AEP across the locations. The AEP ranges from 1.03 TWh in 2012 to 1.23 TWh in 2019, sufficient to power over 100,000 homes annually at a single site. The temporal variabilities in OTEC power are mainly driven by SST changes, as deep-water temperatures remain consistent. Therefore, the high AEPs in 2015 and 2019 can be attributed to the influence of heat flux, wind, and large-scale climate phenomena like NPGO, ENSO, and PDO (Gove et al. 2019), as they are the main drivers determining SSTs around Kona.

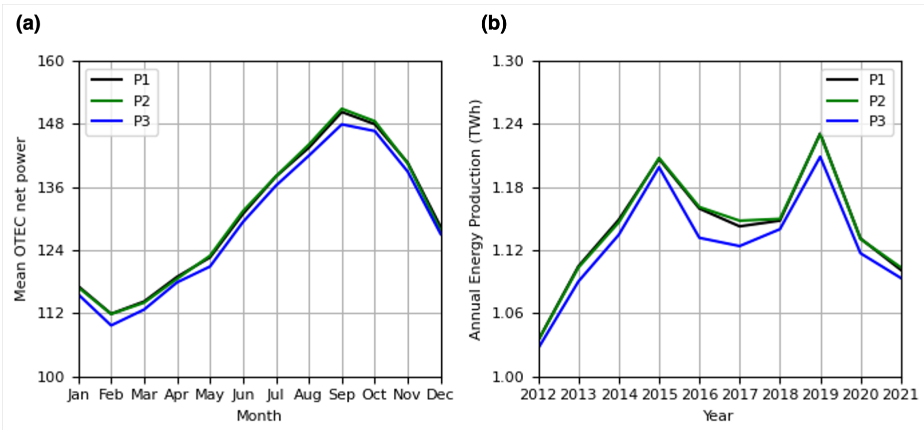

Figure 6. Panel (a) shows the mean net OTEC power production by month, with (b) showing the interannual variation in net power production.

3.0 Design Considerations

Developing an OTEC plant will require engineering design to meet power needs, as well as the physical footprint and specifics of an operational plant. Additional end uses of OTEC beyond power will require design changes, potentially including resizing of intake and discharge water pipes, changing the sequence of water intake and discharge, and redesign and resizing of the shore-based facility or floating platform. In addition, the specific additional end uses will require specialized design that interfaces with the OTEC plant, water piping, and other features.

3.1 Closed, Open, or Hybrid Cycle

OTEC technologies exist as three major types: closed cycle, open cycle, and hybrids of the two. All types of these OTEC systems are at or near high technology readiness level (TRL) 7, though many of the components (e.g., shallow water pipes, pumps, heat exchangers, and turbines) are closer to TRL 9 (Makai 2024). There have been relatively few deployments worldwide and no commercially developed plants worldwide. The individual components of the systems are all well-known engineering capabilities and have been deployed both onshore 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 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 7). Closed cycle OTEC plants are the most efficient as they the temperature differential derived from the use of lowboiling point working fluid.

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 8). There are alternate open-cycle processes that do not result in desalination as well. Open cycle OTEC plants, while less efficient,can be used to desalinate seawater.

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. Hybrid plants exhibit the benefits and challenges of the open and closed cycle plants.

3.2 Onshore v. Offshore OTEC Systems

OTEC systems can be designed as onshore systems, which pipe cold seawater from the deep and warm surface seawater to a plant onshore for processing, or as offshore systems that pipe seawater to a plant on a floating barge or vessel. Onshore systems are generally less expensive to stand up and maintain, as access from shore is simplified. However, reaching large scale OTEC generation will eventually require larger offshore OTEC plants.

Systems for OTEC power and other uses that are based on land rely on piping of cold deep water and warm near-surface water to shore through pipe laid along the seafloor to the appropriate depth. The water piped to shore is run through the OTEC plant, and other processes as appropriate, then returned to the ocean through a single mixed discharge or separate cold and warm water discharge pipes (Figure 7). The intricacies of each type of OTEC process (Rankin closed-cycle, open-cycle, hybrid design) will determine the design within the plant. For the purposes of this study, we have considered the OTEC plant to be a black box that is adapted appropriately.

Early pre-commercial and commercial OTEC systems are likely to be relatively small (~1-5MW) and are most likely to be placed onshore. These plants, in addition to supplying power, are conducive to adding seawater air conditioning (SWAC) including residential and industrial cooling, as well as desalination systems (using open-cycle OTEC), as these end uses are all required on land.

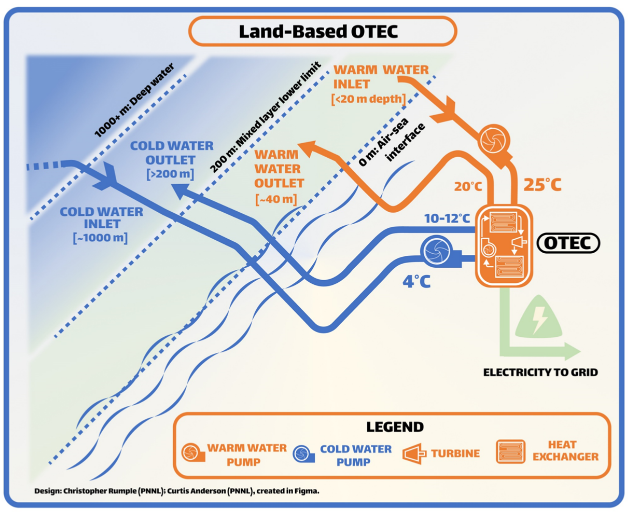

Figure 7. Onshore OTEC plant.

As commercial OTEC systems come online, they are more likely to move offshore, with larger power capacity (~10-100 MW) on floating platforms (Figure 8). Deep cold and surface warm process water will be taken up by pipes originating on the platform, as will combined or separate discharge water pipes. Power from floating OTEC platforms will be dispatched to land through export power cables. While cold seawater could be sent to shore through pipes for SWAC and other cooling, this use would entail considerable additional infrastructure and is less likely to be employed for cooling. Similarly, open-cycle OTEC plants offshore could be used for seawater desalination, but the common wisdom is that these plants will top out at about 5 MW due to the necessary increase in size of the turbines and other components over their closed-cycle counterparts. This scaling, coupled with the need to transport the freshwater to land, makes desalination offshore less appealing.

Offshore OTEC plants are likely to be most useful for power production, as well as large-scale industrial uses such as critical mineral extraction and efuel production. Each of these uses would require the addition of a plant fit-for-purpose to be added on to the OTEC processes on the floating platform and a means to offload the products, such as transport barges or ships. The critical mineral process is examined in more detail here, while the production of hydrogen or ammonia efuels is left as a future addition. As OTEC becomes a more established technology, there is potential for floating OTEC platforms to be deployed at great distances from shore, either free-floating or anchored to the seabed, with no export cable to shore. These floating platforms could provide power for production of efuels for shipping (perhaps even acting as power stations for refueling at sea), and power Onshore systems are generally less expensive to stand up and maintain, as access from shore is simplified. However, reaching large scale OTEC generation will eventually require larger offshore OTEC plants.

In addition to use of deep cold water and warm surface seawater for generating power, there is potential for using the cold deep water before or after it is applied to the OTEC process, as well as using the warm surface water after power generation.

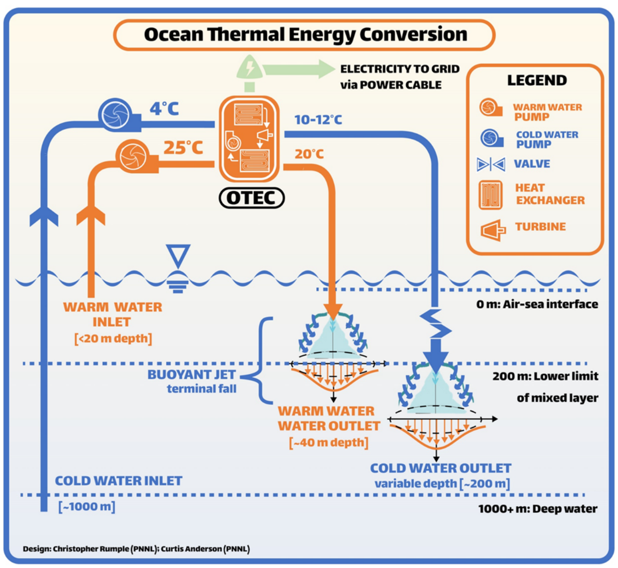

Figure 8. Offshore OTEC plant.

