Renewable Energy 201 (2022) 60–69

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Site selection of Ocean Thermal Energy Conversion (OTEC) plants for Barbados

Kashawn Hall [a,*], Solange Kelly [b], Legena Henry [a]

[a] The University of the West Indies, Cave Hill, Barbados
[b] The University of Trinidad and Tobago, Trinidad and Tobago

ARTICLE INFO

Keywords:
Ocean thermal energy conversion (OTEC)
Renewable energy
Site selection
Multi-criteria decision analysis
Caribbean
Barbados

ABSTRACT

Tropical climates provide ideal year-round marine thermal gradients that meet the requirements for the operation of commercial Ocean Thermal Energy Conversion (OTEC) plants. This study assesses Barbados' OTEC resources and viability at several locations around the island. The island's coastline was divided into four quadrants and four proposed plant locations were selected within each quadrant based on the shortest distance to the coast. These locations were ranked via a multi-criteria decision analysis using the AHP-TOPSIS methodology. The results of the analysis ranked east coast plant locations highest, with the north, south and west coasts following in that order. The results of this study can guide OTEC development as well as marine planning and investment on the island.

1. Introduction

With the set goal of restraining rising global temperatures to within 2 °C, 196 signed country parties of the 'Paris Agreement' have sworn to recognize the adverse effects of climate change and what it can pose upon Small Island Developing States (SIDS) in 2015 ([1], pp 13). Six years later, the 2021 United Nations Climate Change Conference (COP26) 'Recognizes that the impacts of climate change will be much lower at the temperature increase of 1.5 °C compared with 2 °C, and resolves to pursue efforts to limit the temperature increase to 1.5 °C' ([2], pp3). Limited by their small land space and population, SIDS have a high dependency on the importation of goods and services, where 87% of primary energy consumed is from the importation of petroleum goods [3]. With this, regionwide contributions to the overall goal of greater energy efficiency have seen the implementation of many renewables throughout the islands.

To further renewable energy (RE) penetration, the Caribbean Marine Energy Technology (CariMET) Forum was hosted through November 6th - 7th, 2019 in Grenada. This forum set goals into introducing ocean-based technologies, among which was Ocean Thermal Energy Conversion (OTEC). OTEC exploits the ocean's naturally occurring thermal gradient to generate electrical energy [4,5]. Solar radiation emitted from the sun meets the earth's oceans, warming its upper layer. This warm water remains in the upper layer of the ocean whilst the colder seawater sinks due to density stratification and thermohaline circulation. The temperature stratified seawater represents the natural thermal gradient found within the world's oceans. OTEC generation is then a heat engine - a system that converts thermal energy to mechanical energy - utilizing the warm/cold seawater as heat sources/sinks [6].

OTEC is a baseload energy technology, requiring a minimum temperature differential of 20 °C to be considered viable [7,8]. To investigate this, we first look to the deep, cold seawater source. Water of around 4–6 °C can be found around 1000 m deep within the world's ocean [7], which maintains this low temperature range consistently. In some cases, this cold seawater source can be found higher up the water column than the rule of thumb 1000 m depth, leading to shorter cold seawater intake lengths and greater technical feasibility [5]. Nevertheless, with the relative consistency of the deep-water temperature, the temperature differential is then dependent on the warm seawater temperature. Fig. 1 highlights the sea surface temperatures of the global ocean, showing the Tropics as a clear OTEC hot spot, with temperature differentials 20 °C or higher [9]. Consideration of temperature differential availability must also include the longevity of the temperature state as well. Some locations may experience sea surface temperature fluctuations throughout the year. This would require both off-design and design point investigation to ensure the viability of OTEC power output

---

* Corresponding author. Howell's Cross Road, St. Michael, Barbados.
E-mail addresses: kashawn.hall@mycavehill.uwi.edu, shawnhall.kh@gmail.com (K. Hall), Solange.Kelly@utt.edu.tt (S. Kelly), legena.henry@cavehill.uwi.edu (L. Henry).

https://doi.org/10.1016/j.renene.2022.11.049
Received 24 May 2022; Received in revised form 3 November 2022; Accepted 12 November 2022
Available online 17 November 2022
0960-1481/© 2022 Elsevier Ltd. All rights reserved.

continually [10]. This is why locations with quasi-uniformity of surface water temperature, showing little seasonal impact year-round are ideal [6].

Barbados is a Small Island Developing State in the Caribbean (See Fig. 1), being 166 square miles and having a population of approximately 288,000 people [11]. Much like other small island developing states, Barbados relies heavily on international imports on petroleum-based products for energy. As a SIDS, Barbados is highly dependent on international imports and as such is highly vulnerable to international factors and price fluctuations. Barbados' average electricity consumption is 926.8 GWh (BNEP) and according to the IRENA country profile, in 2019 the island had an energy generation of 1165 GWh, 1121 GWh from non-RE sources and 44 GWh from RE (96%/4%) (RE generation was 100% solar) [12].

This paper assesses OTEC site selection considerations for Barbados. Once finalized, the considerations are used to investigate the thermal structure of the designated study area(s) to further assess the viability for sustained commercial OTEC generation for the island. This will include a literature review in Section 2, data acquisition and methodology in Section 3, data visualization and results in Section 4 and the discussion in Section 5.

2. Literature review

They are a few common guiding factors that determine optimum locations for OTEC operations throughout literature. Thermal difference is usually considered first and foremost - in the case of Uehara et al. [4], they focused primarily on temperature profiles to determine the conceptual placement of an OTEC plant in the Philippines. In order to determine temporal variability of the thermal gradient, Nihous [14] employed the Hybrid Coordinate Ocean Model (HYCOM) to generate daily ocean temperature data over a 2-year period. VanZwieten et al. [15] also utilized the HYCOM platform to access electrical power potential in Florida. VanZwieten stated HYCOM was an applicable means of estimating OTEC thermal potential with the greatest error occurring at shallower depths. Hamedi et al. [8], not having the necessary data within their study area in the Oman Sea used an analog approach that utilized general profiles and data from the neighboring Arabian Sea to access the thermal resource. While this solidifies the necessity for temperature data, Uehara [4] provided addition conditions that should be considered - these were further elaborated on by Devis-Morales [5]. For example, bathymetry must be considered as it affects decision making on plant type [4] and distance to applicable thermal resource - a relatively steep slope (15°-20°) and smooth seafloor is beneficial for reducing pipeline/cable length [5]. Specific wave data and ocean current data was also listed as necessary considerations, wave heights of 3.7 m (6 m maximums) were listed as extreme operational conditions by Ref. [5], wind speed and natural disaster likelihood were stated as well [4,5]. Langer et al. [16] created a gridded mesh within the Exclusive economic zone (EEZ) of Indonesia to find the most optimal location for a plant. With each grid point (27.8 km × 27.8 km gridded mesh) representative of an OTEC plant, they were evaluated based on longitude and latitude of the OTEC site, longitude and latitude of connection points (capital city), province of connection points, distance between plant and connection points, seawater temperature difference, water depth and PPA tariff at connection point.

