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An Assessment of the Financial Feasibility of an OTEC Ecopark: A Case Study at Cozumel Island

Jessica Guadalupe Tobal-Cupul¹, Erika Paola Garduño-Ruiz^{2,*}, Emiliano Gorr-Pozzi³ , Jorge Olmedo-González⁴ , Emily Diane Martínez⁵, Andrés Rosales⁵, Dulce Daniela Navarro-Moreno², Jonathan Emmanuel Benítez-Gallardo², Fabiola García-Vega², Michelle Wang⁵, Santiago Zamora-Castillo⁶, Yandy Rodríguez-Cueto² , Graciela Rivera² , Alejandro García-Huante², José A. Zertuche-González³ , Estela Cerezo-Acevedo¹ and Rodolfo Silva^{2,*} 

¹ Department of Basic Sciences and Engineering, Universidad del Caribe, Cancun 77528, Mexico; jtobal@ucaribe.edu.mx (J.G.T.-C.); ecerezo@ucaribe.edu.mx (E.C.-A.)

² Instituto de Ingeniería, Ciudad Universitaria, Circuito Exterior S/N, Coyoacán, Mexico City 04510, Mexico; danielanavarrom1@gmail.com (D.D.N.-M.); egallardo766@gmail.com (J.E.B.-G.); fgarcia@iingen.unam.mx (F.G.-V.); yandyro84@gmail.com (Y.R.-C.); griverac@iingen.unam.mx (G.R.); agarciahu@iingen.unam.mx (A.G.-H.)

³ Instituto de Investigaciones Oceanológicas, Universidad Autónoma de Baja California, Ensenada 22870, Mexico; emigorr@uabc.edu.mx (E.G.-P.); zertuche@uabc.edu.mx (J.A.Z.-G.)

⁴ Laboratorio de Electroquímica, Instituto Politécnico Nacional-ESIQIE, UPALM, GAM, Mexico City 07738, Mexico; jorgeolmedog@outlook.com

⁵ Thayer School of Engineering at Dartmouth, Hanover, NH 03755, USA; emily.d.martinez.th@dartmouth.edu (E.D.M.); arosales871@gmail.com (A.R.); michelle.s.wang.th@dartmouth.edu (M.W.)

⁶ Dartmouth College, Hanover, NH 03755, USA; santiago.zamora.castillo.21@dartmouth.edu

* Correspondence: paola.quimar@gmail.com (E.P.G.-R.); rsilvac@iingen.unam.mx (R.S.)



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Abstract: The aim of this article is to show how an OTEC Ecopark could provide comprehensive, sustainable, and quality products that satisfy the diverse needs of coastal communities in Mexico. An offshore 60 MW hybrid Ocean Thermal Energy Conversion (OTEC) plant is proposed, which will provide products that will not only fulfill the water, energy, and food needs of the coastal communities, but also energize the local blue economy. An assessment of the financial feasibility of the plant as well as a comparative analysis against other forms of energy generation was carried out. The methodology section includes a market description, literature review for the technical design, methods for mitigating socio-environmental risks, and an analysis of operational risks. To determine financial feasibility, the CAPEX, OPEX and annual revenue, including the sale of CELs and carbon credits, were evaluated. The Internal Rate of Return suggests that the system would pay for itself in year 5 of the system's 30-year life. The methodology used for this case study, with site-specific adaptations, can be applied to other coastal communities across the globe.

Keywords: OTEC Ecopark; financial feasibility; offshore aquaculture; Levelized Cost of Energy; capacity factor



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1. Introduction

Ocean Thermal Energy Conversion (OTEC) is a marine energy that converts heat into mechanical energy through a thermodynamic cycle, which uses the temperature difference (20 °C or more) between the warm surface water of the ocean and cold ocean water from ~1000 m depth. Base load power is produced, as well as valuable by-products, such as desalinated water [1] and deep ocean water (DOW) that can be utilized in various sustainable activities such as aquaculture, cold agriculture, and sea water air conditioning (SWAC) [2]. The OTEC system is feasible in tropical and subtropical areas with studies showing that almost 100 countries have the required thermal gradient (difference in temperature between

surface and sub-surface waters) [3]. Historically, analyses of theoretical OTEC systems show a high Levelized Cost of Energy (LCOE) and non-viable economic projections associated with the technology discouraging the development of commercial plants [4].

In order to promote OTEC development, some researchers have focused on improving the technical aspects of OTEC, performing thermodynamic and mechanical analyses and creating multipurpose OTEC plant designs in order to improve OTEC's efficiency and decrease costs. Khan et al. [5] reviews several OTEC designs, highlighting the evaluation of the working fluids and cycle configuration to increase OTEC performance and therefore, lower costs. Related, Zhang et al. [6] suggests that solving problems with fluid mechanics, such as the steam turbine design, the effects of the hydrodynamics of the cold-water pipe and of the floating platform, should be prioritized to increase the efficiency of an OTEC system and decrease maintenance and construction expenses. Finally, Barberis et al. [7], proposes utilizing an OTEC's plant by-products to increase plant viability through a techno-economic evaluation of an OTEC plant that also produces water for SWAC.

Vega [4] states that in the global electricity market, plants of a larger nominal size, 50 MW or over, would be competitive [8]. Previous studies have also suggested that the economic diversification of OTEC technology in an Ecopark could give it a financial advantage over other forms of sustainable energy generation.

An Ecopark [8,9] is a multi-purpose integrated system where a range of products and services are produced that are beneficial to the population: water, energy, and food security, thus building a strong foundation for the local blue economy [10,11]. One example of an OTEC Ecopark is the Hawaii Ocean Science and Technology Park, in Kailua Kona, developed by Makai Ocean Engineering Ltd., the OTEC plant prototype has a maximum power generation capacity of 100 kW, enough to power 120 homes. 600 jobs have been created at the park which when connected to the US grid, became a financial success with an annual income approaching \$150 M [12]. Another example is a 100 kW OTEC plant at Kumejima Island, Okinawa, Japan, which was built by the Okinawa Deep Seawater Research Institute and Xenosys Inc. At this plant, ocean energy is generated, and research is conducted while being an active tourist attraction. DOW applications such as oyster farms, a prawn hatchery, and the cultivation of seaweed [13] have improved the local economy in Japan and South Korea by generating new blue economy markets with annual revenues of \$22.5 M [14,15].

Other projects are in development currently to utilize OTEC by-products: PRO-TECH [16] is a project in Puerto Rico where facilities to provide energy, SWAC, food, cosmetics, and medical treatments are planned. The STARTREPS OTEC-project is a partnership between Japan and other countries in the region to make OTEC a competitive alternative through the coupling of electricity generation with by-products [17]. Finally, Bluerise [18], a company focused on ocean resources, plans to develop an Ecopark in Curaçao for energy, SWAC and food.

As OTEC is reliant on a thermal gradient, not all coastal communities could host an OTEC Ecopark. The coastlines of Mexico have many locations with optimal characteristics for harvesting ocean thermal energy. Bárcenas-Graniel [19] and Garduño-Ruiz et al. [20] state that the island of Cozumel, in the Mexican Caribbean, has great potential for OTEC of more than 50 MW due to its large temperature gradient during all year round and unique bathymetric conditions.

Cozumel is a coastal community and an international tourist destination. During peak demand hours, Cozumel's electrical grid is currently at its limit due to its outdated infrastructure in need of replacement [20] Moreover, there has been an increasing demand for water, energy, and food due to the fast-growing population of Cozumel (2.75%), despite the node prices that are relatively higher than other areas in Mexico [21]. All these factors make OTEC deployment an attractive business opportunity.

Various initiatives that aim to convert the island into a model for social and environmental sustainability, especially in energy production have already been initiated by the local government in Cozumel. Local industries, specifically hotels, have begun adapting to the foreseen increase in energy demand by providing ecological lodging services that

conserve energy [22]. In this sense, OTEC Ecopark could offer a sustainable option for local economic growth [23], as well as reducing the carbon-footprint associated with electricity generation and supply, in line with UN Sustainable Development Goals (SDGs).

The main aim of this paper is to assess the financial feasibility of an offshore, 60 MW hybrid OTEC plant (60 MW-H-OTEC), as part of an Ecopark off Cozumel Island. The assessment shows how this Ecopark would provide opportunities for economic growth and diversification of the island economy, thus enhancing community resilience. The Ecopark would: (1) produce energy, permitting wider access to high-quality electricity, and consequently satisfying present and projected energy demands, as well as diversifying the national energy matrix; (2) supply desalinated water; and (3) provide the necessary conditions to enable Offshore Seaweed Aquaculture (OSA) of *Ulva* spp. both for food production and carbon capture. This study aims to offer a viability assessment for OTEC Ecoparks for potential sites in Mexico [20], and around the world, in order to encourage the promotion and development of OTEC commercialization [24].

2. Materials and Methods

As OTEC technology is not novel, we aim to build on previous work to determine costs and production rates while considering a mass and energy balance, energy losses and component sizing of a potential plant. A comparative assessment was completed to identify the benefits of the OTEC Ecopark as well as risk mitigation strategies to address both possible socio-environmental impacts and operational risks.

The study is divided into seven sections: descriptions of the study area, market opportunities, adaptations to the plant design of previous works, an economic feasibility assessment, an assessment of comparative energy systems, socio-environmental risks, and recommendations for mitigating operational risk.

2.1. Study Area

The area studied is 5-km off the south-eastern coast of Cozumel Island, in the Mexican Caribbean Sea (Figure 1), extending east from the 1000 m isobath to 100 km off Cozumel. To avoid any conflict with fragile coastal ecosystem processes, a buffer of 5 km from the beach was established.