3.3 Potential Value-Added Uses for OTEC

Several additional uses for OTEC have been discussed among experts, with the most common being SWAC and other forms of seawater cooling, including industrial cooling and district cooling. Open-cycle OTEC plants can be outfitted with desalination plants to provide freshwater from seawater. In addition, the nutrient-rich deep ocean water could be used to enhance growth of micro- or macroalgae in aquaculture ponds or raceways, or used to fertilize the nutrient-poor surface waters of the tropics. Additional potential uses include generating ammonia or hydrogen for fuels and extracting critical minerals from seawater. Each potential use is explained in more detail.

Each additional use of OTEC water, as described in the introduction, requires a specific set of conditions for operation including the source and volume of water needed. Onshore systems are generally less expensive to stand up and maintain, as access from shore is simplified. However, reaching large scale OTEC generation will eventually require larger offshore OTEC plants. Which of these additional uses are practical as add-ons to OTEC power production and how each use might be operated in tandem with other uses is explained further, and the tradeoffs of energy production, additional infrastructure, and operational complexities are examined as part of the tradeoffs analysis later in this report. The uses of the seawater from an OTEC operation are described in Table 1.

Table 1. Summary of use of seawater to provide power and other uses associated with OTEC.

Value from seawater	Process	Cold deep water	Warm surface water	Comments
Power	Heat exchange between cold and warm ocean water	Pumped from depth	Pumped from near surface	
SWAC & district cooling	Circulating cold water through cooling units	Use of cold water after OTEC process, or portion of cold water for OTEC split before power generation	N/A	If cold water after OTEC is too warm to remove humidity, cold water can be taken before power generation
Desalination	Addition of open-cycle desalination plant to onshore OTEC plant	Use of condensed fluid from OTEC process chamber	Use of condensed fluid from OTEC process chamber	
Aquaculture support	Cooling of ponds and tanks	Use of cold water after OTEC process	N/A	
CME	Adsorption of critical minerals from seawater	N/A	Use of warm surface water after OTEC process	Periodic filling of contact tank, soaking, and emptying of tank
efuels	Addition of an efuels plant on the OTEC platform, using OTEC-generated power.	Electrolysis of seawater from cold or warm water after power production	Electrolysis of seawater from cold or warm water after power production	Future use

Note: CME = critical mineral extraction; N/A = not applicable; OTEC = Ocean Thermal Energy Conversion; SWAC = seawater air conditioning.

Designs of an OTEC plant that can accommodate power production and other uses must be viewed individually to determine the feasibility of construction, operation, maintenance, and resilience to harsh conditions and extreme events. While the detailed design of each iteration and the associated financial and hazard risk assessment is beyond the scope of this project, the initial design of each system has been prepared.

3.3.1 Seawater Air Conditioning (SWAC), Industrial Cooling, District Cooling

Deep cold ocean water can be used for cooling, in place of electricity. The temperature differential to achieve SWAC does not need to be as large as that for a functional OTEC system, potentially allowing the use of cold water brought from depth to be used prior to, or after, running the water through an OTEC heat exchange process. Typically, SWAC is used for residential use, or use in cooling industrial processes such as algal growth in tanks or raceways (industrial cooling), or in buildings and residences in clusters (district cooling). While cold seawater can be run through piping in buildings or residences, most commonly the deep cold water would be used in a heat exchange process at a central location, providing cooling for freshwater circulated through a building or tank (Figure 9). A SWAC plant, with or without OTEC in tandem, would be most useful for a shore-based plant, as piping the cold water from an offshore floating plant would add additional complexity and cost. SWAC can also be used to reduce humidity in buildings, much as a conventional air conditioning unit does.

Adding SWAC or other cooling to an OTEC system creates the challenge of rerouting cold water from the system, either before its use in OTEC power generation, or after power production but before discharge. Each of these options presents unique challenges. Rerouting cold deep water before power production decreases the amount of power that can be generated. Rerouting water after power production does not affect the power but requires additional piping. Also, if the post power production cold water is not sufficiently cold, it may be used for cooling but may be insufficient to reduce humidity—a key requirement for SWAC.

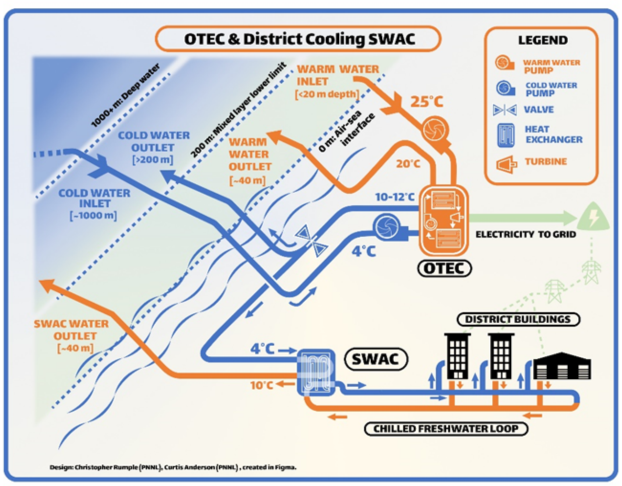

Figure 9. Onshore OTEC plant with SWAC for district and residential cooling.

The return of cold water to the ocean after SWAC or other cooling depends on the temperature of the discharge water, which determines the depth where the water must be returned. Additional details of the analysis of a buoyant jet for discharge can be found in 8.0 Appendix A.

3.3.2 Seawater Desalination

Dry tropical islands suffer significantly from lack of freshwater. Open-cycle OTEC plants (those that use seawater as the heat exchange medium) can be fitted with a desalination plant that uses the output from the OTEC condensation process. Open-cycle OTEC plants are less efficient than closed cycle, resulting in the need for larger turbines and heat exchangers to generate sufficient power and desalinated water. Although there is no theoretical maximum size to an open-cycle plant, the practicalities of turbine and heat exchanger sizes lead experts to believe that 5 MW is likely the largest open-cycle plant that can be designed and operated successfully. The amount of process water needed for an open-cycle plant is almost double the volume needed for a similarly rated closed-cycle plant.

Desalination is most likely to be associated with a shore-based OTEC plant to reduce the complexities of pumping freshwater to shore (Figure 10). However, on possible future large floating OTEC platforms that include crew, a plant could be fitted with an additional open-cycle operational plant to produce desalinated water for use onboard.

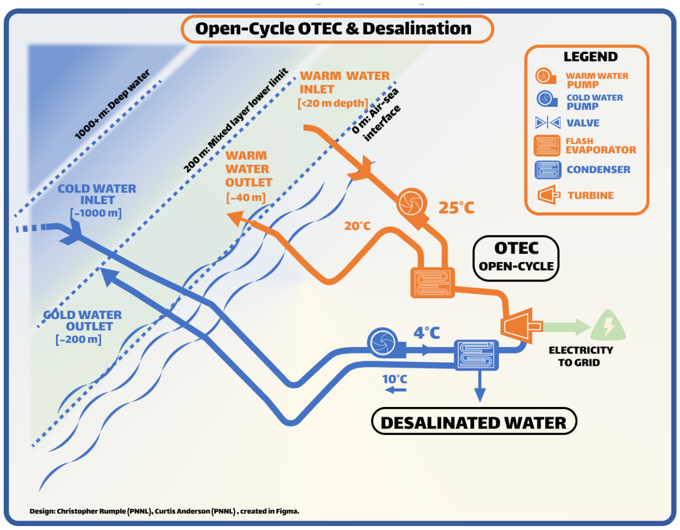

Figure 10. Onshore OTEC plant with SWAC for district and residential cooling.

The major challenges of adding a desalination plant to an onshore OTEC system is the need to increase the footprint of the site to accommodate the larger heat exchangers and turbines of an open-cycle OTEC system, the additional cost and maintenance complexity of adding a desalination plant, and the need for piping and other infrastructure to store and distribute the freshwater generated.

3.3.3 Use of Deep Ocean Water for Enhancing Algal Growth

Surface tropical waters are depleted of the essential nutrients for phytoplankton growth (due to lack of overturn of the water column that replenishes nutrients in temperate and polar areas). The deep ocean water that will be brought to the surface for exchange with warm surface waters for OTEC are rich in the essential dissolved nutrients, including nitrate, nitrite, phosphate, silicate, as well as organic and inorganic micronutrients. At first glance, this appears to be an excellent opportunity for enhancement of phytoplankton (microalgae) and seaweed (macroalgae) growth in aquaculture ponds or raceways. However, the carbon load in deep seawater may present a significant barrier to this use. There are two options for using the deep-water nutrients for algal growth: 1) ensuring that the deep water is never exposed to the atmosphere, but discharged directly after the nutrients have been taken up by the micro- or macroalgae; or 2) scrubbing the carbon after the use of the nutrients for algal aquaculture. The former is not very practical as most micro- and macro-algal cultures are carried out in open ponds, tanks, or raceways. Capturing the carbon from the free surfaces would be a huge expensive lift. The second method, carbon scrubbing, may be feasible technically, but at great cost. An investigation into these methods can be found in Appendix B.