Much like Langer et al., Garduño-Ruiz et al. [17] were guided by more considerations than thermal potential in deciding the optimal location of an OTEC plant along the coasts of Mexico. Although still heavily weighted, factors other than thermal potential can influence the final decision. As seen in their study, one of their two final options had the lowest thermal power potential out of their four (4) potential sites. Once the EEZ on both the Pacific Ocean and Caribbean Sea coasts of Mexico were mapped, the authors considered along with the thermal resources; (i) bathymetry, (ii) OTEC net power (based on theoretical calculations using the temperature differences), (iii) persistence of net power, (iv) distance to cold-water intake at 1000 m depth, (v) extreme events, distance to the electricity grid, (vi) protected areas, (vii) marginalization index, (viii) homes without electricity and (ix) local marginal. These criteria were placed within a multi-criteria decision

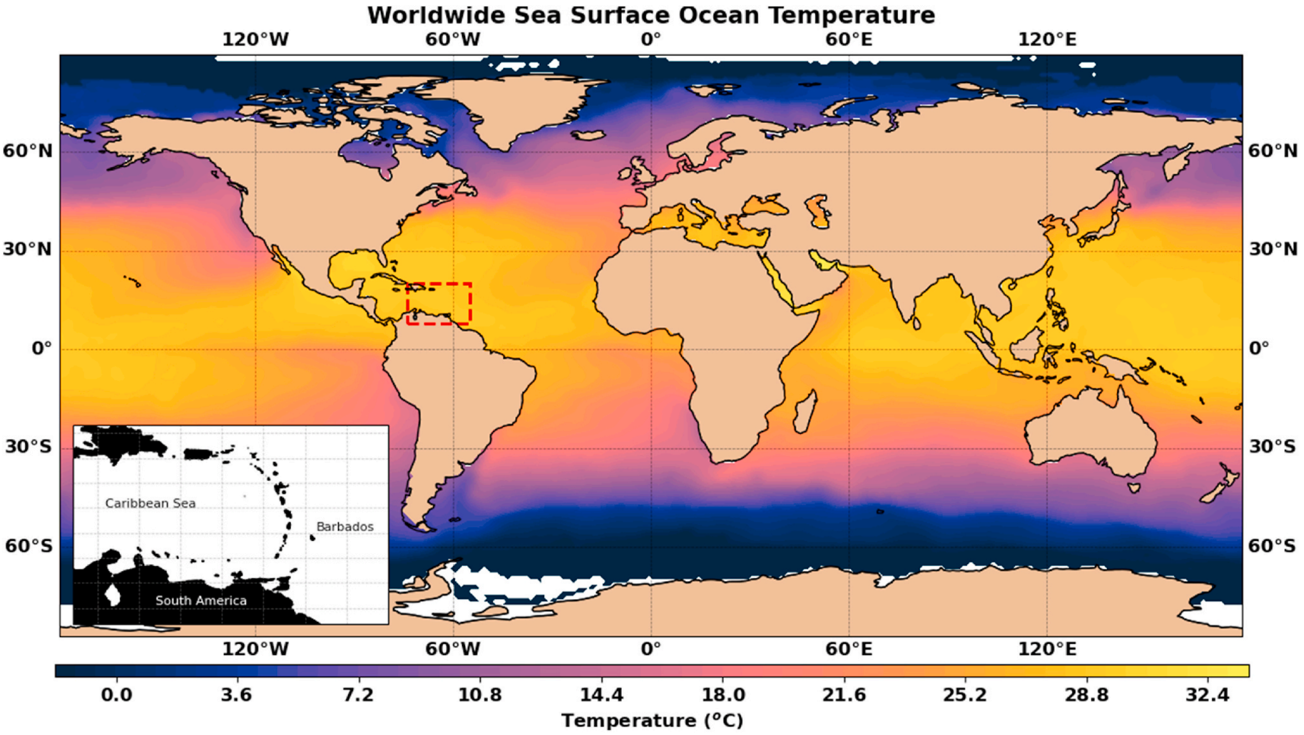


Fig. 1. Worldwide average ocean temperature. The red rectangle on the plot indicates a portion of the Caribbean island chain. The inset map in the bottom left showcases the position within the red rectangle containing the island of Barbados at 13.194° N, 59.543° W. Adapted from Ref. [13].

matrix and using the Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) the authors came to two potential sites.

In 2020, a technical note on Ocean Energy in Barbados [18] was developed for the Inter-American Development Bank to present information and assess the future potential of marine renewable energy for deployment in Barbados, namely among them OTEC. The assessment of OTEC was done via a weighted sum analysis map with the following considerations: (i) temperature change, (ii) distance from shore, (iii) ruggedness, slope, (iv) leasing blocks, and (v) offshore infrastructure. Within a buffer zone of 35 km from the coasts and a shallow mask inward from the 750 m isobaths, suitable locations from their analysis appear around the west, north and east coasts, with the most suitable locations being found on the west coast [18]. The authors gave the rationale that "the west side of the island may prove to be more attractive to developers given the reduced wave exposure due to the shadowing effect of the island from the prevailing swell direction. An additional consideration is the presence and relative strength of the electrical infrastructure on the west versus east coast" [18].

OTEC intakes cold water from the deep ocean and disperses 'used' seawater into the upper levels of the ocean. This discharge can lead to thermal shock of surrounding biota [19]. Prolonged discharge at a higher temperature can also alter the thermal gradient of the area, causing a permanent change of the thermocline [19]. To minimize the effects of thermal stress on the receiving environment, depths of dispersion can be monitored to ensure the surrounding temperature is like that of the effluent. As water is taken into the system, there is the possibility of marine life being impinged on the intake screens of the system or being ingested into the main system [20]. In the case of CC-OTEC, leakage of working fluid and coatings to prevent external biofouling could be toxic to marine life [20]. Artificial upwelling sites due to the deep-water discharge increases localized nutrients in the area [21]. Continued upwelling can lead to eutrophication. In order to mitigate any environmental impacts due to eutrophication, discharge pipes should be placed beneath the sunlight zone in order to avoid the growth of algae blooms [22]. Nevertheless, it should also be highlighted that there are potentially beneficial by-products of OTEC. The increased nutrient levels can promote some algae growth, which could potentially absorb atmospheric carbon dioxide. The cold-water effluent can also support mariculture, chilled soil agriculture and sea water air conditioning. Depending on the OTEC cycle, desalinated water can also be a by-product [23]. Although explored in the literature, these environmental points were not included in the site selection analysis. These considerations round out the site selection process within the examined literature noting applicable caveats within certain studies. Additionally, consideration must also be given to the presence of electrical generating systems and infrastructure around the site location. To access the availability of sites around Barbados, considerations such as protected/world heritage zones, marine space use, maritime traffic density and coral reef locations will be considered. These are necessary considerations as islands usually have the highest population densities at the coastline and Barbados, being a tourism driven economy [3], utilizes its coasts as a major selling point. Interruptions due to construction, operations and maintenance of an OTEC plant, whether on land or floating, can impact the nation's economy.

3. Materials and methods

Data were obtained as follows: Ocean temperature representation data were obtained from the National Oceanic and Atmospheric Administration (NOAA) [24] - which created the World Ocean Atlas 2018 (WOA18) which includes maps of climatological distribution fields of temperature at selected standard depth levels of the World Ocean on 1° and 1/4° latitude-longitude grids These climatologies are based on the objective analysis of historical oceanographic profiles (Bathythermographs, Conductivity-Temperature-Depth (CTD) packages, profiling floats, moored and drifting buoys, gliders, undulating oceanographic recorders) and select surface-only data. The in-situ level data were interpolated to standard vertical depth levels and if observations occurred at the desired standard depths, the values were substituted in. For this study, the monthly climatologies were considered [25]. -, Bathymetric Data were taken from the General Bathymetric Chart of the Oceans (GEBCO) [26] (which provide elevation data on a 15 arc-second grid globally). The Barbados shapefile containing administrative boundaries was taken from DIVA-GIS [27]. Atlantic tropical and subtropical cyclone data were taken from the National Hurricane Center [28]. Marine protected area shapefiles for the island were obtained from Protected Planet [29]. Marine traffic density data was obtained from Ref. [30] and Coral location data from Reefbase [31]. Areas of fishing, marine space use and coastal infrastructure maps were received from the Barbados Ministry of Energy.

3.1. Data analysis methodology

To guide the site selection process, key considerations were assessed to determine an ideal location for an OTEC plant off the coast of Barbados: Temperature conditions around the island, the shortest distance from the proposed plant location to the coast, the shortest distance to the Port of Barbados from the proposed plant locations, the shortest distance to the nearest electrical station from the proposed plant locations, marine protected zones, coastal features/infrastructure, coastal space use, marine traffic and historical storm conditions. To access these criteria, data described above were visualized in QGIS.

Once mapped, the island was split into north, east, south and west coasts (Fig. 2) and the shortest distance from the 1300 m isobath to the coast was chosen as the floating plant location in each quadrant. The 1300 m isobath was selected to prevent disturbance to the seabed from cold intake pipe (1 km in length) [32]. Thermal difference (the temperature at 20 m depth minus the temperature at 1000 m depth), linear distances (measured via QGIS) to the coast, electrical station and the Port of Barbados (Fig. 3), the number of space use nodes, coastal infrastructure nodes (visual discerned and counted) and fishing areas (measured via QGIS) (Fig. 4) were used as criteria to populate a weighted decision matrix. The criteria weights were determined using the Analytic Hierarchy Process (AHP) [33,34] and the TOPSIS method was used to rank the plant locations [34,35].