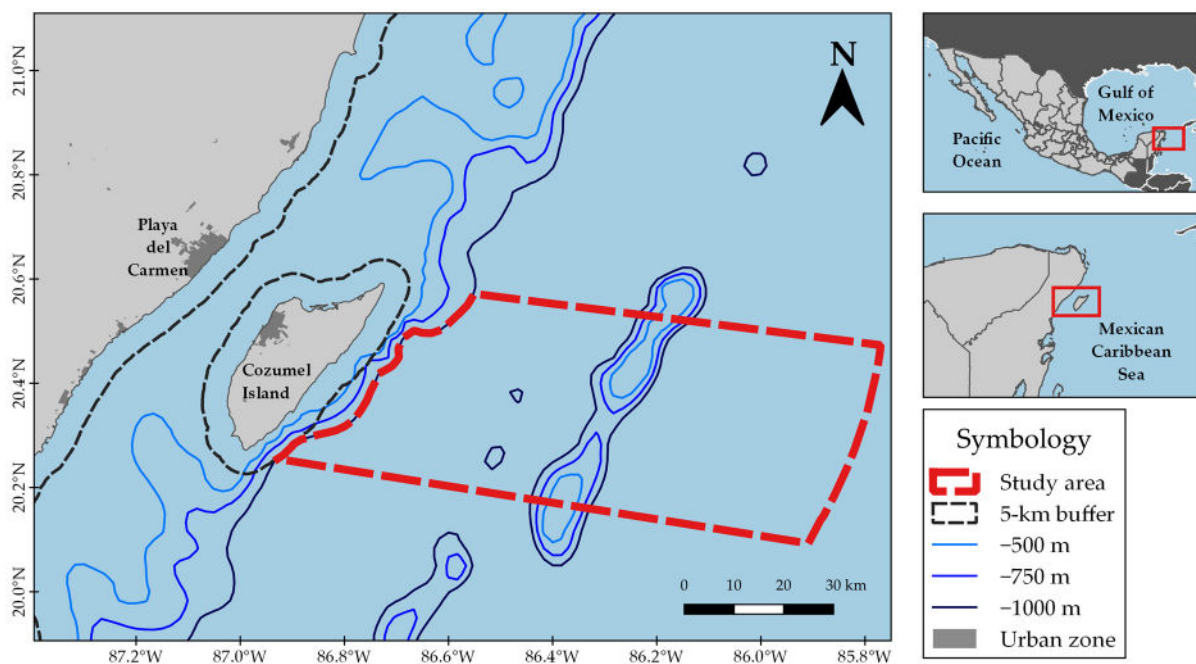


Figure 1. Location of the study area.

Cozumel is located, off the eastern coast of the state of Quintana Roo (Figure 1). The urban zone of this island is on the west coast, parallel with the larger Playa del Carmen, on the mainland. East of the island, depths of 500 m, 750 m and 1000 m are found less than 5 km from the coast. The euphotic zone is at 142 m [25] with surface water in the Mexican Caribbean at a mean temperature of 27.9 °C, while at 1000 m depth, at a mean temperature of 5 °C [20].

2.2. Market Description

In the 2020 Mexican census, 55.3 million people (46% of total population) were recorded as living in coastal states, with Quintana Roo being one of the most densely populated [26]. Rising population and economic growth have increased the demand for water, energy, and food (WEF) around Cozumel [27].

In this section the market opportunities for an OTEC Ecopark are described. Each of the OTEC Ecopark products (desalinated water, energy, and OSA), are analysed as to how they would meet WEF needs in the area, supporting sustainable development, crucial to the UN's SDGs (Figure 2).

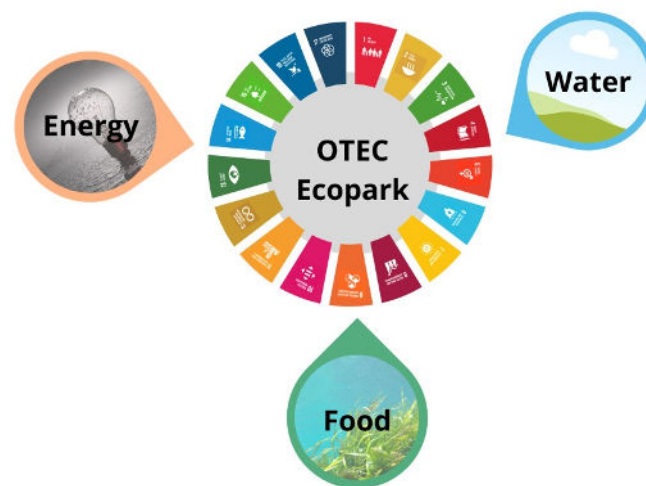


Figure 2. Water, Energy and Food (WEF) linked to an OTEC Ecopark.

2.2.1. Energy

OTEC can diversify the Mexican energy matrix and contribute to Mexico achieving the 7th SDG to “Ensure availability and sustainable management of water and sanitation for all by 2030. OTEC could be an alternative to Fossil Fuel energy generation, producing clean, base load power for coastal communities. The theoretical global potential for OTEC is approximately 30,000,000 MW [4]; in Mexico specifically, this would mean ~100–200 MW of theoretical global potential [28,29].

In terms of electricity needs, 1.3% of households in Mexico, approximately 2 million inhabitants, do not have access to a reliable source of electricity [28]. In Cozumel, 0.22% of homes do not have access to electricity [20]. Furthermore, as stated by the National Center of Energy Control (CENACE in Spanish) [21], the price paid for electricity in Cozumel is higher than elsewhere in Mexico due to the high cost of supplying electricity to the island from the mainland.

To integrate OTEC energy into the electrical grid, the guidelines for pool-based electricity markets that currently operate in Mexico must be adhered to. Guidelines state that OTEC electricity must be sold in the wholesale electricity market, where final energy cost regards generation cost [21]. Therefore, even though energy obtained from OTEC is available and has a high-capacity factor (92%), it is unrealistic to believe that cheaper electrical energy is a real possibility [20]. The guidelines also indicate that renewable energy sources can generate Renewable Energy Certificates, known in Mexico as Clean Energy Certificates (CELs, in Spanish) which can be sold on the wholesale electricity market. CELs

were designed by the Energy Regulatory Commission (CRE, in Spanish) to achieve the Mexican renewable energy generation target, so certain wholesale electricity market participants are required to purchase CELs to credit their clean energy obligations. Each certificate is equivalent to 1 MWh/year generated [21]. These state that OTEC electricity must be sold in the wholesale electricity market, where final energy cost

2.2.2. Desalinated Water

In Mexico, more than half of all households which have access to running water only have access intermittently. This is particularly true in smaller settlements and in poorer areas [30]. Thus, in order to fully achieve the 6th SDG (“Ensure availability and sustainable management of water and sanitation for all by 2030”), increasing access to reliable clean water for these households is an imperative.

Desalination plants are a promising means to satisfy present and future water demands in coastal areas. According to the Mexican Institute of Water Technology, since 2007, 435 desalination plants have been installed at 320 sites in Mexico [31]. The state of Quintana Roo has the greatest number of these plants (124, 28% of the total) due to its proximity to the ocean and its population’s increasing demand for water. In Cozumel, this demand is attributed primarily to the growing tourism industry. Figures from 2014 show that the island had a population of 86,400, and a demand of 111 litres per inhabitant per day [32,33]. OTEC technology could provide relief in this area by producing clean, desalinated water, at the same time as reducing the fossil fuel emissions generated in other desalination processes [34].

2.2.3. Offshore Seaweed Aquaculture (OSA)

Seaweed farms have become an important sector within the global blue economy. With an annual production of ~32.4 million tons (wet weight) in 2018, valued at \$13.3 billion, seaweed production is expected to increase to \$22.13 billion by 2024 [35,36]. This growth is mainly due to the versatility of seaweed in a range of markets. The intrinsic characteristics of seaweeds allow them to have a rapid increase in biomass and contribute to climate change adaptation by acting as highly efficient carbon sinks [37], as well as protecting the seashore from erosion, raising pH, supplying oxygen to the aquatic ecosystem, and locally reducing the effects of ocean acidification and deoxygenation [38,39].

Vega [40] explains that the vast nutrient-rich DOW flows generated by OTEC can be used to sustain seaweed farming, supporting SDGs 2 (to “end hunger, achieve food security and improved nutrition and promote sustainable agriculture”) and 14 (to “conserve and sustainable use the oceans, seas and marine resources for sustainable development”) [41] ultimately promoting the sustainable development of coastal communities [15].

The present work proposes a coupled OTEC-OSA system that can generate multiple benefits in seaweed cultivation in Cozumel. This coupling could facilitate higher control of variables that improve in-situ water intake quality and crop metabolism. In addition, the OSA, by being located offshore and coupled to OTEC, can take advantage of on-site DOW, reducing the costs associated with piping and pumping DOW. Through its offshore design, this system would minimize competition with other local island activities, as it does not require island space or island freshwater. Finally, it would help minimize potential environmental impacts, including the carbon footprint associated with electricity generation and consumption [42–44]. Another advantage that OSA creates in being located offshore is that the dimensions or scale of the cropping system are not limited, which guarantees an optimal culture load density. The low intra-annual climatic variability of the study area is also conducive to a long cultivation period for seaweed throughout the year [45].

In this paper, *Ulva* spp. was selected as the cultivated seaweed in the OTEC Ecopark, as large quantities of biomass with a high commercial value could be produced [46]. This green macroalgae is valuable for human consumption, animal feed, biofilters, pharmaceuticals, and as biomass for biofuels [35,47,48]. It would also capture atmospheric carbon, reducing the carbon footprint and create carbon credits [37]. The amount of carbon sequestered by

Ulva spp. was calculated, using the conversion factor of Chung et al. [37], which considers 30% of the dry biomass, and 7.6% of sea-salt [48].

2.3. Technical Design

From a literature review and assessment of pre-existing plant designs and methodologies the OTEC plant proposed in this work was designed, and the costs and production rates were determined.

The OTEC Ecopark consists of a 60 MW OTEC hybrid plant (60 MW-H-OTEC) and an off-shore aquaculture pond. The 60 MW-H-OTEC plant includes an energy production sub-module and a sub-module for desalinated water. A third sub-module uses DOW for OSA, considered as the main advantage of the plant in terms of financial feasibility (Figure 3).