Based on the experience of tenants at NELHA, the deep cold ocean water plays a critical role in cooling aquaculture ponds, raceways, and tanks, allowing onshore aquaculture of microalgae, macroalgae, and larval shellfish to thrive in hot tropical areas (Figure 11).

The major challenge to using cold deep water for cooling is covered in Section 3.3.1 on SWAC.

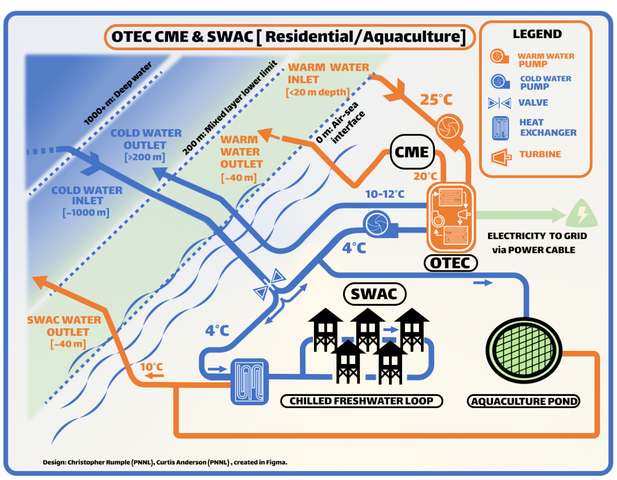

Figure 11. Onshore OTEC plant with cooling of aquaculture ponds, as well as residential cooling.

3.3.4 EFuels

As offshore OTEC plants become established, the power generated could be used to create green hydrogen by electrolysis from seawater for storage and transport by specialized vessels. Adding a nitrogen plant to the platform would allow the generation of ammonia (with N_2 separated from the air) as a hydrogen carrier (Figure 12); specialized ammonia transport vessels are already in use around the world.

The major challenges of adding an efuel plant to an offshore OTEC platform include the complexity of storing and using the OTEC-generated electricity at sea, the cost and complexity of operating and maintaining an efuel plant, as well as storing and transporting the efuel as ammonia or hydrogen with the associated docking and lightering facilities on the platform for ships.

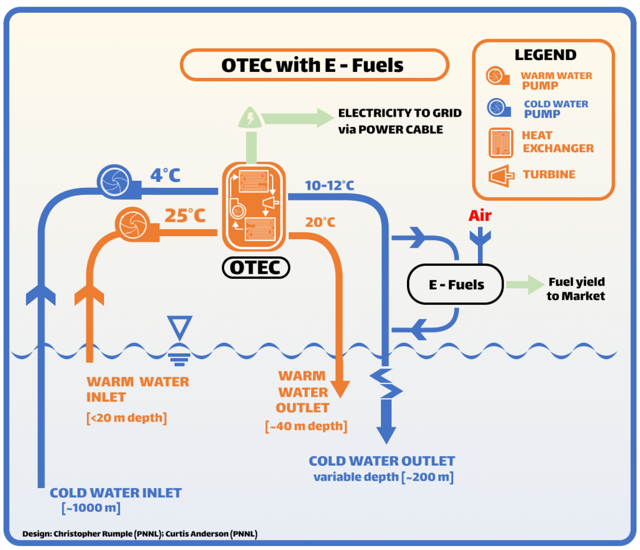

Figure 12.Schematic of adding an efuels generation plant to an offshore OTEC platform. Developing this use will require docking or lightering facilities for ships to transport the efuels.

3.3.5 Critical Mineral Extraction

All metals and earth minerals found on land are present in the ocean, dissolved in seawater in dilute forms. Mining these elements from seawater requires the movement of large volumes of seawater, which has made their recovery prohibitively expensive in terms of energy using current technology. However, the large volumes of seawater moved as part of OTEC processes could help to initiate critical mineral recovery, using efficient, cost-effective absorbents that scavenge specific elements. Recovering critical elements from seawater could alleviate concerns for shortages and politically sensitive mining on land, as well as avoid significant concerns over seabed mining.

Extracting critical minerals from seawater on an OTEC platform at sea will require the addition of an exposure tank to hold the adsorbent material, pipes and pumping to divert volumes of warm water after OTEC power production into the exposure tank, infrastuture to also pump and pipe the water from the exposure tank to the discharge pipes, as well as all the engineering structures and processes to wash the adsorbed minerals from the material and refurbish the adsorbent for the next round of extraction (Figure 13).

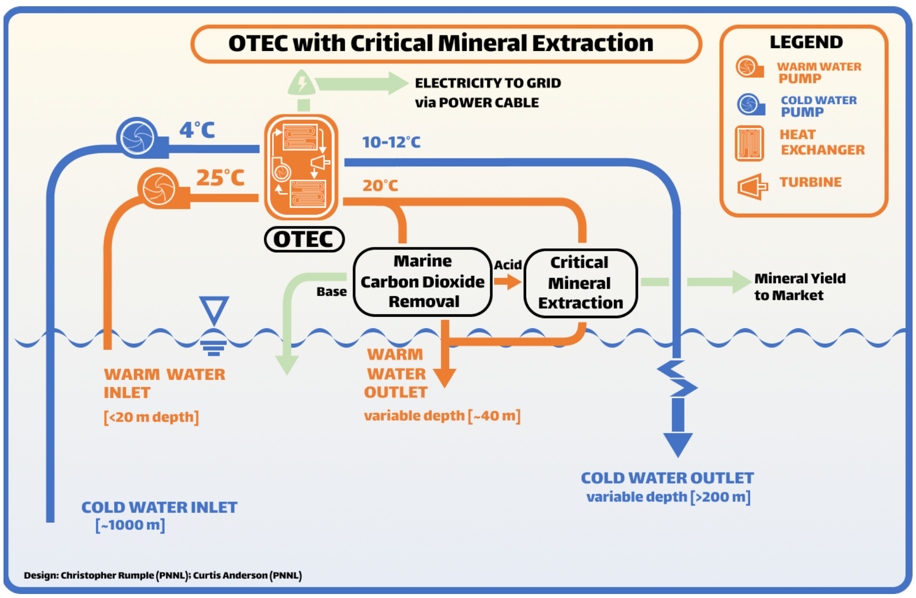

Figure 13. OTEC platform with critical mineral extraction contact chamber. The potential for adding marine carbon dioxide removal (mCDR) is also pictured in this figure although additional analysis was not carried out for this use.

4.0 Environmental Effects & Permitting

Under this task, PNNL explored the evolving regulatory landscape around OTEC and examined data and information on baseline assessments, monitoring, and potential mitigation needed to permit and lease a multi-use OTEC platform in U.S. waters. PNNL also created an open-source model of the cold water return and simulated a cold-water return plume from a theoretical plant in Kailua-Kona, Hawaii.

There is presently no permitting process for OTEC in the U.S. The 1980 Ocean Thermal Energy Conversion Act granted regulatory authority for OTEC to NOAA and allowed for research sites for OTEC to proceed without a license. Regulations under the Act were developed in 1981 as "Licensing of Ocean Thermal Energy Conversion Facilities and Plantships" (Federal Register 1981). These regulations were rescinded as part of the Paperwork Reduction Act of 1995. Since then, there has been no regulatory authority to permit and license OTEC in the U.S. NOAA's Office of Coastal Management currently examines OTEC and SWAC applications as they are presented under (Pers. Comm. K. Kehoe, NOAA). Responsibility for licensing the connection to the national grid will lie with the Federal Energy Regulatory Commission once commercial applications are received (DOE 2023).

Due to the lack of regulation and few applications for OTEC and SWAC in the U.S., there is little record of the environmental effects that are most likely to affect permitting and licensing. In addition, with few operational OTEC plants around the world, and no commercial scale plants, there have been relatively few assessments of potential environmental effects. In 2010, a NOAA-sponsored study summarized the available literature, hosted a workshop, and identified a range of potential environmental issues that might arise from the installation and operation of an OTEC plant (CCRC 2010). These effects have generally not been examined and most are thought to be unlikely outcomes and/or only potentially manifest at very large-scale OTEC development. As documented in a previous PNNL-led project (Copping and Farr 2023), the potential effects that should be considered for small-scale OTEC development, both onshore and offshore, revolve around the cold water return, entrainment of deep-sea biota, and chemical releases in the air and water due to the operation of the plant.

4.1 Cold Water Return

The volume of cold deep seawater that is brought to the surface for OTEC processes exceeds that of the warm water used for heat exchange by a ratio of approximately 2 to 1. The process water must be returned to the ocean after the heat exchange process: the cold deep water is likely to be in the order of 6-10^{o}C warmer than at the start of the process, and the warm water cooler by 3-5^{o}C. The process water can be returned separately or as a combined return. It is essential that the water returned to the ocean is not substantially different in temperature and density to the receiving water as to cause either temperature shock to organisms living in the ocean, or to cause localized instability in the water column (Comfort and Vega 2011; Rajagopalan and Nihous 2013; Giraud et al. 2019). The temperature of the warm water after OTEC processing is not very different from ambient water, while the cold water return differs significantly.