The AHP was developed by Thomas Saaty [33,36]. This methodology is a multicriteria approach to making a decision. The AHP approach first requires a problem to be defined. The problem is then structured as a hierarchy (top level being the overarching goal, second level being the criteria by which the goal is judged by and the bottom level being the alternates) where a pair-wise comparison matrix is used to determine priorities of the criteria and their weightings [33,36]. The pair-wise matrix is populated using the upper level to compare the elements directly below with respects to itself (eg. a pair-wise comparison matrix would be constructed of the criteria in the second level with respect to the goal in the top level). For this study the overarching goal (top level) is the determination of the optimal position for an offshore OTEC plant location, with the criteria making up the second level. Since the AHP approach will be only be used to obtain the weights for these criteria, the hierarchy tree stops at the second level.

The TOPSIS methodology was developed by Yoon and Hwang [35]. The ideology was that the best alternative should have the shortest distance away from the 'ideal' solution and inversely, the worst alternative being the farthest away. To measure these metrics, raw metrics from data sources are normalized, weighted and the 'ideal' best/worst values extracted from weighted normalized values. The Euclidean distance from ideal best/worst would then be used to find the best alternative.

3.1.1. AHP methodology

A pair-wise comparison matrix, A, is constructed (see Table 2). The criteria, C_n, are ranked based on importance comparative to one another based on the overall goal and are given values, a_{ij}, using the weight scheme in Table 1. Elements that are compared to themselves have an equal importance of 1 (eg, a_{11}, a_{22} etc.) and reciprocal entries (eg. a_{12}, a_{21}) are inverse, $a_{12} = 1/a_{21}$ [33,36].

$$A = \begin{pmatrix} C_1 \; C_2 \cdots C_n \\ a_{11} \; a_{12} \cdots a_{1n} \\ a_{21} \; a_{22} \cdots a_{2n} \\ a_{n1} \; a_{n2} \cdots a_{nn} \end{pmatrix}$$

Once the matrix is fully populated, the priority or criteria weights, W_i, are calculated. The sum of the column values in the matrix are calculated and each element is divided by the sum value to normalize the elements [38]. The priorities are then calculated by averaging the normalized elements along the row.

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{2}$$

The consistency ratio (CR) of the pair-wise matrix is then calculated to check if the consistency of the matrix is acceptable - CR < 0.1 [33]. This is found by dividing the consistency index (CI) by the random coincidence index corresponding to the number of criteria (n) (Table 1) where λ_{max} is the eigenvalue of matrix A [38].

$$\lambda_{max} = \frac{1}{n} \sum_{i=1}^{n} \frac{(aW)_i}{W_i} \tag{3}$$

3.1.2. TOPSIS methodology

Once an acceptable consistency is achieved in the AHP methodology, the priorities are then set to be used as the criteria weights in the TOPSIS method to rank the proposed plant locations. The TOPSIS method requires the raw data to be normalized using equation 4

$$r_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{m} X_{ij}^2}} \tag{4}$$

before applying the weightings to the normalized values ($v_{ij} = w \times r_{ij}$) [17,35]. The Ideal Best/Worst solutions are extracted from the calculated weighted normalized data, being either the best/worst of the weighted normalized values based on the perception of impact of the criteria, whether negative or positive [17,35].

$$A^+ = (v_1^+, v_2^+, \ldots, v_n^+) = \{(\max v_{ij} | j \,\epsilon\, B), (\min v_{ij} | j \,\epsilon\, C)\}$$
$$A^- = (v_1^-, v_2^-, \ldots, v_n^-) = \{(\min v_{ij} | j \,\epsilon\, B), (\max v_{ij} | j \,\epsilon\, C)\}$$

Where.

B = {j = 1, …, n |j} *for positive criteria impacts* and
C = {j = 1, …, n |j} *for negative criteria impacts*

The Euclidean distance from the Ideal Best ($s^+{}_i$) and Ideal Worst (s_i^-) are calculated.

$$s_i^+ = \sqrt{\sum_{j-1}^{n} \left(v_{ij} - v_i^+\right)^2} \tag{5}$$

$$s_i^- = \sqrt{\sum_{j-1}^{n} \left(v_{ij} - v_i^-\right)^2} \tag{6}$$

Finally, Alternative closeness (C_i^+) is then calculated and the alternative with the largest C_i^+ value is ranked the highest.

$$C_i^+ = \frac{s_i^-}{s_i^+ + s_i^-} \tag{7}$$

Table 1
The AHP scale of absolute numbers. Adapted from Ref. [26]. R.I taken from [37].

$$W_i = \frac{1}{n} \sum_j \left(\frac{a_{ij}}{\sum_i a_{ij}} \right) \tag{1}$$

Weight	Definition
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance
2, 4, 6, 8	Intermediate values between adjacent weights

Random Coincidence Index when n = 7, R.I = 1.32.

4. Results

This section will be arranged in a linear fashion. The site selection results inform the investigation of the thermal structure of the water column; thus, the site selection results will occur first. The sections are as follows: Site Selection and its subsection, Maps of Barbados (Section 4.1), the AHP-TOPSIS Multi-criteria analysis (Sections 4.2) and the Thermal Structure of the Water Column (Section 4.3).

4.1. Maps of Barbados

The rolling transition of the bathymetry brings warmer temperature differences off the western and southern coasts of the island in contrast to the steeper descent into cooler temperature differences off the eastern coast (see Fig. 2). This sees the 1.3 km isobath approximately 8.5–11 km from the northeastern to southeastern edge of the island whilst the western coast distances range from approximately 19 km at the northwestern edge to approximately 21 km at the southwestern edge. To the south of the island the 1.3 km isobath can be as far as 55 km away. The WOA18 provides monthly climatological fields (January through December) of temperature at standard depths [25], which were averaged to provide the raw data for interpolation over the study area. In some cases, some data points had up to 5 months out of the year to be averaged whilst others only had 1-month present. Nevertheless, the data presented represents average conditions around the island.

The island's infrastructure is skewed along the western and southern coasts, concentrated around the main city and port of Bridgetown (see Fig. 3). This, coupled with the location of the other cities being along the western and southern portions of the island, focuses most of the electrical stations in these areas. The main feature of Fig. 3 showcases the frequency of marine traffic around the island of Barbados. As Barbados Port Inc. And the privately owned Port St. Charles are on the west coast of the island, the majority of marine traffic occurs on that side of the island. To the south and to the east of the island are local fish markets and their jetties for small fishing vessels, providing additional influx/efflux of marine traffic. Following the established shipping patterns, ship routes are drawn out linking the proposed plant locations to the Barbados port.

Due to the COVID-19 pandemic, the 2020 marine density map is a bit more visually skewed to the west than usual. The presence of anchored cruise liners is mapped off the west coast as the Government of Barbados allowed several ships to berth off the west coast during the pandemic lockdown of 2020 (See comparison to the inset map of the 2019 Marine Density).

The more tranquil west coast of the island invites much more recreational and economic activities and facilities when compared with the east coast (see Fig. 4). Being shaded from the swells from the Atlantic, the west and southwestern coasts hosts the islands two marine protected zones, world heritage sites and much of the coastal infrastructure. Fishing, on the other hand, is a much more widespread occurrence.

This map shows the track of prominent storms that have passed within 75 nautical miles (138.9 km) of Barbados from 2000 to 2019 (see

Table 2
Pairwise comparison matrix of the main criteria and their resulting priorities. Column headings are abbreviated versions of the row headings.