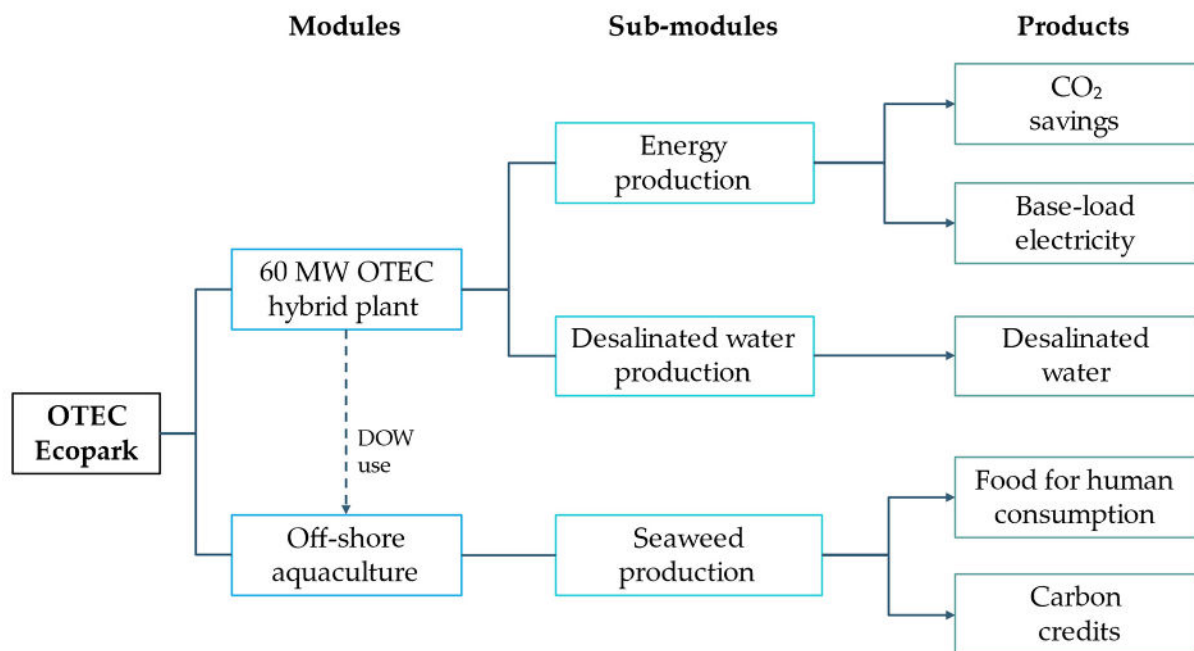


Figure 3. Components of the OTEC Ecopark.

The amount of base load energy produced, and of desalinated water and biomass generated, as well as the ton/day of carbon sequestration, via the cultivation of *Ulva* spp. in OSA, were calculated.

To perform the mass and energy balance for the 60 MW-H-OTEC plant, the Mexican 1 kW Closed-Cycle OTEC plant methodology was adapted [49]. One key difference from Tobal et al. [49] is that here ammonia would be the working fluid as opposed to R152a. To account for the larger scale of our plant, designs of CC-OTEC plants of over 50 MW elsewhere in the literature were referred to. Synthesizing these information sources gave a better approximation of the dimensions and determined the net power consumption for each component.

Various articles were consulted for the design of each sub-module and platform (Table 1), since there is no existing design on the market that considers all of the components of our design. The sizes and characteristics of the components were taken from Vega & Michaelis [24], Adiputra et al. [50] and Bernandoni et al. [51]. In the energy submodule, the CO₂ saved was calculated according to Vega [40], who estimated that 0.7 kg is saved for the annual energy production of a 50 MW OTEC plant. The desalination module was designed following the method of Avery & Wu [52] and Morales [53] who, due to the technical limitations of the process, considered that only 0.5% of the surface water of the sea can be desalinated. The sensitivity analysis of Tobal et al. [49] was performed, using CoolProp of Python, to determine the mean amount of desalinated water that could be obtained by the Ecopark.

Table 1. Methodology used for the design of the OTEC Ecopark.

Submodule	Methodology	Reference
Energy production	60 MW-H-OTEC (Mass and energy balance)	Adapted from Tobal et al. [49]
	CC-OTEC (component sizing)	Adapted from Vega & Michaelis [24]
	Seawater supply and power consumption (components sizing)	Adiputra et al. [50]
	Electrical equipment and interconnection nodes required.	Bernandoni et al. [51]
	Amount of CO ₂ saving by power production	Vega [40]
Desalinated water production	Mass and energy balance (components sizing)	Avery & Wu [52] and Morales [53]
	Desalinated water rate	Sensitivity analysis adapted from Tobal et al. [49]
OSA production	Nutrient concentrations (NO ₃ , PO ₄ , SO ₄) and O ₂ dissolved at 902 m depth from 7 June 2018–10 April 2021 and 0.25 × 0.25 degrees of spatial resolution	Copernicus [54]
	<i>Ulva</i> spp. nutrient demand and net yield per m ²	Hanisak [55]
	Dimensioning a floating pond	Adapted from the macroalgae ponds of Zertuche-González et al. [48]
	CO ₂ capture capacity of <i>Ulva</i> spp. Algae	Chung et al. [37] and Zertuche-González et al. [48]
Platform design	Dimensions of the ship	Adapted from Vega & Michaelis [24]
	3D model of the 60 MW offshore OTEC plant-aquaculture system	SolidWork and Fusion360 softwares

OSA production was estimated, considering the nutrient concentrations at 902 m, based on the COPERNICUS database [54]. This data was used to determine the nutrient demand required to grow *Ulva* spp. in the OSA floating pond, using the continuous resuspension method adapted from Zertuche-González et al. [48]. This method involves a sub-module, coupled to the OTEC Ecopark, that harnesses large flows of cold, nutrient-rich DOW to enhance the growth of *Ulva* spp.

The design for the offshore aquaculture farm was adapted from Zertuche-González et al. [48] and uses a constant, vertical flow of deep ocean water (DOW)-air from the sea bottom to the surface of the ponds. This produces convective hydrodynamic cells that promote the “tumbling” movement of the seaweed which optimizes the time of exposure to surface solar radiation, improves its distribution within the farm and increases the residence time of the physicochemical properties of the DOW within the surface cultures. This technique has been shown to give high densities and yields per unit volume of daily culture [48,56].

Finally, the entire setup of the modules was placed onto a ship-like platform made of steel, adapted from the designs of Vega & Michaelis [24] and Zertuche-González et al. [48] and produced using SolidWorks and Fusion360. Although floating platforms are recommended for OTEC power plants of 100 to 400 MWe, several 20 MW projects include this type of platform, and even for a 1 MW plant this could be a feasible option [52]. Among floating, or offshore, OTEC plants, various types of platforms have been studied for plants of between 50 and 500 MWe (gross) of power [24,50–52,57,58]. To illustrate, OTEC projects such as those presented in Vega & Michaelis [24], Yee [59], Kim [60] have considered 50, 20 and 1 MW offshore OTEC plants, respectively. One advantages of an offshore platform is its considerably less expensive cost than onshore plants, due to these required more cold-water piping [61,62].

2.4. Economic Evaluation

Using the methodology of Vega & Michaelis [24] and the net present value (NPV) of the American dollar. A projected lifespan of 30 years was considered, capital costs (CAPEX), operation, maintenance, repair, replacement costs, plus administrative expenses (OPEX), and the sale of products. We also considered specific Mexican levies, such as ISR (taxes), PTU (Employee Participation in Profit Sharing Payments), in order to generate an accurate cash flow model.

The CAPEX calculations include the following costs: the platform, anchor, submarine cable, pipes and seawater pumps, heat exchangers, turbo generators, electrical systems, ammonia, chlorine, controls, mechanical, electrical installation, and OSA costs. The OPEX calculations are the costs relating to the operation, maintenance, repair, replacement, and administrative expenses.

The OSA cost (CAPEX and OPEX) was taken from recent literature [63] and includes costs of installation, harvest and transport, materials, and maintenance for a lifespan of 10 years. It is assumed that there will be co-operation between the OSA module and that of OTEC, with them sharing some of the transport and labour costs. As literature on the economics of OSA is scarce and covers various production methods and environmental conditions, this information should be treated with caution.

To numerically compare OTEC technology with other power-generation technologies, the LCOE was estimated. For this, a few key assumptions were made: the Capacity Factor (CF) is 92%, and the site annual-average CF is 100%. As such, Equation (1) gives the LCOE of the OTEC plant, where the amortized annual CAPEX (Equation (2)) and OPEX (Equation (3)) values were needed.

$$LCOE (\$/MWh) = CAPEX_{Levelized} + OPEX_{Levelized} \quad (1)$$

$$CAPEX_{Levelized} (\$/MWh) = \frac{CAPEX * CRF}{AEP} \quad (2)$$

$$OPEX_{Levelized} (\$/MWh) = \frac{OPEX * ELF}{AEP} \quad (3)$$

where:

$$CRF = \frac{i * (1 + i)^N}{(1 + i)^N - 1} \quad (4)$$

$$ELF = CRF * PWF \quad (5)$$

$$PWF = \frac{1 + ER}{1 - ER} * \left(1 - \left(\frac{1 + ER}{1 + i} \right)^N \right) \quad (6)$$

where, *AEP* is the annual electricity production; *CRF* refers to the capital recovery factor; *N* is the life of the OTEC system (30 years); *ELF* is the expenses levelizing factor; *PWF* is the present worth factor; *ER* refers to Inflation (3.15%), taken from the annual rate of inflation in Mexico [64]; and *i* is the interest rate (5.40%), taken from EIA [65].

Equation (1) can be expanded on both the cost and revenue sides by considering components such as financial costs, taxes, system degradation [4]. The Internal Rate of Return (IRR) was estimated to determine the economic viability of the project, and a cash flow model was created to provide a first-order approximation of the financial feasibility of this project and to estimate the payback period. The cash flow model includes incomes and outputs of the project and takes into consideration a government loan of 55% in CAPEX, at a fixed annual rate of 11.84%.

As incomes, electricity, water, OSA, CELs and carbon credits are considered. On the other hand, as outputs, salaries, administrative expenses, OSA, social security (35% in Mexico), accumulated investment, maintenance, and replacement, ISR and PTU are considered. As well as costs associated with an accidental spill of the working fluids into the sea was not considered due to the high safety standards in this industry (see Section 3.4).

2.5. OTEC Comparative Assessment

A comparison of daily power variability in different seasons of the year (seasonal variability) of the OTEC plant was undertaken. This included the daily variability of OTEC, solar, and wind energy in Cozumel for the different seasons of the year. The results give the variation of the possible energy supply, with respect to other renewable energies, and it was examined in a general way the complementary needs of these energy systems such as energy storage.

The comparison was made based on the energy consumption for Cozumel, from the statistical yearbook of Quintana Roo state, 2017, which was developed by the National Institute of Statistics and Geography, México [66]. Daily energy demand in different seasons was obtained using data from CENACE [67] and Federal Electricity Commission (CFE, in Spanish) [68].

The daily and monthly thermal gradient data for the OTEC system was obtained from Garduño-Ruiz et al. [20], for solar energy from the Photovoltaic Geographical Information System [69], and for wind energy from NASA's "Energy Data Access Viewer" [70], both for 2015 (due to information availability).

An average of the daily potential energy was obtained for each season. For this assessment, the definition of seasonality on the Mexican coast of Felix-Delgado et al. [71], was used, which considers the months of winter (December–February), spring (March–May), summer (June–August) and autumn (September–November).