To avoid environmental concerns, the cold water return (mixed with the returning warm water) should be discharged at an intermediate depth where the density of organisms is lower than in near-surface waters, and the water will sink to reach a constant density with the ambient water. This depth is generally considered below the seasonal thermocline (50-100 m in most tropical locations) but perhaps above the permanent thermocline (200+ m). To assist in determining the appropriate discharge depth for a mixture of cold and warm water, a numerical model was used to study the potential effects of the cold water return on the ambient ocean environment.

Previous modeling efforts that have examined discharge depths for OTEC plants in Martinique (Giraud et al. 2019) and Hawaii (Grandelli et al. 2012) suggest cold water discharge depths between 70 m and 500 m. Accounting for ambient light levels and the mixed layer depth off Kona, the preferred depth falls between 90 m and 115 m (Comfort and Vega 2011). This study uses a depth of 100 m.

Potential changes in the local water column could result from the introduction of discharge water from OTEC plants that is colder than the ambient temperature. These changes will depend on the quantity of water discharged, which is determined by the size of the OTEC plant. For the purposes of this study, three 100 MW OTEC plants were considered with three separate discharge pipes, all at depths of 100 m (Figure 5). The cumulative discharge from these three plants is much larger than is anticipated for the Kona area, or other tropical islands. The larger plants used in this analysis were chosen to ensure that a change in the oceanography could be noted.

The combined discharge volume of warm and cold water after the OTEC process for each of the three 100 MW plants is expected to consist of water that is approximately 10^oC, at the ambient receiving water salinity, and discharged at a constant rate of 300 m^3/s (Figure 5).

The discharge from the three pipes at 100 m depth will allow the discharge water (at 10^oC) to sink and disperse to the depth where the density meets ambient water. Figure 14 shows the differential in temperature of water (cold water return scenarios minus baseline condition) found at five different depths, due to the addition of the discharge water. The 20 m depth shows no change in temperature as the discharge is deeper and the discharge water is denser than the near-surface water. At 100 m depth (the discharge depth), a small northward plume of colder water is seen in the model, indicating the cold water effect on the ambient water. At 300 m depth, the plume is southward and more pronounced. At 500 m depth, the plume is also southward and even more pronounced. By 700 m depth, the plume is not observed, indicating that the discharge water is being assimilated at somewhere between 500 and 700 m depth. All changes in temperature are 0.1^oC or less from ambient water. A change of temperature of 3^oC is commonly considered to be the cause of instability in the water column (Giraud et al. 2019; Bordbar et al. 2023). The model supports the conclusion that the discharge of OTEC process water at a depth of 100 m off Kona is unlikely to substantially alter the stability of the water column. It should be noted that a near-field plume model was not integrated to simulate the initial dilution of the cold water, which was simply discharged into a large model cell and assumed to be fully mixed and diluted in the grid cell. Therefore, the cold water plume model results tend to underestimate temperature difference in the initial dilution zone near the discharge point. However, given the relatively small flow rate (300 m^3/s) and negligible temperature difference ($<0.1^oC$), we are confident that the conclusions based on the model results still hold in reality.

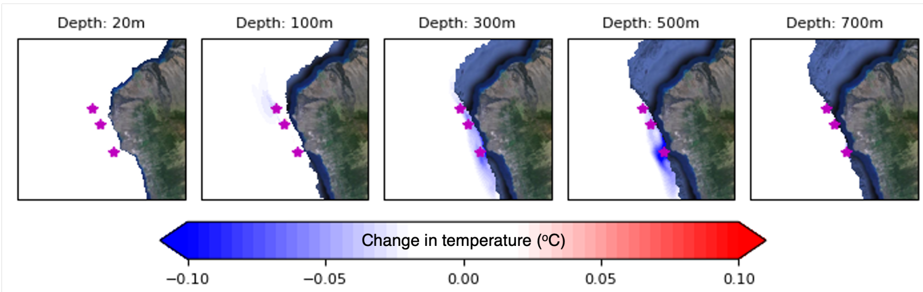

Figure 14. The 10-year mean temperature changes by the mixed water discharge from the three OTEC discharges (magenta stars). The stars indicate the locations of the three OTEC plants. Each frame represents a 2D map of the change in the temperature at different depth.

4.2 Entrainment

Pumping water from depths of 1000 m for heat exchange in the OTEC process has the potential to entrain deep-sea biota. Biota may be lifted to the near-surface waters of the OTEC platform, resulting in injury or death to the organisms due to rapid changes in pressure and temperature. There are no organized studies of this risk, although anecdotal evidence from the operational plants at NELHA and in Kumejima, Japan, suggests that fewer than one macro-organism per year is entrained in moon pools associated with the OTEC piping (Pers. Comms. R. Angell, B. Martin). The density of deep-sea organisms is low due to sparse food resources at depth, with the exception of locations near hydrothermal vents (which do not occur near the NELHA area). The most common organisms at depth are small invertebrates, including porifera (sponges), cnidarians (jellyfish, sea anemones), arthropods (crabs, shrimp), and echinoderms (sea stars), with some bony and cartilaginous fish such as small sharks, eels, tripod fish, ray-fin fish, and angler fish seen near the Kona area in depths greater than 500 m (Chave and Jones 1991). There is an exponential decline in density of deep-sea organisms from 500 to 1000 m (Yeh and Drazen 2009; Ramirez-Llodra et al. 2010), so the risk of entrainment is likely low at 100 m where cold OTEC water will be pumped.

4.3 Chemical Contamination

OTEC plants on land or at sea will contain a variety of lubricants, cleaners, and other chemicals that are used to maintain the plant in working order. In addition, closed system OTEC uses a working fluid of ammonia or other chemical compounds. There is a risk of spillage from any of these chemicals, risking water quality, marine environmental health, and potentially public health. However, managing these hazardous substances for OTEC plants does not differ from other industrial processes and applications at sea or on land. These risks are typically managed through hazardous waste management plans (DOI BOEM 2020) and use well-tested techniques for avoiding and, where necessary, mitigating risk.

5.0 Community Engagement

Under this task, PNNL worked with local community leaders in Hawaii to provide information on OTEC and assess community needs and acceptance of OTEC and associated products and services. Hawaii Sea Grant was tasked by WPTO to conduct outreach and engagement with the community to educate and gauge acceptance for marine energy in the islands. PNNL staff joined forces with Hawaii Sea Grant to provide expert input to outreach activities provided to the Hawaii Sea Grant and State of Hawaii trainers and worked with them to better understand the attitudes toward OTEC and other marine energy generation in the islands.

5.1 Hawaii Sea Grant Webinar

On April 23, 2024, in coordination with Hawaii Sea Grant, PNNL presented a webinar for the Hawaii State Energy Office's Jobs and Outreach Branch and the Kupu `Aina Corps' Clean Energy Wayfinders. The audience included full-time professionals who coordinate community outreach and coordination in Hawaii, and early career professionals who are placed in the communities where they work, through Hawaii Extension. During the webinar, PNNL introduced marine energy and its potential environmental effects, provided an overview of OTEC technologies and considerations, noted multiple sources of information available on Tethys (https://tethys.pnnl.gov), and highlighted several data and information systems that feature additional resources. The extended webinar provided an opportunity for the participants to ask questions and follow up with PNNL staff on details. In total, 18 participants attended the webinar and Q&A period. The presentation is included in Appendix C.

Following the webinar and other training sessions, the Hawaii Sea Grant and State of Hawaii trainers planned to hold a series of workshops with communities around the island, but the workshops have been delayed until Spring 2025.

5.2 NELHA HOST Park Site Tour

During December 2023, PNNL staff visited the NELHA HOST Park site and met with the NELHA Director and Associate Director, several key Makai staff who operate and carry out research on the OTEC plant at NELHA, as well as with several of the NELHA tenants. NELHA's site belongs to the State of Hawaii and consists of 870 acres of land and 3,290 acres of ocean waters and submerged lands. A portion of the land surrounding the OTEC plant is leased to small companies to take advantage of the facilities to incubate, innovate, and improve Hawaii-based shoreline-dependent enterprises. A significant number of the NELHA tenant companies use the deep ocean water brought ashore as part of the OTEC operation, using the water for cooling and other uses.

The most significant use of the cold deep ocean water includes SWAC for NELHA labs and administrative buildings, and industrial cooling for algae growth and oyster larvae spawning and growth. Several of the tenants stated that they could not profitably operate their businesses without the use of the cooling water, as the price of electricity for cooling purpose is very high on Hawaii.