	Ther. Diff.	Dist. Coast	Dist. Station	Dist. Port	Fishing Area	No. Space Use Nodes	No. Coastal Infra. Nodes	Priorities
Thermal Difference	1	1	1	3	8	2	3	**0.23**
Distance to Coast (km)	1	1	1	5	8	2	2	**0.22**
Distance to Electrical Station (km)	1	1	1	5	8	2	2	**0.22**
Distance to Port (km)	1/3	1/5	1/5	1	1/3	1/5	1/5	**0.04**
Area of Fishing areas (km^2)	1/8	1/8	1/8	3	1	1/5	1/5	**0.04**
Number of Space Use Nodes	1/2	1/2	1/2	5	5	1	1	**0.13**
Number of Coastal Infrastructure Nodes	1/3	1/2	1/2	5	5	1	1	**0.12**

$\lambda_{max} = 7.45$ Consistency Index = 0.08 Consistency Ratio = 0.06

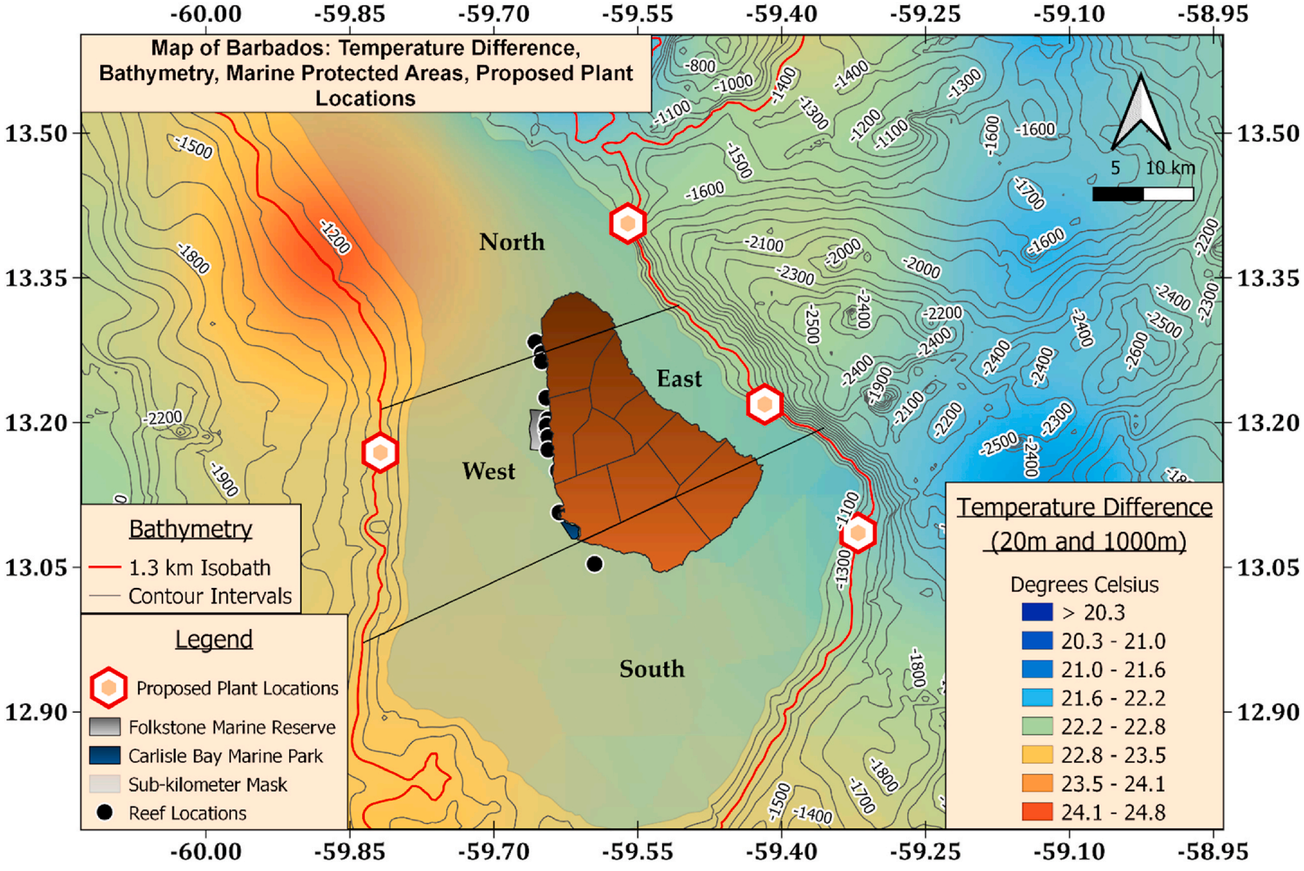


Fig. 2. Map of Barbados: Temperature difference, bathymetry, marine protected areas, proposed plant locations.

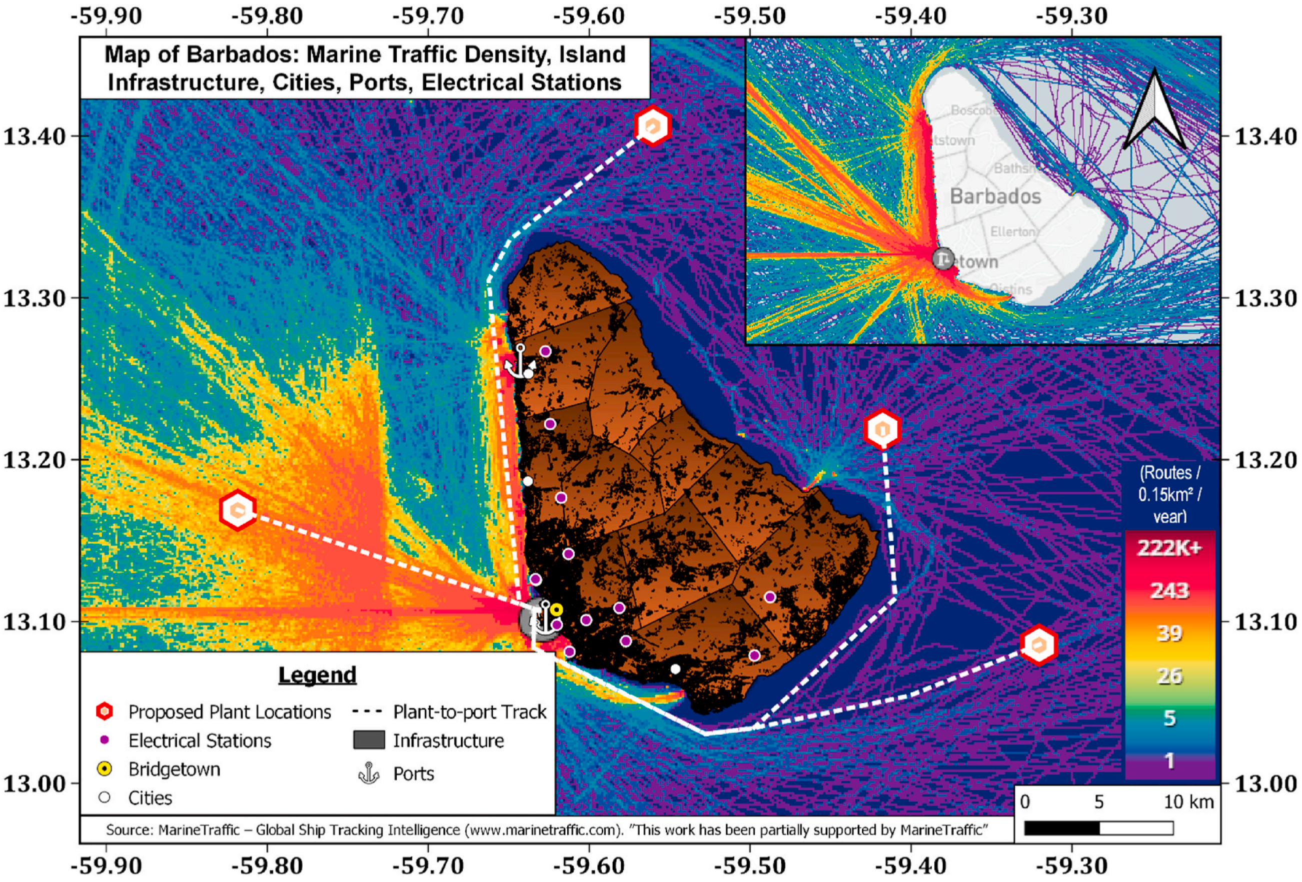
Fig. 5). Storm tracks that intercept this buffer zone are highlighted on the map, with the minimal wind speed of 39 mph (30 m/s) [4]. Within this time period 12 tropical storms passed within the buffer zone with 2 instances of increasing intensities (tropical storm to a category 1 hurricane and category 1 hurricane to category 3).