The average of the daily potential energy for solar and wind power plants of 60 MW was carried out using Equation (7) and Equation (8) respectively.

$$P_{PV} = \frac{E_{PV}G_{CEM}}{G_{dm}\eta} \quad (7)$$

$$P_w = \frac{1}{2} \rho C_p A V^3 \quad (8)$$

where: P_{PV} is the installed power of the photovoltaic system, E_{PV} is the daily power generation, G_{CEM} is the solar standard test irradiance, G_{dm} is the solar irradiance and η is the overall efficiency of the system. P_w is the wind power, ρ is the air density, V is the wind speed, A the cross-sectional area of the turbine and C_p the power coefficient (0.35–0.5).

The LCOE and CF were compared to find the competitiveness of OTEC against other renewable energies. In the reviewed literature, LCOE is the cost per megawatt hour of the construction and operational phases of a power plant for all of its financial life [4,20]. CF is the ratio between the energy produced by a power generation plant for a period of time relative to the energy produced by the same power generation plant if the plant were to operate at full capacity during the same period [20]. This information was obtained from the Levelized Costs of New Generation Resources in the Annual Energy Outlook 2020 [72] for Solar, Wind Onshore and Wind Offshore.

The LCOE for OTEC was evaluated in this paper using a similar discount rate and the dollar worth reported by the U.S. Energy Information Administration (EIA) [72], but it should be noted that inflation at this time was different. The Ocean Energy Systems report [73] was used for additional information concerning OTEC and wave energy. It is important to mention that inflation, the discount rate, and the dollar worth for that year were different from those reported by the OES [73] and adjusted for accordingly in our analysis.

2.6. Socio-Environmental Risks Assessment

OTEC produces clean power. It also actively reduces CO₂ emissions, thus helping to mitigate climate change [74]. Therefore, to fully determine the feasibility of implementing an OTEC Ecopark, we also need to evaluate the positive potential socio-environmental impacts of a large-scale plant. Since there are no currently commercial plants, our assessment of the socio-environmental impacts of OTEC are mostly related to prototypes [20].

In this work, a literature review was carried out to determine the possible impacts on the ecosystems during the construction and operation phases of the OTEC Ecopark. The methodology follows present by Garduño-Ruiz [75], Marin-Coria et al. [76], and Martínez et al. [74]. Some recommendations are given about the discharge of mixture-water (from deep waters and at the sea surface), the use of chemical products, and the installation of submarine power cables, considering the Coral Reef National Park and accompanying tourist activities.

2.7. Operational Risk Recommendations

As with any new energy technology, there are significant risks associated with the operation of the system. In order to mitigate these operational risks, we consulted the literature and experts in the field including Vega [77] and Zertuche [78].

3. Results and Discussion

3.1. Overall Technical Design

The methodology from Table 1 was applied to determine the dimensions and production of each submodule. Figure 4 shows the general system.

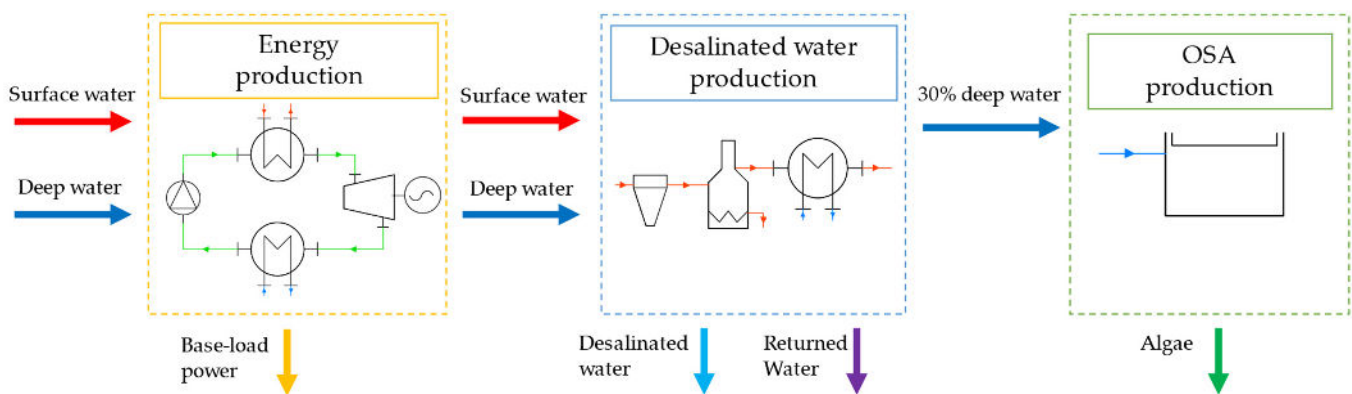


Figure 4. Inputs and outputs for each submodule of the OTEC Ecopark.

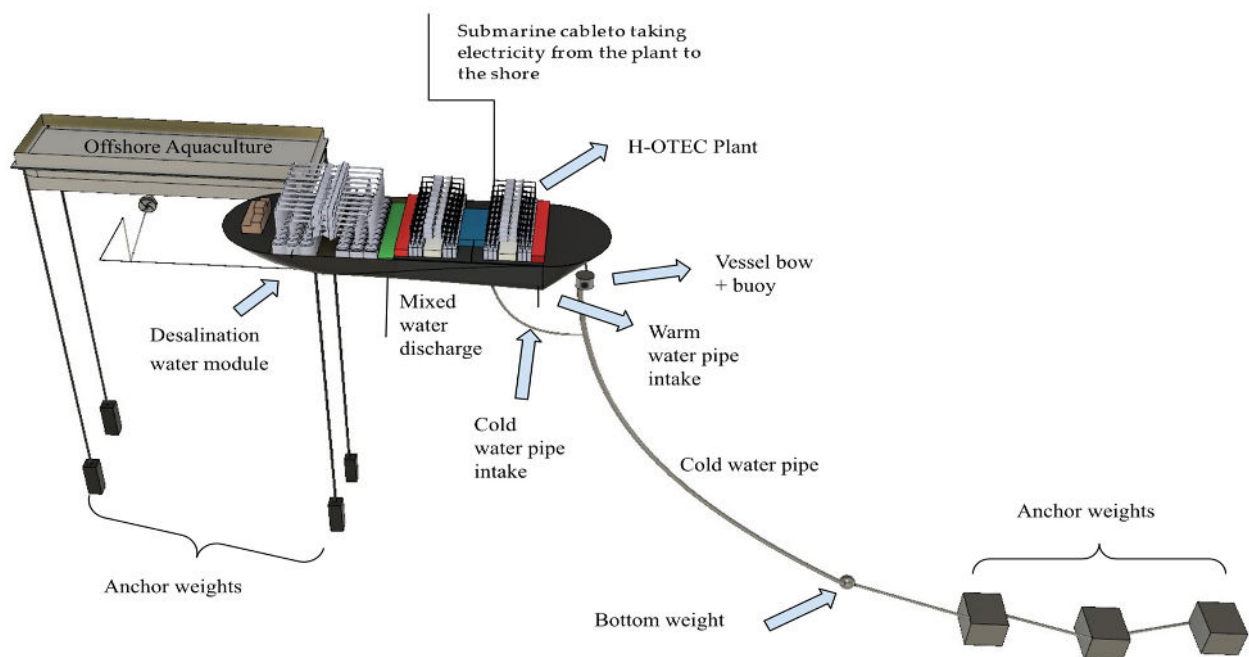
The processes of the OTEC Ecopark begin with the pumping of ammonia through the CC-Rankine, or base load power production module (Figure 4, yellow box). Then, the sea water is pumped through the heat exchangers, and then passes through the desalinated submodule (Figure 4, blue box), where just 0.5% of the surface water flow will be converted into fresh water [24,52]. The DOW flowing out of the second condenser, with an average temperature of 15.1 °C, contains 29.64 mmol/m³ of nitrates [54]. 30% of this water is then used in seaweed production (Figure 4, green box) while the rest is returned to the ocean at a depth of 142 m, in the euphotic zone [25]. The main components of the submodules are presented in Table 2, and their annual net production is described in Section 3.2.

Figure 5 shows the 3D diagram of the OTEC Ecopark. The floating platform is a straight-walled, 276,480 tons ship, with semicircular ends. It is 200 m long, 90 m wide, and 24 m deep, with an operating draft of 16 m in total and contains both the 60 MW-H-OTEC plant and the system for desalinating water. The OTEC plant is 106 m long and 80 m wide, while the desalinated water system is 78 m long and 80 m wide (Appendix B). Adjacent to the ship is the floating OSA pond, of approximately 3000 m length, 1000 m width and 1 m depth.

According to the literature, OTEC platforms are structured similarly to offshore oil and wind platforms which can withstand severe environmental conditions [79,80]. Industry standards focused on mitigating marine fouling exist for the maintenance of these platform and their mooring systems [79,80].

Table 2. Main components of the OTEC Ecopark.

Submodule	Equipment	Characteristics
Energy production	Heat exchangers	40 modules of compact plate-fin developed by Argon National Laboratory
	Turbine	Four 15 MW rotary turbines
	Pumps	Inline submersible propeller-type pumps
	Generator	Four STG generators (15,000 kVA 60 Hz)
	Submarine cable	Four submarine power cables (36 kV)
	Switching station	Voltage transformer (15 kV to 34.5 kV)
Desalinated water production	Water pipes	Sandwich construction structure pipes, 9.9 m \varnothing for cold water pipe, 10.2 m \varnothing for hot water pipe
	Deaerator	As Vega & Michaellis [24]
	Flash-evaporator	As Vega & Michaellis [24]
	Water pipes	Sandwich construction structure pipes, 5.4 m \varnothing for desalinated water pipe, 12.4 m \varnothing for hot water pipe
Platform design	Surface condenser	Brazed aluminium plate-fin configuration
	Floating pond	300 hectares (effective) \times 1 m depth
	Pumps and weights	Anchors

**Figure 5.** 3D diagram of the OTEC Ecopark.

The OES report [81], that is nowadays technically viable to adapt oil and gas production platforms to an OTEC plant less than 10 MW; however, the need for more investment and research on larger plants and the building of a commercialized OTEC plant is discussed. It is therefore important to highlight the early TRL stage of OTEC technology and the importance of studies, especially those with customized component mounting systems [79,80]. Other options for the OTEC Ecopark include (1) multi-use offshore platforms, as proposed for aquaculture and marine energy co-location [82], for example the Blue Growth Farm project funded by the European Commission [83], and (2) the use of the Very Large Floating Structure, which has been considered for energy production [84].

In our analysis, the base load power production submodule's products i.e. the annual energy generation and its CF (92%), was assumed to be used to serve the Cozumel area, transferred through the Interconnected National Grid.