5.3 NELHA HOST Park Tenant Survey

On September 27, 2024, PNNL distributed an online survey to 27 tenants of NELHA's HOST Park to gather information on the value of OTEC power and deep, cold seawater for aquaculture, cooling, and other applications at the HOST Park. The survey was granted an exemption from PNNL's Institutional Research Board for Human Subject research.

The online survey included seven open-ended questions:

1. What is your company name?
2. What does your company do?
3. What NELHA HOST facilities do you use and how?
4. What value does the deep seawater bring to your company?
5. If you had access to renewable energy from a larger OTEC plant, would you be interested in using that power?
6. Would you be supportive of expanding the existing shore-based plant and/or development of a larger floating OTEC plant offshore?
7. Are there any other attributes of OTEC or the deep seawater that would be of value?

Five HOST Park tenants completed the survey. Most respondents work in the aquaculture sector (e.g., breeding and production, research and development), and one provides venture capital, consulting, and programs for sustainable seafood and other blue economy industries. Another provides public exhibitions on marine animals, education, and policy to support ocean conservation.

Survey respondents primarily use the NELHA HOST facilities by leasing lab or office space in the research campus, utilizing surface and deep seawater for aquaculture operations, and utilizing the deep seawater for office cooling (through SWAC). Survey respondents stated that they primarily use the cold, deep seawater available at the facilities to grow microalgae and macroalgae, to mix with surface water to reach optimal temperature conditions for fish broodstock and shellfish larval culture, and to provide air conditioning for office spaces.

If they had access to renewable energy from a larger OTEC plant, three of the five survey respondents would be interested in using that power, while the other two respondents were unsure. Two of the five survey respondents would also be supportive of expanding the existing shore-based plant and/or development of a larger floating OTEC plant offshore. One respondent would be supportive of expanding offshore, but not if the plant were to intrude on the existing shoreline/ancestral grounds. Another respondent noted that, due to their product and operations, a shore-based plant is very convenient.

When asked if there are any other attributes of OTEC or the deep seawater that would be of value to them, one respondent noted that they would be interested in an energy-efficient cooling system for their shipping container units, while another noted Captura's CO_2 capture effort, which is exploring large-scale direct ocean capture of carbon.

6.0 Trade-off Analysis

Under this task, PNNL explored the tradeoffs of designing a multi-use OTEC platform that can produce power and support a range of additional services and products. PNNL examined how use of the OTEC process water or infrastructure may influence the overall performance of the system. These effects may render a particular use non-viable or may need to be mitigated with design or operational changes to the OTEC system, such as changing the order in which the seawater is used (before or after the heat exchange process), resizing the intake or discharge pipes, or resizing the project's footprint. Table 2 summarizes the feasibility of adding additional uses and services to power production for an OTEC plant. The feasibility and challenges of adding each use to OTEC power is discussed in the following sections.

Table 2. Feasibility of of additional uses of OTEC water, in addition to power production. Where no assessment has been made, there is no reasonable intersection between the uses. For example, desalination and aquaculture support are associated with shore-based OTEC plants while critical mineral extraction and efuels are associated with offshore plants.

	Power	Cooling (SWAC)	Aquaculture Support	Desalination	Critical Mineral Extraction	eFuels
Power		Feasible with Modifications	Feasible	Feasible	Feasible	Feasible
Cooling (SWAC)	Feasible with Modifications		Feasible	Feasible with Modifications	Not Feasible	Not Feasible
Aquaculture Support	Feasible	Feasible		Feasible with Modifications		
Desalination	Feasible	Feasible with Modifications	Feasible with Modifications			
Critical Mineral Extraction	Feasible	Not Feasible				
eFuels	Feasible	Not Feasible				

Feasible | Feasible with Modifications | Not Feasible | No Intersection

6.1 OTEC and SWAC

SWAC/other cooling is the most compatible use with onshore OTEC power production systems. Cold water that is diverted from the uptake pipe to cooling will reduce the power production of the OTEC plant; this trade-off can be mitigated by enlarging the rate of cold water uptake, largely through installing larger diameter pipes and pumping capability. If the cooling water is used after power production, the power output will not be affected. A set of pipes and pumps would be needed to move the cooling water into and out of the buildings, chillers, or other refrigeration units. The management of the discharge water rates will need to be adjusted to accommodate the flows.

The scientific literature assumes that approximately one to two times the volume of warm water to cold water flow is needed for an effective OTEC process (Fontaine et al. 2019). Based on literature values, the drop in flow rates (and hence the drop in power output from an OTEC plant) when the cold water is diverted before the heat exchange process will be approximately 22% for a 5 MW onshore plant to 13% for a larger 10 MW offshore plant (Aresti et al. 2023; Barberis et al. 2019; Rocheleau and Grandelli 2011; Fontaine et al. 2019). An example of the flow rate changes can be seen in Table 3, using a 1:1 ratio of warm to cold water. The warm water flow rate was calculated with

$$\dot{V}_{Seawater} = \frac{2 * W_{Gross}/\eta}{C * \Delta T * \rho},$$

where W_{Gross} OTEC grow power output, η is the Carnot efficiency, C is the specific heat of seawater, ΔT is the temperature difference for the warm water before and after OTEC usage, and ρ is the density of water. A factor of 2 was employed as OTEC efficiencies are near 50 percent of the Carnot efficiency. The cold water usage for SWAC before OTEC is the amount needed to handle the cooling load of five thousand, 1000 ft^2 ,houses . A rule of thumb heat load of 2 tons was used. The cooling flow rate was calculated with

$$\dot{V}_{cooling} = \frac{H}{C * \Delta T * \rho},$$

where H is the heating load and ΔT is the temperature change in the seawater, which was 6°C. This calculation does not considered inefficiencies of physical systems and so it represents the minimum flow rate needed (Kobie n.d.)

Table 3. Flow rates for cold and warm water intake rates, in m^3/sec for OTEC power production, combined with other uses.

Use	Shore-based 5 MW COLD	Offshore 10 MW COLD	Shore-based 5 MW WARM	Offshore 10 MW WARM
OTEC only	5.4	10.9	5.4	10.9

SWAC, cooling (after OTEC process)	5.4	10.9	5.4	10.9
SWAC, cooling (before OTEC process)	6.9	12.4	5.4	10.9
CME*	NA	NA	NA	
efuels	NA		NA	
Desalination (open system)	10.31	20.6	10.31	20.6

* The volume of warm water after the OTEC process was calculated for an experimental contact tank of 200 m^3, measuring 6.5x7 m. The volume of water needed to fill the tank, and then added to the discharge to the ocean discharge is negligibly small as compared to the cold and warm water flows.

6.2 OTEC and Desalination

Adding a desalination system to an open-cycle OTEC platform is most likely to be associated with a land-based system, probably 5 MW or less. The additional challenge to adding the desalination system is the limitation of the size of the OTEC power output, increasing the footprint of the system. The power output from the open-cycle system will only be affected to the extent that some electricity will be needed to run the desalination systems, including sensors and controls. The majority of the output of the desalination system (freshwater) will be derived from the condensate from the OTEC process. Additional costs will be incurred for the development and operation of the desalination system. Maintenance costs for the osmotic exchange membranes (for all processes) tend to be high.

6.3 OTEC and Aquaculture Enhancements

The use of deep cold water for algal aquaculture through nutrient enhancement is not practical due to the high carbon load that must be dissipated through carbon capture and sequestration at the point of use. Use of the cooling water after OTEC is very feasible and will not affect the power production. The only changes needed for such a system would be the addition of infrastructure including pipes and pumps that return the cooling water after use for algal or shellfish larvae (and potentially finfish larvae) culture. This infrastructure could be shared with SWAC or district cooling, as described in Section 6.1.

6.4 OTEC and Critical Mineral Extraction

While extraction of critical minerals is not yet industrialized, the feasibility of extracting useful minerals such as lithium, strontium, and others, has been demonstrated using fit-for-purpose adsorbents in a laboratory setting (Li et al. 2021). The ability to deploy these adsorbents in a contact tank is being explored at a theoretical level (Ryan et al. *in review*). Extraction of critical minerals is most likely to be carried out on offshore floating OTEC platforms, with the addition of a tank mounted above water that will be periodically filled from the warm water discharge portion of the OTEC water, allowed to soak, discharged into the discharge pipe, and the adsorbent reset using an acid wash (Ryan et al. *in review*).

Theoretically, we might consider a 20,000 L tank that will fill in less than one minute from the warm water discharge, soak for 30 minutes, and discharge over a period of 10 minutes. The wash water would be added to the OTEC discharge water, unless it is considered hazardous, in which case, a hazardous waste management plan might consider collection on board for periodic disposal.