4.2. *Weighted decision matrix*

Table 1 shows the pair-wise comparison matrix and the resulting priorities. The pair-wise comparison rankings and the subsequent priorities were all selected by the authors. The consistency ratio of the pair-wise comparison matrix is 6%, which is within the 10% upper limit [23]. Table 3 shows the table of raw data of criteria chosen for the weighted decision matrix. Thermal difference and distance to the coast is taken from Fig. 2. Distance to electrical station and port is taken from Fig. 3. Fishing areas, space use and coastal infrastructure nodes were taken from Fig. 4. Bathymetry was not taken into consideration in the weighted decision matrix as each proposed plant location lies on the 1.3 km isobath. Table 4 shows the results of the AHP-TOPSIS method with the highest ranked location being the east coast plant site based on our chosen criteria and priorities.

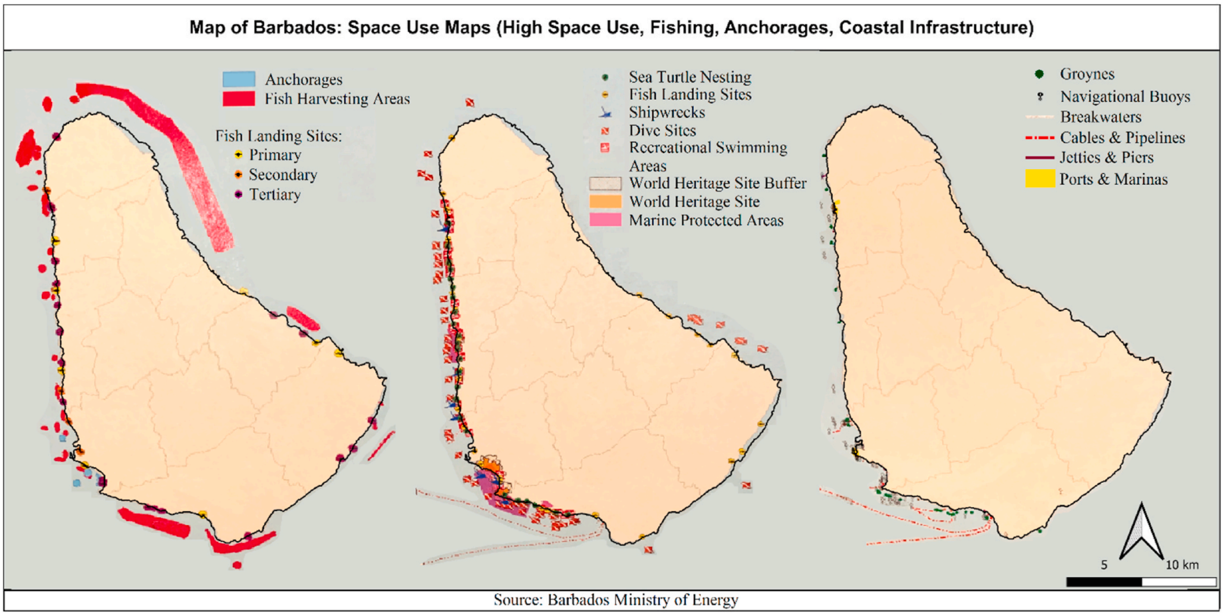
4.3. *Thermal structure of the water column*

The closest grid point within the WOA18 data to the east coast proposed plant site was located at 13.375° latitude and −59.375° longitude. From the data point selected, the WOA18 provided two averaged monthly profiles, June and September. The sea surface temperatures for both June and September profiles are 28.5 °C and 28.99 °C respectively with an average of 28.745 °C. At 20 m depth - which has been used as the OTEC warm water intake depth for many studies [39–41] - the average temperature is 28.56 °C and cold-water intake temperature at 1000 m is 5.53 °C. Fig. 6 depicts the depth at which the 20 °C differential from the 20 m intake temperatures of each profile occurs (Blue lines). At a temperature of 8.637 °C, the September profile reaches its 20 °C differential at a depth of 470.47 m, the June profile at



Source: MarineTraffic – Global Ship Tracking Intelligence (www.marinetraffic.com). "This work has been partially supported by MarineTraffic"

Fig. 3. Map of Barbados: Marine Traffic Density Map 2020, Island Infrastructure, Cities, Ports and Electrical Stations (Inset map: Marine Traffic Density Map 2019).



Source: Barbados Ministry of Energy

Fig. 4. Maps of Barbados: Space use maps (high space use, fishing, anchorages, coastal infrastructure).

545.6 m (8.484 °C) with the average depth being 515.6 m (8.56 °C).

5. Discussion

5.1. Weighted decision matrix

As seen from Table 4, the east coast proposed plant location was ranked the highest of the four proposed locations (locations shown in

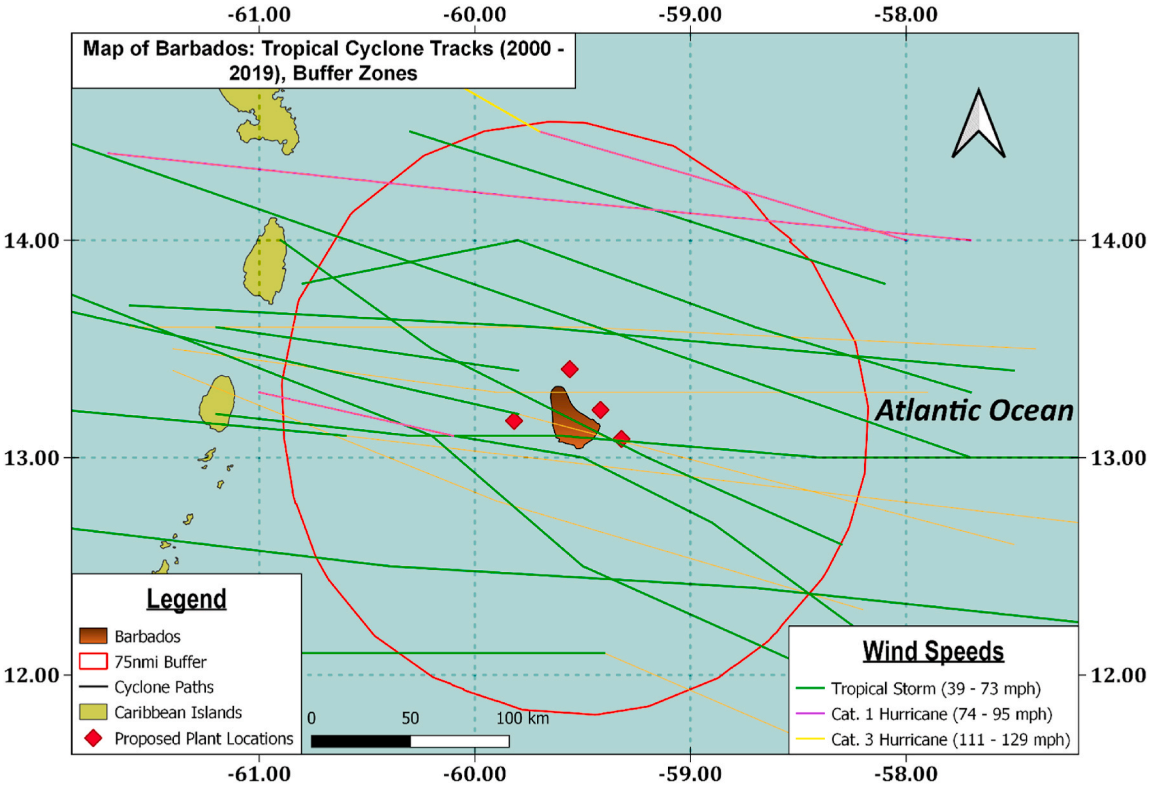


Fig. 5. Map of Barbados: Tropical cyclone tracks (2000–2019), buffer zones).

Table 3
Weighted decision matrix raw data.