To make this possible, the strategic interconnection point for this plant is the Chankanaab electrical node, 44 km away, which operates at 34.5 kV (Figure 6). The charge supplied to this node is expected to be approximately 62.5 MV thus the electrical components will need to be similar to those used in conventional gas plants, as described in Table 2.

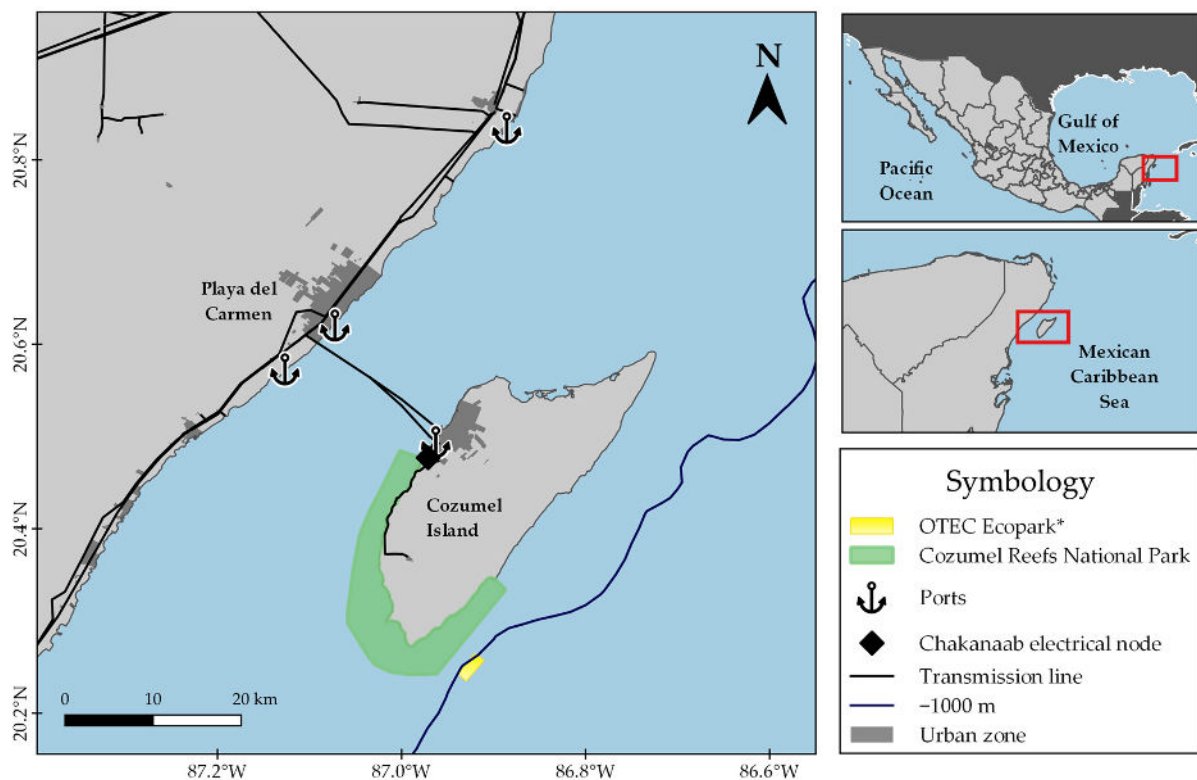


Figure 6. OTEC Ecopark interconnection point.

The desalination submodule of the OTEC Ecopark will be able to produce more than 77,000 m³ of desalinated water per day. This would comfortably meet the needs of a population of 730,000, eight times that of Cozumel [32,33]. Production and commercialization of desalinated water could meet 52% of the projected water demand in the state of Quintana Roo by 2030 [31,85–88].

From the same desalination submodule, 3 million m³ of nutrient-rich deep ocean water per day could also be produced constituting 30% of the total DOW output of the plant. This nutrient-rich stream would include 29.64 mmol/m³ of N₂ [54].

The nutrient-rich water is then fed into the OSA submodule, which then grows seaweed. Assuming a net yield per square meter of 3 kg (wet weight, equivalent to 300 g dry weight) and a N₂ demand of approximately 60 g per m³ over three weeks [55], the daily production per square meter would be 174.5 g of *Ulva* spp. in wet weight, or 23.25 g in dry weight [48]. In a cultivation area of 300 effective hectares this would give a daily production of 25 thousand tons per year in dry weight, or 7 thousand tons of carbon per year excluding salt content.

Unlike analysis done for other OTEC plants, we consider the seasonal variability of mass and energy flow thus varying the value of water input. To illustrate, the Makai OTEC Thermodynamic and Economic Model, for a 142.5 MW gross power CC-OTEC plant (100 MW net power) produced warm and cold-water intake rates of 420,000 and 350,000 kg/s, respectively [89]. Another example was presented by Rieza [90], who proposed an optimization of this model to obtain 100 MW net power with two different scenarios: (1) warm and cold-water

rates of 430,000 and 320,000 kg/s, respectively, and 141.4 MW gross power, and (2) warm and cold-water rates of 500,000 and 370,000 kg/s, respectively and 139.4 MW gross power. On the other hand, Vega & Michaelis [24] considered a water intake rate for an 80 MW gross CC-OTEC plant of 270,400 kg/s for warm water, and 142,300 kg/s for cold water.

3.2. Financial Evaluation

The feasibility assessment of the OTEC Ecopark off Cozumel suggests the following financial outcomes:

- An IRR of 35%, meaning that the project would be profitable over its lifespan (30 years).
- An Investment Recovery Period of 5 years, paying equities and loans.
- NPV of \$2656.78 M at the end of the projected lifespan demonstrating profitability.

The OTEC Ecopark project needs an initial investment of \$655.38 M, with a 45% (\$294.92 M) equity and 55% (\$360.46 M) government capital structure loan. The repayment schedule is composed of equal main payments over a four-year period, with an amortization of 25% of the loan each year.

For the first operational year, a CAPEX (\$655.38 M), an OPEX (\$69.66 M) and an annual revenue (\$348 M, including the sale of CELs/carbon credits) were the inputs used for the financial assessment, see Appendix A. Over a year, the OTEC Ecopark would provide the following benefits (Table 3):

- (1) an expected electricity output of 466,139 MWh/year at a LCOE of \$326.63 MWh with a revenue of \$63.90 M, 18.36% of the total annual revenue.
- (2) desalinated water for human consumption at a rate of 77,026.26 m³/day with revenues of \$21.73 M, 6.24% of the total annual revenue.
- (3) an OSA that will produce 69.75 ton/day *Ulva* spp., in dry weight, and revenues of \$254.59 M, 73.13% of the total annual revenue;
- (4) CEL per MWh produced, with a revenue of \$7.72 M, 2.22% of the total annual revenues.
- (5) carbon credits equivalent to 19.33 ton/day of carbon sequestration (CO₂), with revenues of \$0.08 M, 0.2% of the total annual revenue.

CAPEX, OPEX and revenues vary each year of operation. The CAPEX includes the replacement of machinery and equipment, the OPEX includes salary increases due to inflation and social security payments. For the revenues, the annual increase in revenue from desalinated water and algae sales will increase with inflation.

From this assessment, it was found that the OSA offers most revenue; up to 70% of the total revenue in the first year. The sale tariffs for electricity were taken from CFE [91], for desalinated water from the National Water Commission (CONAGUA [92], in Spanish), and for *Ulva* spp. from MundoHVACR [93] (these values depend on the market). The value of the CELs comes from Forbes [94] and the value of the carbon credits from MundoHVACR [93] the energy production of the OTEC plant and the carbon sequestered by *Ulva* spp.

For the first four years of operation, negative cash flows are predicted, but the OTEC Ecopark will ultimately generate \$2656.78 M net. It is important to note that the cash flows will fall in the 16th year of operations due to the depreciation of various components, while in the 11th and 22nd years, replacements will be needed for the OSA submodule (Figure 7). In line with the 50% reduction in offshore wind LCOE, the financial model assumes that the LCOE of OTEC would decrease by 40% every 10 years [65,95].

Overall, it is seen that an OTEC Ecopark off Cozumel will be both profitable and therefore economically viable. As this would be the first commercial OTEC Ecopark installation would probably take about 5 years [96]. The installation could be staggered, with only one product at a time being developed and marketed. As this begins to make a profit, another product could be added, in line with the needs and opportunities of the market. In line with the profitability of the products (see Table 3) the Ecopark could first have the very profitable OSA submodule, with electricity and water submodules following.

Table 3. LCOE estimations for the project (USD \$ in 2020).

Variable	Indicator	Value
Parameters	CAPEX	\$655.38 M
	Yearly OPEX	\$69.66 M
	Annual electricity production	466,139 MWh
	Daily desalinated water production	77,026.26 m ³ /day
	Daily <i>Ulva</i> spp. Production	69.75 ton/day
	Daily CO ₂ sequestrated (OTEC and <i>Ulva</i> spp.)	19.33 ton/day
Capital payment	CRF: Investment Levelizing Factor for I and N (Capital Recovery Factor)	9.90%
	Levelized Capital Cost (CC * CRF/Annual Electricity Production)	139.14 \$/MWh
OPEX costs	ELF: Expenses Levelized Factor for I, N and escalation	1.25
	PWF: Present Worth Factor accounting for inflation	12.68
	Levelized OPEX (OPEX * ELF/Annual Electricity Production)	187.49 \$/MWh
	LCOE	326.63 \$/MWh
Annual sales (No profit, no credits)	Electricity (rates: \$0.149/kWh)	\$63.90 M
	Water (rates: \$0.77/m ³)	\$21.73 M
	<i>Ulva</i> spp. (\$10,000/ton)	\$254.59 M
	Total Annual Sales (no incomes)	\$340 M
Annual sales with other incomes	CELs (annual)	\$7.72 M
	Carbon Credits (annual)	\$0.08 M
	Total Annual Sales (with incomes)	\$348 M