Because the water used for filling the contact tank will be taken after the OTEC process, power production from the plant will not be affected. The major costs and challenges to the offshore OTEC platform would consist of construction of the contact tank and all associated infrastructure (pipes, pumps, and acid wash tank), as well as additional splitting and controls needed to carry out the filling, emptying, and discharging of process water from the contact tank. Additional information on the potential for critical mineral extraction of lithium is shown in Appendix B.

6.5 OTEC and eFuels

There are not yet any existing commercial efuels processes associated with offshore OTEC platforms. However, this future use could be very important for the development and expansion of offshore OTEC platforms. Challenges and the associated costs for creating an efuels generation process would include: development of the efuels process that includes hydrolysis of seawater from the OTEC warm water discharge and retrieving nitrogen from the air; storage, piping, and lightering ammonia or hydrogen gases to fit-for-purpose ships; docking or lightering facilities for the ships; use of electricity from the OTEC plant; and additional pipes and pumps to discharge the process water after creating efuels into the OTEC discharge pipe.

At this time, there are no apparent technical reasons that efuels could not be created from OTEC electricity and an efuels plant co-located on an offshore OTEC platform.

6.6 Compatible Multiple Uses of an OTEC Platform

The analysis of the various uses of the OTEC water and platform beyond generating power suggests that there are other compatible uses. It is clear, however, that not all the investigated uses can be carried out at once. For example, critical mineral extraction and efuels generation are best suited for an offshore floating platform, while SWAC and other cooling, aquaculture support, and desalination are most likely to be carried out with onshore plants. It appears that there are no impediments to certain uses being implemented together:

6.6.1 Shore-based OTEC Plant

Generating power from OTEC is compatible with SWAC, industrial and residential, and other cooling, as discussed in Section 6.1. Depending on the cooling needs, with or without humidity control, the cooling water might be taken from the initial deep water intake pipe, or after the power production process. These choices will affect the power production and will require engineering design and operation to make them compatible, but present no technical impossibilities. Assuming the support for aquaculture comes from the cooling water allows this use to be compatible as well. Adding a desalination plant, however, changes the equation considerably. The need to develop an open-cycle OTEC plant, which requires pumping substantially greater volumes of cold and warm water compared to a closed-cycle plant, suggests that cooling and desalination are not compatible on the same platform. The use of a hybrid OTEC plant (essentially, two plants, one closed cycle, and one open cycle) could solve this incompatibility. However, the development of a hybrid plant will increase costs substantially and require larger pipes, pumps, and other system components.

6.6.2 Floating Offshore OTEC Plant

Adding critical mineral extraction and an efuels plant to OTEC power production should be feasible. The power production from such an arrangement would be directed partly (for critical mineral extraction) and wholly (for efuels), and the OTEC plant sizing would need to be adjusted to ensure that it meets the needs. While there does not appear to be a technical reason not to carry out both critical mineral extraction and efuels generation on the same OTEC platform, this may not be practical as the efuels use will require major ship docking or lightering facilities on the platform, while the critical minerals extracted from seawater could be harvested with a smaller vessel. It is important to note that these two uses are the least-well investigated.

6.6.3 Scenarios for Multiple Uses of an OTEC Platform

Under this task, PNNL considered the possibility of six potential scenarios for multiple uses of an OTEC platform that might be pursued further in future studies:

1. OTEC power production (closed cycle) with SWAC, industrial (including aquaculture) cooling, residential cooling
2. OTEC power production (open cycle) with desalination
3. OTEC power production (hybrid cycle) with cooling and desalination
4. Floating OTEC power production (closed cycle) with critical mineral extraction and efuel production
5. Floating OTEC power production with critical mineral extraction only
6. Floating OTEC power production with efuel production only.

Of these scenarios, the first two (OTEC power plus cooling and OTEC power plus desalination) appear to be the most feasible in the near term. Small experimental plants have been developed and operated for these uses at NELHA in the United States, at Kumejima in Japan, in the dry Indian islands (Lakshadweep) in the Arabian Sea, and in laboratories in the U.S., the United Kingdom, India, Japan, South Korea, Malaysia, and elsewhere.

7.0 Conclusion & Recommendations

The scientific literature does not include assessments on multiple uses of OTEC platforms, covering a range of uses that have been suggested and/or developed in small experimental or laboratory-scale OTEC plants. The purpose of this study was to begin the process of determining what scenarios for multiple uses of OTEC might be feasible, and to consider the opportunities and challenges of each use with OTEC power production, as well as in tandem with other additional uses.

7.1 Conclusion

The analysis of potential multiple uses of an OTEC platform in addition to power has been organized around five tasks, looking at the available power around Kona, Hawaii, understanding what design considerations are needed to achieve these uses, looking at potential environmental effects and community values, and considering tradeoffs among the uses.

The outcomes of the analyses indicate that there is ample thermal differential between the warm surface water off Kona to operate an OTEC plant. This assessment is based on a new resource characterization model applied to the domain and validated with oceanographic and satellite data. As the islands of the Hawaiian archipelago are barely within the tropical zone, this bodes well for tropical islands in the Pacific Ocean, Caribbean Sea, and other parts of the world oceans within the tropics. The design requirements for each use were considered within the context of assuring that OTEC power production remained feasible, and preliminary designs for each identified use were drawn. Additional analyses examined the potential for using the high levels of dissolved nutrients present in deep ocean water for enhanced growth of algae; these analyses indicated that this was not a practical or reasonable pathway to pursue without extraordinary technological additions and costs being added to the OTEC plant.

The major environmental concern for the development of an OTEC plant revolves around the need to return the deep cold water to an appropriate depth after the OTEC heat exchange process, to avoid creating an unstable localized oceanographic environment and to protect surface water biota from shock. A new open-access OTEC return model was created and linked to the resource characterization model to demonstrate the depth and location where the discharge water should be directed, based on a range of OTEC plant sizes. The outcome shows that for OTEC plants considerably larger than those currently contemplated for coastal and remote island areas, the discharge water can be effectively handled to avoid adverse outcomes. The output of this model can be tailored for other locations and used to assist in the design of the piping and pumps needed for OTEC water uptake and discharge.

Interactions with the local community around the NELHA plant were not as substantial as expected. The project team partnered with Hawaii Sea Grant to engage with community leaders and the public and trained a group of outreach and engagement professionals in the topic area. Due to a series of issues, the Sea Grant workshops and other activities have been substantially delayed and are expected to take place during spring or summer 2025. The project team visited with and engaged many of the tenants and management of the NELHA site, gauging their knowledge, interest, and long-term vision for the existing (and possible future) OTEC plant at

NELHA. Overall, there appears to be interest and commitment to the value of the deep OTEC water and future potential power and other services from the plant.

Following the analysis of each potential use in addition to power production, the challenges of combining each use and the tradeoffs required was examined. The most obvious trade-off is with those uses best suited for a floating offshore platform (critical mineral extraction and efuels production) versus those suited for a shore-based system (cooling and desalination). Within those categories, there are no obvious technical conflicts for critical minerals and efuels, but practical considerations may override this combined use. SWAC and other cooling uses, including supporting aquaculture in tropical climates on land, are all compatible with OTEC power production, while desalination requires an open-cycle plant that is considerably less efficient than the closed-cycle plant considered best for power and cooling, making the addition of desalination unlikely with other uses.

7.2 Recommendations

The purpose of considering additional uses for an OTEC power production platform is to provide additional goods and services that will benefit remote tropical communities on islands and coastlines, and to increase the overall value of the development, bringing down the cost of energy as part of that benefit. Every aspect of adding more uses to an OTEC platform requires a deeper level of investigation than this study was able to carry out. The greatest area of examination that was not possible under this study concerns the economics of developing multiple uses for OTEC that are fit-for-purpose. Just as pressing is the lack of information on the economics of OTEC development itself. A recent study has shined some light on OTEC development costs, but the lack of empirical evidence from extensive commercial plant operations leaves many questions (OES 2024).

From this study, the project team recommends:

1. The most vital aspect of further understanding the multiple uses of OTEC platforms entails the development of a pre-commercial or commercial OTEC plant, around which further investigations and experiments can be focused.

2. The economics of OTEC and the individual additional uses need considerable investigation, but much of this work will depend on the availability of data from functional OTEC plants.

3. Further investigations are needed into the design needs of deep cold water for cooling taken before the use of the cold water in the OTEC heat exchange process. These investigations will help determine how the diversion of water will affect the power production, whether the two processes (cooling and power production) must always run at the same rates, and whether resizing the cold water uptake pipe will allow the OTEC system to run at its rated capacity.

4. There is a need to investigate the limits and design considerations for using cooling water for SWAC and industrial cooling (to support aquaculture) simultaneously, as well as

better understanding the implications for power production when cooling water is taken before and after heat exchange.