Criteria	North Coast	East Coast	South Coast	West Coast
Thermal Difference	22.92	22.86	22.68	23.31
Distance to Coast (km)	9.59	5.86	12.53	19.54
Distance to Electrical Station (km)	17.02	13.75	18.43	20.60
Distance to Port (km)	39.19	43.97	39.57	21.57
Area of Fishing areas (km^2)	17.48	13.00	11.09	4.68
Number of Space Use Nodes	7.00	8.00	43.00	85.00
Number of Coastal Infrastructure Nodes	8.00	0.00	34.00	56.00

Fig. 2). With the difference in temperature between the four sites being only 0.63 °C, the weighted normalized values for temperature were fairly constant between the sites. The difference starts to show in the consideration of distance from the main points of interest. The east coast has the shortest distance to the coast, which directly governs the length of the submarine electrical cables to transfer electricity back to the coast. The distance to electrical stations is somewhat governed by the distance away from the coasts, as well as layout of the substations on the island. Ultimately the three distance criteria are dependent on the bathymetry around the island. Due to the east coast facing the Atlantic Ocean, economic and recreational activity are much more concentrated on the west coast of the island (Fig. 4) with coastal infrastructure following the same pattern. Fishing areas is the only criteria where the east coast had a high (which in this case is a negative impact) weighted normalized value (0.02 in a range of 0.007–0.027), but due to the criteria weightings this did little to change the overall ranking of the east coast. The criteria weights developed by the considerations of the authors saw that the thermal difference was weighted the heaviest, as consistent with [17]. Having a high thermal difference increases the efficiency and net power output of the OTEC cycle [41–43], therefore optimizing the thermal difference and subsequent power output goes a long way, especially in adding to the goal of 100% renewable energy for Barbados [44]. Of equal importance was the cost effectiveness of the plant location. Closer plant locations to the coast require less pipeline and cabling to transfer

Table 4
Weighted decision matrix.

Criteria	Weight	North Coast	East Coast	South Coast	West Coast	Ideal Worst	Ideal Best
Weighted Normalized Values							
Thermal Difference	**0.23**	0.113	0.113	0.112	0.115	0.112	0.115
Distance to Coast (km)	**0.22**	0.083	0.051	0.108	0.169	0.169	0.051
Distance to Electrical Station (km)	**0.22**	0.121	0.098	0.131	0.147	0.147	0.098
Distance to Port (km)	**0.04**	0.020	0.022	0.020	0.011	0.022	0.011
Area of Fishing areas (km^2)	**0.04**	0.027	0.020	0.017	0.007	0.027	0.007
Number of Space Use Nodes	**0.13**	0.009	0.011	0.058	0.114	0.114	0.009
Number of Coastal Infrastructure Nodes	**0.12**	0.015	0.000	0.063	0.104	0.104	0.000
Euclidean Distance from Ideal Best, Si+		0.05	0.02	0.10	0.20		
Euclidean Distance from Ideal Worst, Si-		0.16	0.19	0.09	0.02		
Positive Ideal Solution, Pi		**0.77**	**0.92**	**0.47**	**0.11**		
Rank		**2**	**1**	**3**	**4**		

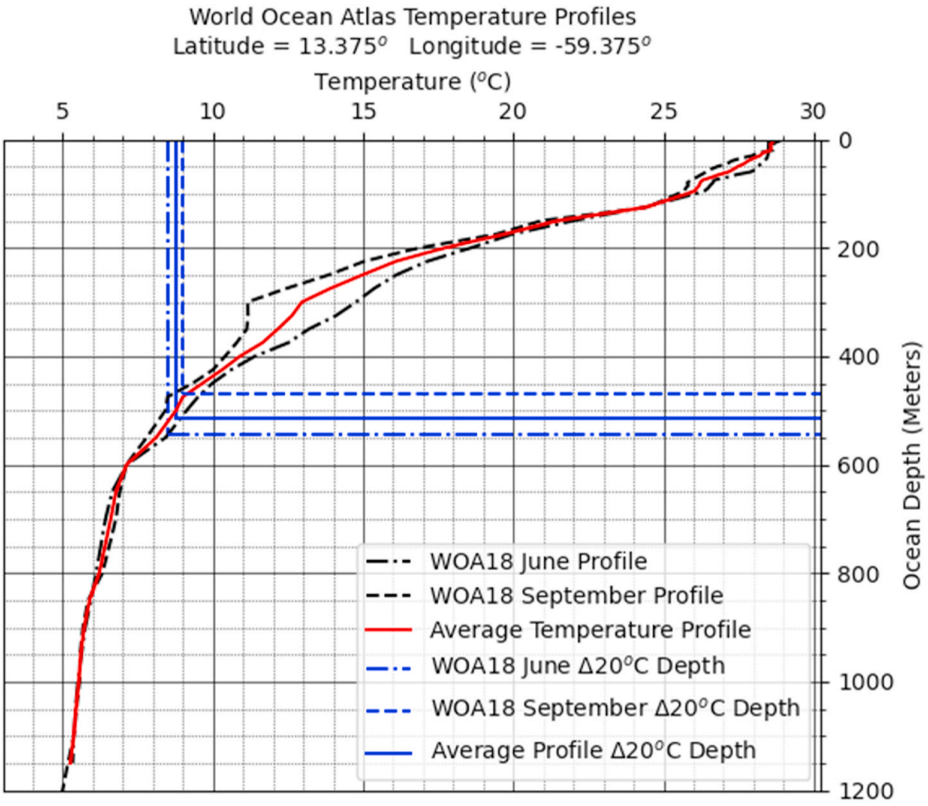


Fig. 6. Temperature profiles created using WOA18 Data.

electricity and desalinated water/chilled seawater (if necessary) inland. Closeness to electrical stations are to the same effect. Coastal infrastructure present along the island's coast serve to preserve the coastline and its extensive recreational and economic use. Preserving these nodes are integral to Barbados' tourism driven economy. Distance to the port is considered for transport of goods and services, labor force and maintenance. In extreme cases of emergency, the distance from port to plant would be a determining factor in speed of response but outside of that it falls behind the other criteria in priority. The impact on fishing areas was given a lower priority as the area of fish-able waters in comparison to the plant footprint would be large.

5.2. *Thermal resource*

The near coast temperature differences in Fig. 2 are greater than is to be expected when taking the shallowing bathymetry as you approach the island's coastline into account. This occurs because the small geographical area of Barbados fits inside of the 0.25° grid spacing of the WOA18. Since there are no grid point closer to the coast, the interpolation doesn't take the change in bathymetry into account. Thus, the temperature difference is interpolated such that depths of 1000 m are always constant. To remedy this occurrence, there is a mask applied from the coastline of the island to the 1000 m isobath as to only represent the thermal interpolation starting from the 1000 m isobath.

The greater thermal differences are shown to the west of the island, peaking at approximately 24 °C along the northwestern edge of the island. The western side of the island is shown to have warmer thermal differences stretching to the southern edge of the island. This is likely due to the western coast being situated in the Caribbean basin which is exposed to the warmer surface waters of the global conveyor belt (thermohaline circulation) as opposed to the eastern coast. To this end, the western coast of the island would provide the greater thermal resources because of the higher thermal difference.

Nevertheless, when all factors were considered, the east coast plant placement was ranked the highest. Temperature profiles from the east coast (Fig. 6) shows the sensitivity of temperature changes on deep water intake depths. A small difference of 0.153 °C in surface intake temperature translates to a difference of 75 m at the 20 °C differential depth. This showcases the necessity of consistent mixed layer temperatures year-round as it can impact OTEC efficiency and intake pipeline length.

5.3. *Bathymetry*

The seabed is at its steepest gradient on the east coast of the island, with isobaths closely knit together to showcase the drop off at the Caribbean shelf into the Atlantic basin. This feature of the east coast contrasts with the west coast's smooth transition from land to 1300 m depth. The northern and southern plant positions were skewed to the eastern side of the island due to the steep gradient observed. Considering not only the slope of the seabed but also the distance to required depth, the eastern coast provides more favorable conditions when compared with the other coasts. Distances from the northeastern to southeastern edge of the island to the 1300 m isobath range from approximately 4.5-7 km whilst the western coast distances range from approximately 12 km at the northwestern edge to approximately 18 km at the southwestern edge. Fig. 6 also shows the potential to decrease the distance from the potential plant to the east coast. The required depth for the minimum temperature difference is achieved approximately 500 m higher than the suggested 1000 m depth. This gives the option of situating the plants on the 800 m isobath instead of the 1300 m isobath. This would maintain the minimum thermal difference (20 °C) whilst reducing the distance to the coast, assuming temperature profiles remain similar to Fig. 6 year-round. This rationale is seen in Ref. [5], where the minimum temperature was found in depths between 500 and 700 m, stating the shallower intake depths could increase technical feasibility and economic savings.