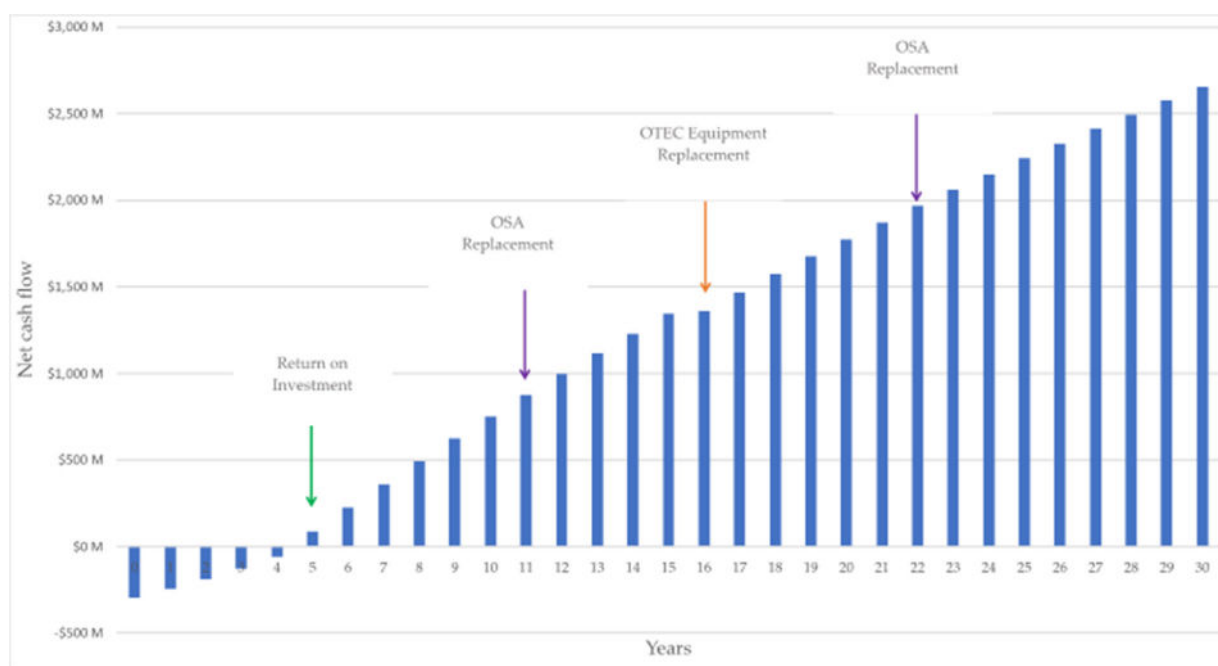


Figure 7. 30-year cash flow model for the OTEC Ecopark.

In future work, the financial projection could be re-evaluated considering aspects of scale economy, such as a reduction of the LCOE [65], and other factors related to technical and environmental features. For example, the energy losses caused by transmission and distribution, and costs associated with operational risks, such as leaks of working fluids.

3.3. Comparison of the OTEC Ecopark with Other Renewable Energy Alternatives

Compared to other renewable energy technologies such as wind and solar, OTEC's advantages include: reliable baseload power, low carbon emissions, flexible land requirements, and resiliency to extreme weather events. One of its greatest advantages is its CF (92%) [96]. In contrast to the intermittent nature of other renewable technologies, which makes them unlikely to satisfy a household's energy demand throughout the day, OTEC, like nuclear power, can generate electricity constantly. Moreover, the additional products of an Ecopark facilitate an easy market entry, thanks to the positive social and economic effects they create.

Figure 8 shows the daily generation profile for each season. The potential energy from OTEC is greatest in summer and autumn, whereas solar energy has its peak in spring and summer, and wind energy in autumn.

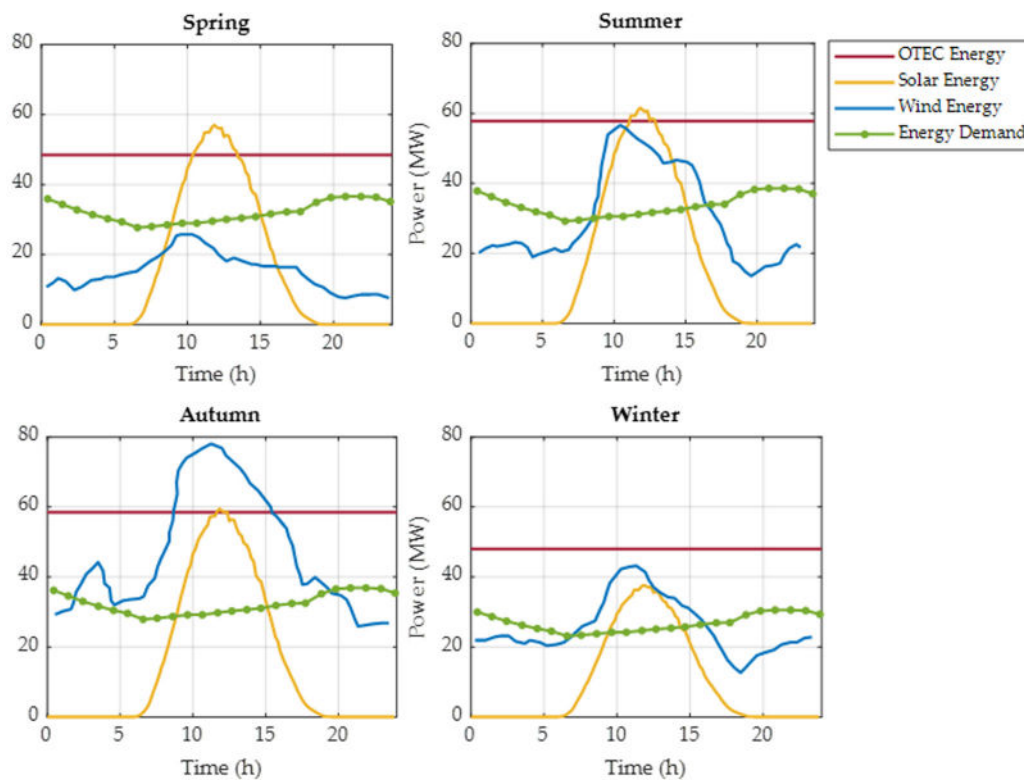


Figure 8. Comparison of seasonal power generation in Cozumel: OTEC, solar and wind energies.

The seasonal variations of OTEC do not exceed 16% of the average energy produced, while solar energy and wind energy can vary by 50% and almost 100% respectively. As the seasonal variability of OTEC is far less, this translates into greater energy security.

LCOE Comparison

Based on power generation alone, with data from [65,73] and this paper, a comparison of the LCOE and CF of various power plants is presented in Figure 9. The LCOE of a 60 MW-H-OTEC floating power plant was 326.80 \$ MWh, which is higher than the cost of an OTEC plant estimated by OES [73]. However, the economic conditions (such as inflation and discount rate) were different in the OES analyses. Although the OTEC LCOE is higher

than that of other renewable technologies, OTEC's high reliability to supply baseload power is its competitive advantage against other renewable technologies.

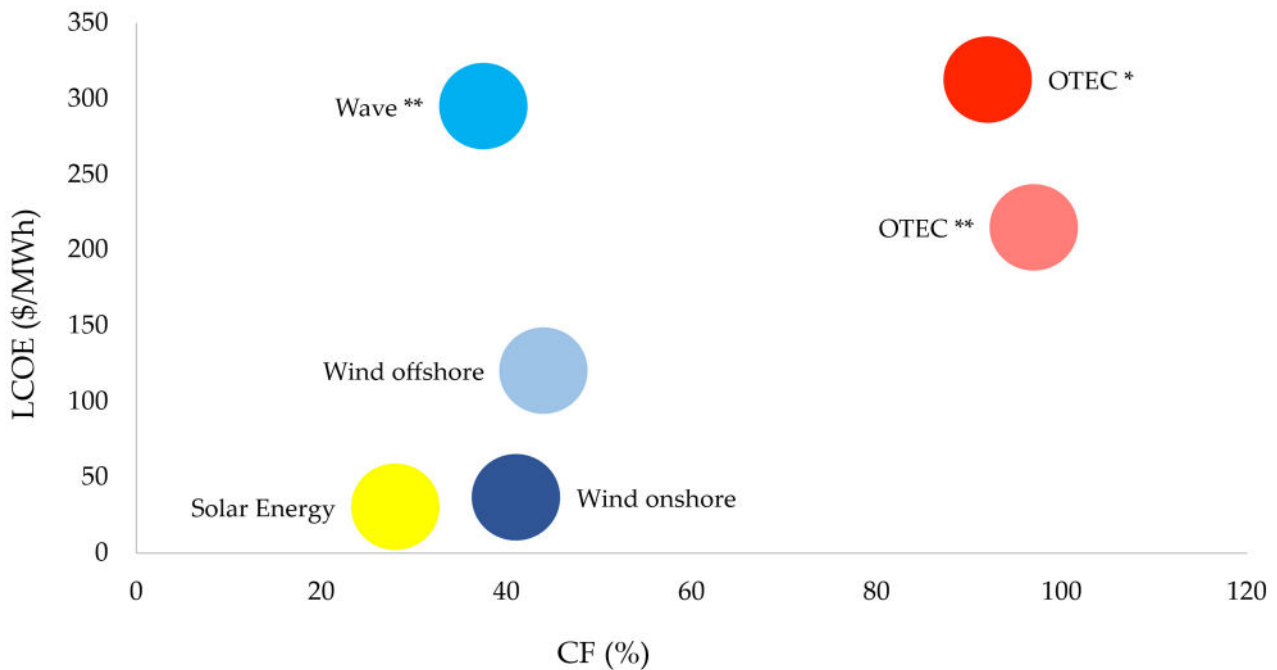


Figure 9. Comparison of the LCOE and CF for OTEC and other renewable energies (Own elaboration based on data from the present work *, EIA [65]; OES [73] **).

Thus, the CF of the OTEC plant can be much higher (92%) [20] than solar energy (28%) [65] and wave energy (38%). Additionally, prioritizing investment in research and development can lead to significant reductions in LCOE over a decade [65,95].

OTEC offers a promising way to diversify the energy matrix while also serving a community's non-energy needs. In this way, OTEC does not necessarily compete against other renewable energy technologies, as OTEC can broadly contribute to the local economy through its sale of by-products. Presently, the LCOE estimation accounts for only for energy generation and should be updated to include CAPEX based on present technology. With the inclusion of the sale of by-products, OTEC can be economically viable despite its high LCOE.

3.4. Mitigating Socio-Environmental Risks

According to Zamorano-Guzmán [97], the construction and operational phases are the most important in relation to environmental impacts. In these phases, environmental alterations affect organisms and marine fauna; humans; landscape; vegetation; as well as hydrodynamic; geomorphology and physicochemical factors. These alterations can be caused by (a) the laying of pipes (b) the presence of the platform and (c) the demolition of infrastructure and generation of rubble in the decommissioning phase. Some of these impacts are shown in Table 4, which was modified from Garduño-Ruiz [75].