5. The practicalities of using an open OTEC system in conjunction with a desalination plant must be examined to understand how much power can be generated in addition to freshwater production.

6. The practicality of placing a critical mineral extraction system and an efuels generation system on an offshore OTEC platform must be investigated, including the basic functions and requirements for each of these operations.

7. The modeled water discharge depth and piping size must be validated with field data from an operational OTEC plant.

8. Regulatory concerns beyond the cold water return aspects of environmental effects should be discussed with local and federal regulators, in conjunction with some educational outreach, to ensure that permitting is smooth and efficient for future OTEC plants in the United States and elsewhere.

9. Additional outreach to the Kona community and elsewhere in Hawaii is needed to validate the initial findings of community acceptance and support for OTEC.

10. The portability of these findings and further analysis to other islands in the Pacific and elsewhere is needed to ensure that the range of OTEC potential is realized.

7.3 Next Steps

The next steps in this project are to collaborate with Hawaii Sea Grant on further community outreach through a series of webinars and workshops planned for 2025. The project team will also prepare a journal article on the outcome of the project in 2025.

Finally, the principal investigator and task lead will work closely on a related project on Guam, coordinating with the government of Guam, the Guam Power Authority, and the U.S. Department of Defense to develop the technical details needed to deploy OTEC and SWAC on the island.

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Appendix A – Near-Field Buoyant Jet Calculations

This appendix will consider the sizable momentum flux of the buoyant jet of OTEC's cold and warm water discharge as a potential source of value. Here, the characteristics of a buoyant jets terminal fall length scale from the discharge point, and the viscous entrainment of local seawater into the buoyant jet as parameters to assess the value proposition posed by OTEC's momentum addition to the ocean. These parameters, calculated from 1st order relations, show that cold water discharge pipe length could be reduced in length and that OTEC's buoyant jets may have a net carbon negative influence during OTEC operation.

This carbon negative influence may be driven by the transport of solutes (i.e., CO_2) from the surface layer (source) to below the mixing layer (sink), by the discharged seawater (i.e., buoyant jet). Here, the entrainment of local seawater into the buoyant jet by viscous effects allows the entrained seawater to be transported to the terminal fall length scale of the buoyant jet, which can be on the order of 100 meters. This transport by the buoyant jet could, locally, increase the atmospheric response times between the atmospheric gases surface layer and that of the deep ocean. The simple analysis used here is discussed in chapter 9 of Fischer et al. (1979). Note: This analysis should not be confused with the numerical modeling work shown in the main body of this report.

A buoyant jet is a flow with surplus of momentum that issues into a quiescent medium with a density gradient. In this case, the momentum carries the OTEC's discharge seawater through the ocean's layers while the density difference drives buoyancy forces on the discharge flow, which can enhance or hinder advection. Figure A.1 shows the geometries of a buoyant jet, where D is discharge pipe diameter, Q is volume flux of the effluent, ρ_e is the density of the effluent, μ_t is the terminal volume flux and the Z_t is the terminal fall of the buoyant jet from the ocean's surface. The exit geometry will be a critical feature for the effluent discharge as it will affect the terminal fall of the buoyant jet in the mixing layer (below the euphotic zone). This is to minimize effect of algal blooms and CO2 off-gas while keeping the discharge pipe length to a minimum.

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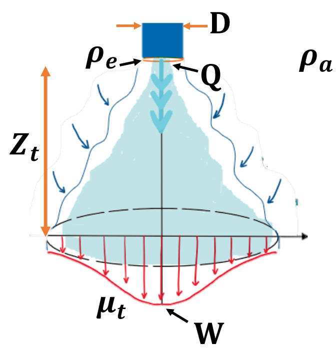

Figure A.1. Buoyant Jet Nomenclature.

A buoyant jet will have a terminal fall distance with respect to its output source. For example, the fluid drawn from 1000 m depth in the ocean and then released at 200 m depth in the ocean will not fall back to 1000 m due to entrainment and buoyancy effects. Figure A.2 shows the amount of entrained fluid by the cold seawater buoyant jet. Here, the amount the buoyant jet entrains is generally an order of magnitude greater in volume flux than the discharge source. This entrained seawater and its properties (e.g., dissolved gases to nutrients) are then carried to the buoyant jet's terminal fall, which is where the buoyant jet stops its downward direction.

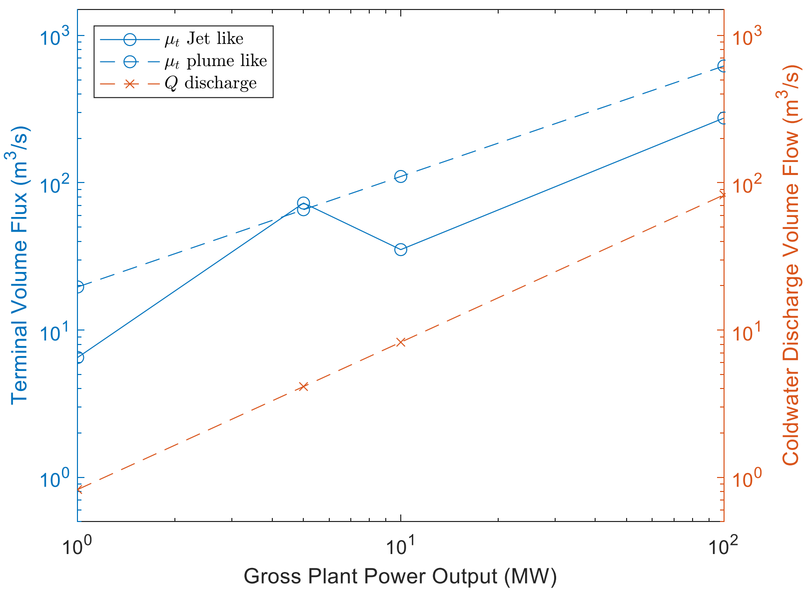

Figure A.2. Cold seawater discharge volume flux to volume flux rate at the terminal fall of the cold seawater buoyant jet (Makai n.d.).

It is assumed in this analysis that the buoyant jet issues into a quiescent environment, no cross flow, with a linear density stratification. Water column properties were taken from Cycle 2 of the Argo Float number 1902685 with additional properties calculated with the ocean state relations (i.e., density of seawater at atmospheric pressure using UNESCO 1983 (EOS 1980) polynomial)Discharge diameters for a given sized OTEC Plant were taken from Makai Ocean Engineering (Makai n.d.).

Table A.1. Inputs into Buoyant Jet Analysis.

	Inputs
Discharge Depth of Warm Water (m)	70.5
Intake Depth of Warm Water (m)	20.1
Intake Depth of Cold Water (m)	973.7
Discharge Depth of Cold Water (m)	199.8
Ambient Density at Cold Water Discharge (kg/m^3)	1026.1
Discharge Depth of Cold Water (m)	199.8
Discharge Diameter 1 MW plant (m)	1.2
Discharge Diameter 5 MW plant (m)	1.2
Discharge Diameter 10 MW plant (m)	4.0
Discharge Diameter 100 MW plant (m)	10.1
Cold Water Discharge Temperature (Celsius)	10.4
Warm Water Discharge Temperature (Celsius)	20.4
OTEC Efficiency	3.0%

The terminal fall of the buoyant jet is critical to understanding how the OTEC's piping system could be further used in value creation. Figure A.3 shows the terminal fall of OTEC's warm water discharge from the ocean's surface. Though the given parameters indicate that this flow is dominated by mometum and thus is jet like, but the plume like solution as a still plot. The jumps in the jet-like solutions are from the changing diameter of the discharge pipe, as this effects the mometum flux. For a 100 MW OTEC plant, the bouyant jet from the warm water discharge crosses over the depth at which the cold water discharge occurs. This demonstrates the possibility of an OTEC plant using the discharge to connect the air-sea interface, so that the seawater that is entrained in the surface layer could be sent below the mixed layer. This could effectively increase the local residence time between CO_2 in the atmosphere and the deep ocean carbon sink to orders of minutes. However, further work is warranted to address this effect as the analysis here is limited.