5.4. *Coastal infrastructure, protected areas and marine traffic*

As with many islands, most of Barbados' economic infrastructure is built up around the ports of the island. This includes the tourism sector with most hotels and attractions making use of the island's coastlines. In addition, some of the highest population densities on the island are located near-coastal areas. This impacts the land area availability for potential inland plants/substation for offshore piping and electrical lines. Based on Figs. 2–4, the west coast is saturated with fisheries, economic and recreational activities, protected zones and heavy marine traffic. The offshore plant would have direct impacts on these activities and infrastructure during construction and maintenance phases. An offshore plant would disrupt marine traffic around the chosen site, whether recreational, fisheries or freighting. Floating plants require anchoring, which damage the seabed along with the sweeping action of swinging mooring chains. Underground cabling could disturb recreational dive sites and coral reefs [32]. This cabling can generate low frequency sound and electromagnetic fields as they transmit power to land-based facilities [32]. These cables would extend inland to a substation located on the coast, which would result in the closure of the area for construction and some form of restriction to the area post construction. As positive support to the floating alternative, biota found at and sub 1 km is limited, in comparison to the nearshore coast, where reefs house more ocean life [32]. Comparatively, the east coast suffers with little of the previously stated impacts. Little infrastructure, limited recreational activity, low marine traffic and absence of protected zones provide an open coastline resulting in far less obstructions to any social or economic activity. The negative would be the absence of electrical substations on the east coast of the island. This would necessitate a new connection to deliver the incoming power to the grid. Possible retrofits to the existing Conset Bay jetty area could be performed to facilitate fast travel between the coast and the east coast plant. This would significantly shorten the distance travelled to the plant site, decreasing response times in emergency situations and allowing ease of transport for any personnel or goods to and from the plant site.

5.5. *Storm conditions*

Barbados is the most easterly of the Caribbean islands, and although located at 13° latitude, it is not close enough to the equator to avoid tropical cyclones. Any tropical storm or hurricane that would directly impact the island would impact the entirety of the island given its size. As a result, a comparison of storm impacts on the individual plans was not performed. The Atlantic basin has an active hurricane season starting June 1st through November 30th [45]. In order to protect the OTEC plant from such natural occurrences, plantships have been available since OTEC's early demonstration days. For example, Georges Claude housed his plant in a ship [39,46]. Vega et al. [40] suggests that plantships be outfitted with a detachable cold-water intake pipe to allow the plantship to move away from incoming storm tracks. This configuration would best benefit any OTEC development in Barbados.

5.6. *The two Barbados case studies*

The IDB analysis [18] parallels this study but shows how different criteria can lead to differing outcomes. The IDB study had a broader scope, ranking the entirety of their acceptable OTEC study area around the coasts of Barbados, whilst this study chose the closest point to the coast within four predetermined quadrants as the proposed plant locations. The IDB study allows for flexibility of choice while this study sought to lock in a location by optimizing the distance to the coast. The criteria for the IDB study that intersected with this study were: temperature change, distance from shore and offshore infrastructure. The IDB study then went on to consider ruggedness, slope and leasing blocks. Although not included as part of the criteria, wave exposure/prevailing wave direction, close distance to port facilities and difference in electrical station infrastructure between the west and east coasts were mentioned as potential strengths of the west coast. Apart from the three intersecting criteria, this study considered: distance to electrical station, distance to port, area of fishing areas, number of space use nodes and number of coastal infrastructure nodes, two of which were mentioned but not included in the IDB study criteria for their weighted analysis.

The weights of the criteria in the IDB were not shown so it is not possible to tell how the areas of analysis were ranked, but the west and the east were the two competing sides, with the west having areas of the most suitable rank. From visual inspection of their OTEC suitability analysis map ([18], pp 44), the east coast locations offer the shorter distances to the coast and no visible offshore infrastructure. It is mentioned within the document ([18], pp 41) that slightly warmer temperature differences exist to the southwest of the island, but that does not correlate to the area of most suitability, leaving ruggedness slope and leasing blocks. Due to the tightly knitted feature of the contour intervals of the east coast, the west coast would rank higher on ruggedness and slope, as they are both geotechnical factors. This leaves leasing blocks, which aren't explained or shown in the document. Nevertheless, these criteria allowed for the west coast to be ranked highest in the IDB study.

This study found the west coast to be the least applicable for OTEC development based on the criteria examined, with the west coast losing out most on the distance factors and the myriad of space use nodes situated on that coast. The distance from the west coast plant location was 3.3 times farther away from the coast to that of the east coast location and because of this fact, the distance to the nearest electrical station is still farther away, despite the abundance of stations on the west coast. The thermal differences between the west and east coast plant locations differ by 0.45 °C based on the averaged collected data (west coast being slightly greater). With the weightings of the distance to coast and the thermal difference being essentially equal, it would be hard validating the difference in temperature against the capital required to have a plant 3 times the distance away. Avoiding densely populated areas of economic and recreational activity is sensible to avoid as much as possible any negative impacts due to disruptions (construction and maintenance) and perception to/by the general public.

6. Conclusions

OTEC requires as a rule of thumb 20 °C thermal difference between intake points for optimal energy production. Within tropical climates, this requirement can be met year-round. In this study the island of Barbados was considered and the OTEC resources around the island were investigated to assess the viability of proposed plant locations for OTEC generation around the island. This was done via a multi-criteria decision analysis using the AHP-TOPSIS method.

Barbados was divided into 4 quadrant and 4 plant locations were selected within each quadrant based off of distance to the coast. The criteria selected for the multi-criteria decision analysis were: thermal difference, the shortest distance from the coast to the proposed plant location, the shortest distance to the Port of Barbados from the proposed plant location, the shortest distance to the nearest electrical station from the proposed plant location, coastal features/infrastructure, coastal space use and areas of fishing. Each criterion was weighted using the AHP and the 4 plant locations were ranked using the TOPSIS method.

The results of our analysis ranked the east coast plant location the highest of the 4, being a short distance away from the coast, with little economic or recreational markers around the area, no coastal infrastructure and a thermal difference approximately 3 °C higher than the recommended 20 °C. After the east coast were the north, south and west coasts in that order of ranking. The results of this study can aid in OTEC development for the island of Barbados.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CRediT authorship contribution statement

Kashawn Hall: Conceptualization, Methodology, Validation, Investigation, Resources, Writing – original draft, Writing – review & editing, Visualization, Supervision. **Solange Kelly:** Writing – review & editing. **Legena Henry:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors would like to thank the Caribbean Institute for Meteorology and Hydrology for providing the learning opportunities which were utilized in this study.

References

[1] United Nations, "The Paris Agreement", Accessed June 04, 2019, https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement.

[2] United Nations Framework Convention on Climate Change, "Outcomes of the Glasgow Climate Change Conference - Advance Unedited Versions (AUVs), Glasgow Climate Pact", Accessed November 29, 2021, https://unfccc.int/process-and-meetings/conferences/glasgow-climate-change-conference-october-november-2021/outcomes-of-the-glasgow-climate-change-conference.

[3] Arnold McIntyre, Ahmed El-Ashram, Marcio Ronci, Julien Reynaud, Ms Natasha Xingyuan Che, Ke Wang, Mr Sebastian Acevedo Mejia, Mr Mark Scott Lutz, Caribbean Energy: Macro-Related Challenges, International Monetary Fund, 2016.

[4] Haruo Uehara, Carmelo O. Dilao, Tsutomu Nakaoka, Conceptual design of ocean thermal energy conversion (OTEC) power plants in the Philippines, Sol. Energy 41 (5) (1988) 431–441.

[5] Andrea Devis-Morales, Raúl A. Montoya-Sánchez, Andrés F. Osorio, Luis J. Otero-Díaz, Ocean thermal energy resources in Colombia, Renew. Energy 66 (2014) 759–769.

[6] Mohammed Faizal, M. Rafiuddin Ahmed, Experimental studies on a closed cycle demonstration OTEC plant working on small temperature difference, Renew. Energy 51 (2013) 234–240.