From an extensive literature review and consultation with experts, we identified the most serious environmental impacts that an OTEC Ecopark could generate. These impacts arise from the discharge of the returned water into the sea, the uses of chemical products for cleaning the plant, the installation of submarine cables, and social perception, Table 5.

Table 4. Possible impacts from to the implementation of an OTEC Ecopark in a two-stage scheme (construction and operation).

Phase	Activity	Impact
Construction (C)	C1. Material transportation	Changes in the community of marine and terrestrial fauna (C1, C2, C3, C5, C6)
	C2. Construction of civil works (modules, anchorage, noise, vibrations, warehouses, etc.)	Impact on the community of residents due to landscape change. The possible social rejection of the project (C1, C2, C4, C5)
	C3. Laying of pipes	Maritime routes disruption. Visual impacts on the local landscape (C2, C3, C4, C5)
	C4. Maritime navigation routes	Changes in the vegetation distribution (C3, C5, C6)
	C5. Platform	Disruption of wave patterns and changes in oceanic circulation zones (C3, C4, C5)
	C6. Excavation	Sediment transport modification and coastal erosion processes (C2, C3, C6)
Operation (O)	O1. Platform	Modification of the marine fauna community and migrations. Changes in distribution, production, and abundance of the organisms. Risks of Collision. New habitat deployment. Alteration in behavior and distribution of birds (O1, O2, O3, O4, O6, O7, O8)
	O2. Noise and vibrations	Impact on the community of inhabitants, especially in tourism activities due to change of landscape (O1, O2, O3, O5)
	O3. Discharge of water with another type of physical-chemical composition (working fluid, brine, anti-biofouling materials, sanitary waste, and nutrient transport)	Maritime routes disruption. Visual impacts on the local landscape. Land-use changes (O1, O4, O5, O6, O7).
	O4. Pipelines	(O1, O4, O5, O6, O7)
	O5. Electrical substation	Change and disruption of the vegetation (O1, O4, O5, O6, O7)
	O6. Submarine power cable	Sediment transport disruption. Possible re-suspension of sediment. Coastal erosion processes. Nutrient plume spread and eutrophication. Changes in the thermohaline structure. Release of toxic discharge. Voltage and electromagnetic field exposure (O1, O4, O5, O6, O7, O8)
	O7. Anchorage	
	O8. Sea water extraction	

Modified from Garduño-Ruiz [75].

The Cozumel Reefs National Park, a popular tourist attraction [102] located 1.8 km away from the OTEC Ecopark study area [103], could be harmed by the operation of an OTEC Ecopark, due to the deep-water discharge plume. Although 5 some recommendations are given in Table to minimise the negative impact of these activities, constant monitoring of physicochemical variables is required during deployment to help detect leaks in real-time that could have repercussions on the coral reef. Likewise, future work is recommended to make detailed analyses of the potential environmental effects of an OTEC Ecopark, by modelling water pollution discharge and Coral Reefs affectation during OTEC plant operation, for example.

Table 5. General summary of the OTEC Ecopark technical evaluation.

Activity	Consequence	Mitigation
Discharge of mixture-water	Harmful algal blooms alter the ocean's chemical composition (Rivera et al., [22]).	Discharging the water below the euphotic zone (142.62 m) [25], and using DOW for by-products
Use of chemicals products	Local ecosystems affected Hazardous to employees	Following industry safety protocols; measuring physicochemical parameters continuously in areas of potential release [98,99]. <i>Ulva</i> spp. cultivation can help absorb undue ammonia release [48,100].
Installation of submarine cables	Damage to the Cozumel reef structure, increase in water turbidity, and intensify of underwater noise	Collaborate with federal, state legislation and local institutions to conduct on-site monitoring and detect negative environmental impacts.
Social perception	Negative social perception [20,101]	Strengthening communications, transparency, social engagement through outreach, environmental education and social networks, participation of the community, taking into consideration the General Administrative Provisions on the Evaluation of Social Impact in the Energy Sector.

On the other hand, while OSA is still in the early stages of development, its environmental impact is presumed to be smaller than that of land-based aquaculture [43,104]. Indeed, offshore aquaculture is considered to have positive impacts. For instance, as it grows, seaweed can remove inorganic nutrients (a remedial effect), sequester carbon, and absorb any ammonia that could leak from the energy sub-module of the plant [48,100].

There are no large-scale socio-environmental impact assessments of OTEC, as there are few operational OTEC Ecoparks. Similarly, some risks associated with OTEC, such as with the submarine cables, cannot be quantified until installation has begun.

In considering social impacts of an OTEC Ecopark the following benefits to the local community are seen: (1) electricity will become available to those without it at present; (2) access to high quality electricity will increase, helping the state meet energy demands when the national electrical grid is overloaded; (3) additional products can help diversify the economic activities of the area. However, public acceptance of an OTEC Ecopark is vital. Thus, it is imperative to practice communication and transparency with the local community in order to increase citizen awareness and participation in sustainable development projects like this OTEC plant, as noted by Thomsen [105]. It is also necessary to promote good practices for evaluating the environmental and social impacts of all energy projects.

Regarding tourism activities, an OTEC Ecopark, offshore from Cozumel Island, is not competing for common space with the tourism industry and is expected to be dismissed. The project would be opposite the area with highest tourist density on the island (the urban area where ferries and cruise ships arrive) [106]. However, future work should evaluate potential conflicts between the OTEC Ecopark and existing marine activities (fishing, maritime transport, and ecotourism, mainly) through robust marine spatial planning. This should allow the generation of suitable management plans and strategies, where social conflicts are minimised, marine species and habitats are protected, and sustainable development is promoted.

On the other hand, the OTEC Ecopark proposed in this paper could have a significant positive impact on the blue economy of Cozumel. The Ecopark would promote awareness of environmental issues, practice a more sustainable resource management program, and bring steady jobs to residents during the offseason. According to Li [107], the stimulation of tourism activities could generate greater pressure on the environment, especially when local demand peaks during the main holiday season [108]. In addition, community awareness and political will could foster more efficient management to accelerate the island's sustainability [109].

3.5. Operational Risk Recommendations

The heat exchangers in an OTEC Ecopark require careful maintenance to guarantee their functioning [77]. Every heat exchanger module needs to be serviced for at least 1 week each year. As the Ecopark has four heat exchanger submodules, the plant will run 48 of the 52 weeks of the year, a plant CF of 92%. This will affect the electricity, freshwater, and aquaculture production. Because of the seasonal variations in the zone studied, scheduled maintenance should be performed in winter months, when the temperature differential of the water is lowest. Some authors also recommend that chlorine is used 1 h/day in the surface water inlet, at a concentration of 70 parts per billion, to prevent biofouling caused by marine organisms [52].

Maintenance is proposed for the winter months as the efficiency of an OTEC plant and chance of severe weather is lowest. Additionally, according to CFE [68], electricity consumption is lowest for this municipality during this time. The maintenance should be carried out in modules and at times of low energy demand [20]. However, as the OTEC Ecopark will be connected to the National Electricity Grid, other factors have to be taken into account with CENACE to assure that Cozumel tourists and inhabitants have electricity even during maintenance, including that of other electricity plants nearby. These factors will only be known during production, and these will be different regarding location and its electricity grid characteristics.

To ensure that the equipment will function safely while immersed in saltwater, as well as to prevent environmental harm, the system must have embedded control and measurement instruments. The system will also include sensors to measure the temperature, pressure and flow along the closed cycle ammonia lines [110].

It is also important to measure the salinity and pH of the input and output water that pass through the desalination submodule [77] to ensure the quality of the freshwater, aquaculture water and re-injection water, which we have proposed to be 67% deep water and 33% surface water. Furthermore, as a leakage of ammonia or chlorine would be toxic for the marine organisms, these gases must also be monitored [110].

Given that the most attractive regions for OTEC plants are subtropical and tropical, extreme weather conditions must be considered. Tropical cyclones (TC) are the biggest threat to OTEC installation, as there is a high probability that these will become hurricanes. These risks can be mitigated by complying with basic construction standards and developing management plans that ensure that operations are not affected during these natural hazards. This type of plant is designed to survive a theoretical impact of a 100-year return period storm and other catastrophic events (e. g. earthquakes, extreme winds, waves, and currents) [111]. As an added safety measure, we also considered a hurricane contingency plan, where the procedure to disconnect the platform from the submarine cable and the water pipes and relocate the platform away from the storm is described [77].

3.6. Comparison with Other OTEC Ecoparks

To meet the demand for WEF in coastal regions OTEC technology and by-products have been harnessed in pilot projects around the world, mainly on island sites [112]. Although each location has specific needs, these OTEC developments and the proposed Cozumel OTEC Ecopark share the physical feasibility for OTEC application, an interest in developing industries based on OTEC by-products and the development of the islands through the use of electricity from ocean temperature differentials. Some of these projects are compared here, taking into account their location and plant configuration, the monitoring of environmental variables, and the diversification of the markets.

Unlike the OTEC Cozumel Ecopark, the BlueRise in Curaçao [18] and San Andres in Colombia [8] are land-based Ecoparks. The New Energy for Martinique and Overseas (NEMO) project at Martinique [113] is developed using a floating barge similar to the OTEC Ecopark in Cozumel. On the other hand, to preserve coastal biodiversity, like the Cozumel OTEC Ecopark, the PROTECH project in Puerto Rico seeks to minimize potential environmental impacts by implementing measures already tested in similar facilities [114],

such as Kailua Kona, Hawaii [8] and Okinawa, Japan [113] plants that constantly monitor oceanographic and biological conditions in operation and maintenance processes.

As with the Cozumel OTEC Ecopark, some projects have proposed market diversification to meet community needs and make the OTEC plant more profitable. The Bluerise and the San Andres OTEC Ecoparks have industrial clusters of SWAC, water desalination, and food production [8,113]. PROTECH is the plant with most market diversification: energy, desalinated water, and SWAC that meet the needs of various industries [114]. At the OTEC technology demonstration in Okinawa, Japan, the OTEC plant showed how it compensates economic losses when the thermal gradient is below 20 °C [13] by diversifying its market; supplying DOW to cosmetic companies and promoting tourism through environmental education and outreach via plant visits for tourists.

Socio-economic and political factors are also relevant when comparing potential OTEC locations. OTEC systems can satisfy energy demand for remote and isolated communities, but the local communication systems and infrastructure must be taken into account for the construction and operation phase of an Ecopark [40]. In addition, the sizing of the OTEC plant must be consistent with the size of the population and its demands. Other multi-purpose projects on offshore platforms such as Daguang, Daranshan, and Sehnghshan in China have demonstrated the great potential of marine energy to serve remote and isolated communities, providing them not only with a sustainable, safe, and affordable energy source but also with socio-economic benefits such as food and jobs [83].