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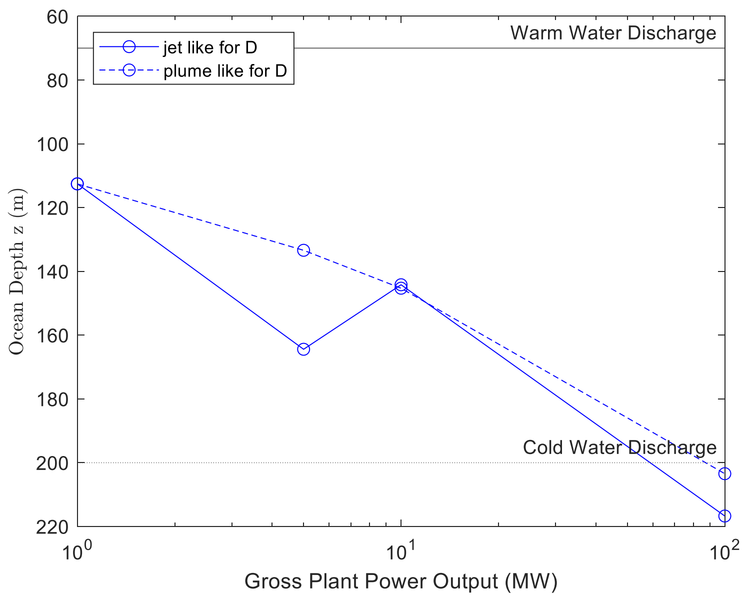

Figure A.4. Buoyant jet terminal fall for OTEC's warm water discharge.

Appendix B – Decarbonization of Deep Ocean Water

The potential for using the nutrient dense deep ocean seawater as a fertilizer for aquaculture should be explored. However, issues arise from off-gassing of CO_2 from the deep seawater, which is estimated to have 5x of atmospheric levels. This would imply that off-gassing would impose a net carbon addition to the atmosphere. The amount of carbon addition to the atmosphere for two-hundred and 40 100 MW OTEC power plants would produce 0.022 gigatons of CO_2 per year, assuming the unlikely scenario of 100 percent CO2 off-gassing (Avery and Wu 1994). In comparisons, this is 8% of global annual volcanic activity (0.26 gigatons/yr) and 10% of estimated atmospheric CO_2 addition by the equivalent power generation of coal-fired power stations (0.22 gigatons/yr) (USGS 2024). Though this extreme off-gassing estimation puts OTEC in line with other carbon sources, further research may be warranted.

The cold water discharge pipe offers a mechanism to return the off-gassed CO_2. Figure B.1 shows on offshore OTEC plant colocated with an aquaculture facility. Here, the deep seawater is pre-treated in the off-gassing chamber. This chamber allows a settling time for the off-gassing to occur and allows the deep seawater to warm up for aquaculture use. An eductor is then used to entrain the chamber's gases into the cold water return. This chamber will be self-contained from the atmosphere as it will prevent both CO_2 from interacting with the atmosphere and prevent increasing CO_2 concentrations in the deep ocean. An additional solution includes the off-gassing chamber being used as an algae CO_2 scrubber (Gao et al. 2023). The deep seawater could be recirculated until most of the nutrients are taken up, which includes CO_2. However, the algal biomass may have to be returned to the deep ocean to ensure no carbon addition to the atmosphere.

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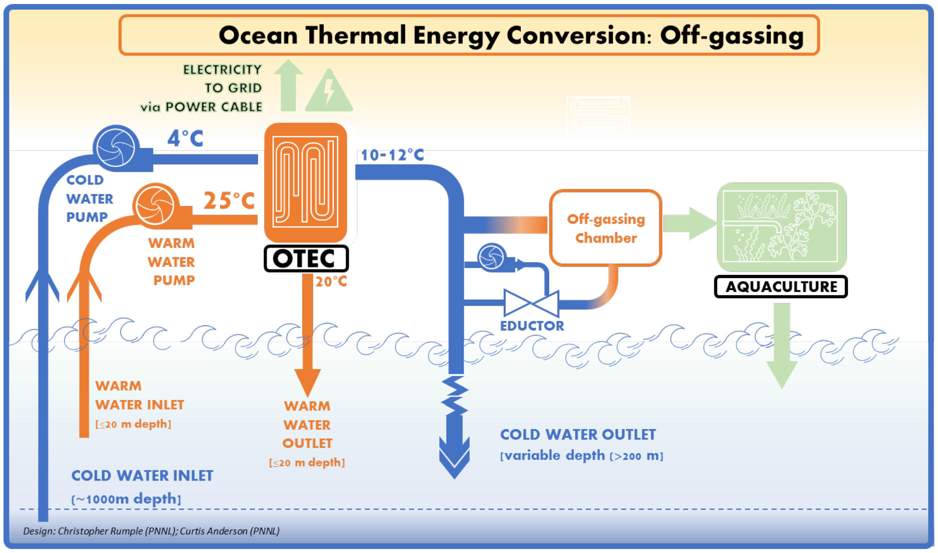

Figure B.1. Solution concept for prevent CO2 off-gassing to the atmosphere.

References:

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Appendix C – Community Engagement Presentation for Hawaii Sea Grant and State of Hawaii Energy Office

Appendix D – Critical Mineral Extraction of Lithium from Seawater

In the energy and technology industries, certain minerals are more useful than others. One of these is lithium. It is the building block for many of our modern technologies and is critical to energy storage and the global transition to clean energy. Extracting this critical mineral is no small task. Even though it is present throughout the Earth's crust and oceans, lithium is unevenly concentrated across the globe in ores and brines. Australia, Chile, China and Argentina are the top countries commercially producing this metal and these four countries contain more than 98% of the global lithium supply (Yang et al. 2018). The most widely used method of obtaining this element is hard-rock mining. However, lithium can also be extracted from brine and other aqueous solutions, such as seawater. The amount of lithium in the ocean totals 230 billion tons which is four orders of magnitude larger than the 14 million tons of lithium resources on land (Yang et al. 2018). This vast reserve has the potential to be tapped by direct seawater extraction of lithium. Currently, the most widely used method of obtaining this element is hard-rock mining. Alternative methods of critical mineral extraction (CME) including direct seawater extraction have the potential to be less energy-intensive and have a lesser environmental impact when compared to mining hard-rock ore. Furthermore, seawater resources of lithium are more accessible and evenly distributed across the globe than other concentrated lithium ore and brine deposits.

The reason behind choosing critical mineral extraction for a secondary use alongside OTEC development lies in the physical movement of water and associated pumping costs. Both processes require large amounts of seawater to be pumped through their systems, making their colocation an effective and cost-beneficial choice. The concentration of minerals within the ocean is quite low; lithium has the highest concentration among other critical minerals at 0.178 mg L^{-1}, hence the need for large volumes of seawater to be processed to produce profitable yields of minerals (Ryan et al. 2023). An OTEC's plumbing infrastructure and massive flow rates make it well suited for this type of mining. Figure D.1 shows through put lithium CME with an OTEC plant theoretically could produce over 1 metric ton in a 24-hour period, for 100 MW plant. Here, the assumption is that all the present lithium is extracted at the same rate as flow leaving the OTEC plant. (i.e., the accumulated amount of lithium in the OTEC's warm water discharge over a 24-hr period.) Practical applications will likely have less efficiencies, but the large lithium mass flux provided by the OTEC's plumbing shows the ease of access to this plentiful resource.

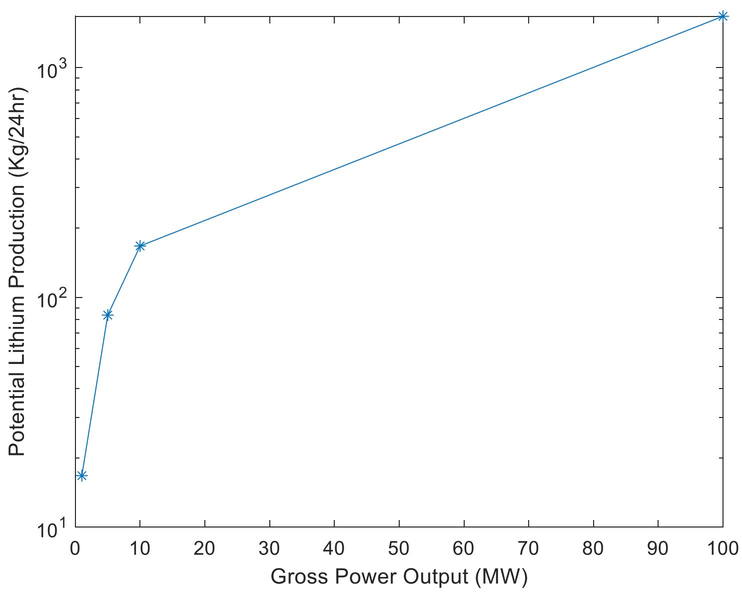

Figure D.1. Click or tap here to enter text.

The method of direct lithium extraction that will be highlighted in this analysis is sorbent extraction. Li-ion sorbents absorb lithium into their structure with size-based or charge-based selectivity. Once a sorbent has reached a maximum capacity and attracted all the Li-ions it can, the Li+ can be recovered through a regeneration step using an acidic regenerant solution that promotes ion exchange. Post-regeneration, the sorbent may need to be flushed with freshwater to limit acidification and improve effectiveness across multiple cycles. For this reason, an open-cycle OTEC plant is best suited for colocation with lithium CME since one of the byproducts of these open systems is freshwater in the seawater flash evaporation step.

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