[7] S.M. Masutani, P.K. Takahashi, Ocean thermal energy conversion (OTEC), Oceanography 22 (609) (2001) 625.

[8] Amir-Sina Hamedi, Sadegh Sadeghzadeh, Conceptual design of a 5 MW OTEC power plant in the Oman Sea, Journal of Marine Engineering & Technology 16 (2) (2017) 94–102.

[9] Bindu Lohani, A. Luis, Vega. *Wave Energy Conversion And Ocean Thermal Energy Conversion Potential In Developing Member Countries*, Asian Development Bank, 2014.

[10] Andrea Giostri, Alessandro Romei, Marco Binotti, Off-design performance of closed OTEC cycles for power generation, Renew. Energy 170 (2021) 1353–1366.

[11] Worldometer, Barbados population (LIVE). https://www.worldometers.info/world-population/barbados-population/. (Accessed 22 August 2022). Accessed.

[12] IRENA, Statistical profiles. https://www.irena.org/Statistics/Statistical-Profiles. (Accessed 22 August 2022). Accessed.

[13] Met Office, "More advanced mapping with cartopy and matplotlib", Accessed August 08, 2020, https://scitools.org.uk/cartopy/docs/v0.11/matplotlib/advanced_plotting.html.

[14] Gérard C. Nihous, Mapping available Ocean Thermal Energy Conversion resources around the main Hawaiian Islands with state-of-the-art tools, J. Renew. Sustain. Energy 2 (4) (2010), 43104.

[15] James H. VanZwieten, Lynn T. Rauchenstein, Louis Lee, An assessment of Florida's ocean thermal energy conversion (OTEC) resource, Renew. Sustain. Energy Rev. 75 (2017) 683–691.

[16] Jannis Langer, Aida Astuti Cahyaningwidi, Charis Chalkiadakis, Jaco Quist, Hoes Olivier, Kornelis Blok, Plant siting and economic potential of ocean thermal energy conversion in Indonesia a novel GIS-based methodology, Energy 224 (2021), 120121.

[17] Garduño-Ruiz, Erika Paola, Rodolfo Silva, Yandy Rodríguez-Cueto, Alejandro García-Huante, Jorge Olmedo-González, M. Luisa Martínez, Astrid Wojtarowski, Raúl Martell-Dubois, Sergio Cerdeira-Estrada, Criteria for optimal site selection for ocean thermal energy conversion (Otec) plants in Mexico, Energies 14 (8) (2021) 2121.

[18] Johnston, Sweyn, J. McGlynn, V. R. Prado, "Ocean Energy in Barbados: A Review of Clean Technology Options, Available Resource and Locational Guidance for Potential Areas of Interest for Commercial Development", Accessed October 10, 2020, https://publications.iadb.org/en/ocean-energy-barbados-review-clean-technology-options-available-resource-and-locational-guidance.

[19] S.W.Y. Ma, C.S.W. Kueh, G.W.L. Chiu, S.R. Wild, J.Y. Yip, Environmental management of coastal cooling water discharges in Hong Kong, 8-9–9 pt 7, Water Sci. Technol. 38 (1998) 267–274.

[20] Linus Hammar, Martin Gullström, Thomas G. Dahlgren, Maria E. Asplund, Ines Braga Goncalves, Sverker Molander, Introducing ocean energy industries to a busy marine environment, Renew. Sustain. Energy Rev. 74 (2017) 178–185.

[21] S.A. Abbasi*, Naseema Abbasi, 00/02019 the likely adverse environmental impacts of renewable energy sources, Appl. Energy 65 (November) (2000) 121–144, https://doi.org/10.1016/s0140-6701(00)92689-4.

[22] Jonathan Lilley, Denise E. Konan, D.T. Lerner, D.M. Karl, Potential Benefits, Impacts, and Public Opinion of Seawater Air Conditioning in Waikiki, 2012.

[23] Joseph Appiott, Amardeep Dhanju, Biliana Cicin-Sain, Encouraging renewable energy in the offshore environment, March, Ocean Coast Manag. 90 (2014) 58–64, https://doi.org/10.1016/j.ocecoaman.2013.11.001.

[24] National Centers for Environmental Information, "WORLD OCEAN ATLAS SELECT (WOAselect), Accessed June 29, 2020, https://www.nodc.noaa.gov/OC5/SELECT/woaselect/woaselect.html.

[25] R.A.M. Locarnini, O. Baranova, T. Boyer, M. Zweng, H. Garcia, J. Reagan, D. Seidov, K. Weathers, C. Paver, I. Smolyar, World Ocean Atlas 2018, in: A. Mishonov Technical (Ed.), NOAA Atlas NESDIS 81, vol. 1, 2018, p. 52. Temperature.

[26] British Oceanographic Data Centre, "GEBCO 2020 gridded bathymetry data download", Accessed June 27, 2020, https://download.gebco.net/.

[27] DIVA-GIS, Download data by country. https://www.diva-gis.org/gdata. (Accessed 16 July 2020). Accessed.

[28] Christopher W. Landsea, James L. Franklin, Atlantic hurricane database uncertainty and presentation of a new database format, Mon. Weather Rev. 141 (10) (2013) 3576–3592.

[29] ProtectedPlanet, "Protected Areas (WDPA)", accessed June 04, 2020, https://cutt.ly/ojrhyGp.

[30] MarineTraffic, "Density Maps", accessed June 17, 2020, https://cutt.ly/rjrhwpV.

[31] ReefBase, A global information system for coral reefs. http://www.reefbase.org. (Accessed 16 June 2020). Accessed.

[32] Damien A. Devault, Anne Péné-Annette, Analysis of the environmental issues concerning the deployment of an OTEC power plant in Martinique, Environ. Sci. Pollut. Control Ser. 24 (33) (2017) 25582–25601.

[33] Thomas L. Saaty, How to make a decision: the analytic hierarchy process, Eur. J. Oper. Res. 48 (1) (1990) 9–26.

[34] Mohit Tyagi, Pradeep Kumar, Dinesh Kumar, A hybrid approach using AHP-TOPSIS for analyzing e-SCM performance, Procedia Eng. 97 (2014) 2195–2203.

[35] Ching-Lai Hwang, Kwangsun Yoon, Methods for multiple attribute decision making, in: Multiple Attribute Decision Making, Springer, Berlin, Heidelberg, 1981, pp. 58–191.

[36] Thomas L. Saaty, Decision making with the analytic hierarchy process, Int. J. Serv. Sci. 1 (1) (2008) 83–98.

[37] Roseanna W. Saaty, The analytic hierarchy process—what it is and how it is used, Math. Model. 9 (3–5) (1987) 161–176.

[38] Antonio C. Caputo, Pacifico M. Pelagagge, Paolo Salini, AHP-based methodology for selecting safety devices of industrial machinery, Saf. Sci. 53 (2013) 202–218.

[39] Luis A. Vega, Ocean thermal energy conversion primer, Mar. Technol. Soc. J. 36 (4) (2002) 25–35.

[40] Luis A. Vega, Dominic Michaelis, First generation 50 MW OTEC plantship for the production of electricity and desalinated water, in: Offshore Technology Conference, OnePetro, 2010.

[41] Krishnakumar Rajagopalan, Gérard C. Nihous, Estimates of global Ocean Thermal Energy Conversion (OTEC) resources using an ocean general circulation model, Renew. Energy 50 (2013) 532–540.

[42] Noboru Yamada, Akira Hoshi, Yasuyuki Ikegami, Performance simulation of solar-boosted ocean thermal energy conversion plant, Renew. Energy 34 (7) (2009) 1752–1758.

[43] Jannis Langer, Jaco Quist, Kornelis Blok, Recent progress in the economics of ocean thermal energy conversion: critical review and research agenda, Renew. Sustain. Energy Rev. 130 (2020), 109960.

[44] Ministry of Energy and Water Resources, "Barbados national energy policy 2019-2030", Accessed February 07, 2019, https://sandbox.7scorp.com/nrd2020/download/national-energy-policy-2019-2030/.

[45] National Hurricane Center and Central Pacific Hurricane Center, "Tropical cyclone climatology", Accessed October 16, 2020,https://www. nhc.noaa.gov/climo/.

[46] Georges Claude, Power from the tropical seas, Mech. Eng. 52 (12) (1930) 1039–1044.