4. Conclusions

A theoretical 60 MW offshore OTEC plant coupled to an offshore aquaculture farm (OSA) in a technological Ecopark off the island of Cozumel was conceived and analysed. It was shown that this Ecopark can meet the needs of coastal communities for energy production, desalinated water, and food production through *Ulva* spp. cultivation. The study was carried out through a technical-economic evaluation of the OTEC Ecopark. Considering the main socio-environmental and operational risks, the OTEC plant was compared to other renewable energy technologies.

As main result, the financial assessment showed that OTEC Ecopark is economically viable, having a CAPEX of \$655.38 M, an OPEX of \$69.66 M and annual revenue of \$348 M. These values should be taken as indicative of the economic viability of this system. The most profitable product was OSA, followed by electricity and finally water production.

In addition, the implementation of an OTEC Ecopark could be carried out in a staggered manner following the profitability of the products, or based on the needs of the community, in prioritizing the order of the building of the submodules. This could result in an increase in public or private investment.

More specialized technical studies are needed to elaborate in detail the investment for the OTEC Ecopark. For example, the optimum distance between the platform and the interconnection node must be determined to calculate the length of the submarine cable and the energy losses caused by transmission and distribution. Also, costs associated to operational risks, such as working fluid leaking must be considered in the detailed financial feasibility study. Also, studies related to social impacts in Cozumel caused by OSA production would help community engagement in the region and encourage OTEC development nationwide.

It is evident that although OTEC is a promising renewable energy source, further research is still required. Particularly in the development of large-scale plant installation technologies and the evaluation of the benefits of by-products. It is hoped that this article will serve as motivation to drive the deployment of OTEC Ecoparks and facilitate comprehensive sustainable solutions that help foster more resilient coastal communities around the world.

We would like to emphasise that this methodology could be applied to other potential OTEC sites, but that consideration of the specific characteristics for that site would be important for design variables (i.e., temperature, distance to the coast), economic variables

(i.e., taxes and local electricity market schemes), and environmental characteristics (i.e., natural protected areas restrictions).

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Abbreviations

OTEC	Ocean Thermal Energy Conversion
OSA	Offshore Seaweed Aquaculture
DOW	Deep Ocean Water
SWAC	Sea Water Air Conditioning
CC	Closed Cycle
H	Hybrid
LCOE	Levelized Cost of Energy
WEF	Water, Energy, and Food
SDGs	UN Sustainable Development Goals
CELS	Clean Energy Certificates
NPV	Net Present Value
CAPEX	Capital Costs
OPEX	Operation, Maintenance, Repair, Replacement and Administrative Expenses
ISR	Taxes
PTU	Employee Participation in Profit Sharing Payments
CF	Capacity Factor
AEP	Annual Electricity Production

CRF	Capital Recovery Factor
N	System life
ELF	Expenses Levelizing Factor
PWF	Present Worth Factor
ERF	Inflation
i	Interest
IRR	Internal Rate of Return
P_{PV}	Installed Power of the Photovoltaic System
E_{PV}	Daily Power Generation
G_{CEM}	Solar Standard Test Irradiance
G_{dm}	Solar Irradiance
η	Efficiency of the System
P_w	Wind Power
ρ	Air Density
V	Wind Speed
A	Cross-Sectional Area of the Turbine
C_p	Power Coefficient

Appendix A. Specifications for the Financial Feasibility Assessment of OTEC Ecopark

Size	60 MW-Gross			
Cycle	Hybrid			
Date	April 2021			
Component	CAPEX (\$M)	OPEX		
		Reparation and Replacement (\$M)		Operation and Administrative Expenses 1st Year (\$M)
Platform	145.09	-	4.84	-
Anchor	34.82	-	1.16	-
Submarine power cable	59.49	-	1.98	-
Seawater pipes (installed)	87.05	-	2.90	-
Seawater pumps (installed)	34.82	2.32	-	-
Power block (15 MW gross modules)	-	-	-	-
Heat exchangers	137.83	9.19	-	-
Turbo-generators	47.88	3.19	-	-
Electrical/Ammonia/Chlorine/Controls	44.98	-	1.50	-
Installation Mechanical & Electrical	62.39	-	2.08	-
Offshore Aquaculture (OSA)	1.04	15-years 0.10	30-years -	-
Total	655.38	10-years 29.27		40.40

Notes:

CAPEX

Information for USA/Japan/EU Manufacturers

Assume the sum of all other cost are equivalent to Closed Cycle

OSA cost from Sander et al. [63].

OPEX

A total staff of 17 is required to manage and operate floating plant in shifts 24/7

It is assumed that OSA and OTEC sharing transport and labor costs.

OSA cost (\$5.33 M) from Sander et al. [63]

Using MX Labor Rates the O&M portion and social security for the first year are \$0.015 M

Administrative expenses for the first year are \$40.40 M

To estimate the R&R portion for the first year: Pumps, HXs and T-G replaced in 15-years all other components in 30-years.

First year estimate for R&R portion is (as given in this Table) \$29.27 M

Appendix B. 60 MW H-OTEC Platform Diagrams

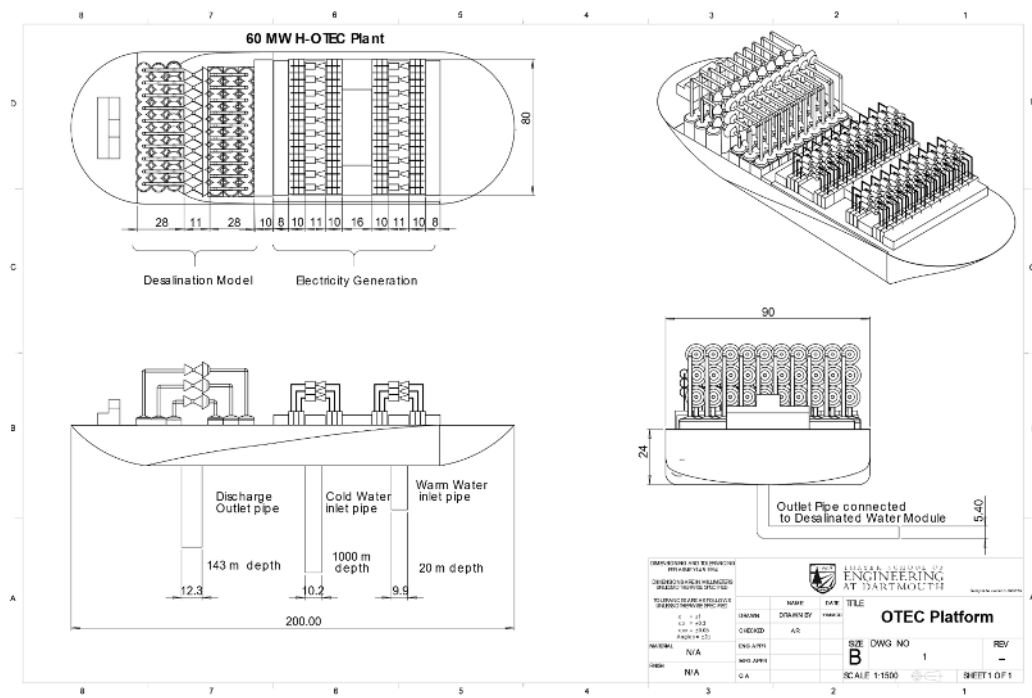


Figure A1. 60 MW H-OTEC Platform CAD Diagram.

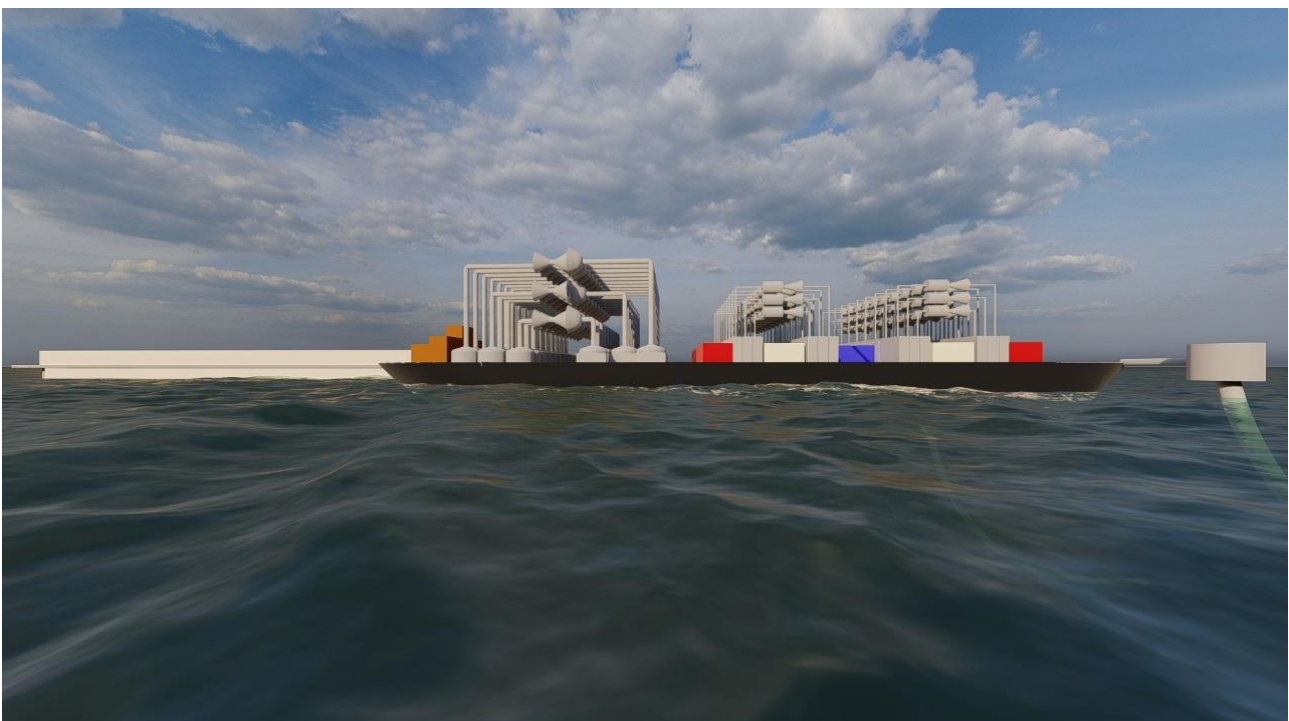


Figure A2. 60 MW H-OTEC Platform and Floating Pond 3D Model.

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