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Ocean Thermal Energy Conversion—Flexible Enabling Technology for Variable Renewable Energy Integration in the Caribbean

Robert J. Brecha [1,2,3,4,*], Katherine Schoenenberger [2], Masaō Ashtine [5] and Randy Koon Koon [6]

1 Climate Analytics, Ritterstr. 3, 10969 Berlin, Germany
2 Hanley Sustainability Institute, University of Dayton, Dayton, OH 45469, USA; kschoenenberger1@udayton.edu
3 Renewable and Clean Energy Program, University of Dayton, Dayton, OH 45469, USA
4 Physics Department, University of Dayton, Dayton, OH 45469, USA
5 Department of Engineering, University of Oxford, Oxford OX1 2JD, UK; masao.ashtine@oerc.ox.ac.uk
6 Department of Physics, University of the West Indies, Mona, Kingston 7, Jamaica; randy.koonkoon@uwimona.edu.jm
* Correspondence: robert.brecha@climateanalytics.org

Abstract: Many Caribbean island nations have historically been heavily dependent on imported fossil fuels for both power and transportation, while at the same time being at an enhanced risk from the impacts of climate change, although their emissions represent a very tiny fraction of the global total responsible for climate change. Small island developing states (SIDSs) are among the leaders in advocating for the ambitious 1.5 °C Paris Agreement target and the transition to 100% sustainable, renewable energy systems. In this work, three central results are presented. First, through GIS mapping of all Caribbean islands, the potential for near-coastal deep-water as a resource for ocean thermal energy conversion (OTEC) is shown, and these results are coupled with an estimate of the countries for which OTEC would be most advantageous due to a lack of other dispatchable renewable power options. Secondly, hourly data have been utilized to explicitly show the trade-offs between battery storage needs and dispatchable renewable sources such as OTEC in 100% renewable electricity systems, both in technological and economic terms. Finally, the utility of near-shore, open-cycle OTEC with accompanying desalination is shown to enable a higher penetration of renewable energy and lead to lower system levelized costs than those of a conventional fossil fuel system.

Keywords: ocean thermal energy conversion; OTEC; seawater air conditioning; SWAC; desalination; variable renewable energy; wind power; solar PV; 100% renewable energy; Caribbean

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1. Introduction

Although responsible for a negligible fraction of historic emissions, small island developing states (SIDSs), including those in the Caribbean, have committed to fulfilling ratified obligations outlined in the Paris Agreement. Critical reasons for the strong regional support for the 1.5 °C (rise) temperature target are the dire threat from sea-level rise, temperature changes, and tropical cyclones that are already increasing measurably, and will do so even more in a world beyond 1.5 °C [1]. One of the key findings of the Intergovernmental Panel on Climate Change (IPCC) Special Report on Global Warming of 1.5 °C [2,3] is that the world needs to be carbon-emissions neutral by 2050 or shortly thereafter. If this target is taken as a guiding concept, roughly thirty years remain for most, if not all, countries to decarbonize their energy systems; in a world largely free of fossil fuels, it will be critical for SIDSs to accelerate this transition.

Ocean energy technologies can help play a role in enabling island states to reach targets of energy self-sufficiency [3,4]. Three basic, but linked ideas are behind the continued interest in ocean thermal energy conversion (OTEC) as an enabling technology in particular [5–8]. First, as shares of increasingly economical variable renewable energy (VRE) sources such as wind and solar photovoltaics are incorporated into the energy mix, there will still be a need for dispatchable electricity sources to complement variability [9]. Secondly, much as with sun and wind, ocean energy as a primary resource is essentially infinite and not depletable. Thirdly, OTEC can also provide extra services beyond the generation of electricity, such as the desalination of water, cooling of buildings, and aquaculture [10].

In spite of these important driving factors and some continued interest in OTEC by research groups and commercial ventures around the world, uptake has thus far been slow. Predictably, one of the valid reasons for the lack of adoption has been the relatively high up-front cost that is expected for any emerging technology. In general, technologies follow an experience learning curve, described by decreasing costs per installed unit or per unit of generated electricity, expressed as a function of total cumulative installed capacity [11–13]. Solar photovoltaics (PVs) represent a classic example, with installation costs dropping by about 25% for each doubling of installed capacity, following this trend for the past four decades [14]. Technology such as OTEC, largely still within a demonstration phase, will inevitably be comparatively costly when factoring in more mature systems.

Another factor that can also lead to hesitation on the part of developers of potential OTEC projects is the relatively limited geographical area over which OTEC can be a viable technology [7,8,15]. In fact, compared to wind and solar energy, it is likely that the decreases in cost for OTEC projects may not show dramatic declines beyond those seen in moving from experimental projects to more standardized technology implementation. For OTEC and accompanying desalination and perhaps seawater air conditioning (SWAC) to be implemented, developers require (i) a viable coastline resource (including the absence of Marine Protected Areas or sensitive wetlands, for example); (ii) bathymetry that allows for relatively deep ocean waters (~1000 m or more) within reasonable proximity (~5 km or less); and finally, (iii) towns or fairly urbanized developments with electricity transmission infrastructure near these coastal areas.

While not likely to become a worldwide mass-market technology, OTEC and desalination can play a limited but important role in complementing variable renewables in certain cases. Therefore, bathymetric data for all island countries and overseas territories in the Caribbean have been examined to determine which are the most likely candidates using the three proximity criteria above, together with a fourth criterion that sufficient, less expensive, or more developed dispatchable renewable resources (e.g., hydropower or geothermal) are not readily available. Most crucially, this research shows at least two reasons that OTEC should not be judged as a technology in isolation, for example in terms of the levelized cost of electricity (LCOE) generated.

The first argument for OTEC is focused on applications where the power systems are heavily dependent on variable renewables; as such, the value of a dispatchable source goes beyond the actual electrical energy generated, but in the ancillary services that can be provided to the system in terms of stability. While batteries are increasingly an economically viable option for backup [16,17], a balance between storage and dispatchable power will be necessary, with consideration of the overall system-wide LCOE, not that of each technology individually, being a more prudent way to view planning toward a 100% renewable energy (RE) future. This is especially true in the context of SIDSs in the Caribbean, many of which are just beginning transitions from a nearly complete reliance on oil and gas for power generation, and thus have the opportunity for taking a longer-term systemic view of power system transformation. The second strand of the economic argument is that the combination of OTEC with auxiliary desalination as a combined system provides multiple services; another potential benefit is the further combination of OTEC and desalination with SWAC as an additional output that is of great added value on many islands which continue to face increasing pressures owing to climate change [18].

The following subsections present a brief overview of the energy landscape in the Caribbean region, linking resource and economic factors (Section 1.1). In Section 1.2, a summary of various regional dispatchable RE resources is given, with an eye toward a transition to 100% RE. OTEC as a specific technology is presented in terms of both physical and economic factors, including considerations of desalination and seawater air conditioning as by-products (Section 1.3). Methodologies used in the mapping, economic, and renewable energy integration analysis are presented in Section 2, leading to the results described in Section 3. The filtering criteria (Section 2.1) are used in Section 3.1 for a preliminary selection of potential Caribbean sites for OTEC based on GIS mapping of bathymetry. In Section 3.2, the representative hourly demand and wind and solar data are used to gain an understanding of the challenges of integrating high levels of VRE sources into the power system, leading therefore to the necessity of complementary technologies such as OTEC. Section 3.3 presents results for the levelized cost of electricity for the integrated system for various combinations of renewable energy capacities together with battery storage. Section 4 is a discussion of the results, and Section 5 provides some conclusions concerning the adoption of OTEC for Caribbean SIDSs.

1.1. Status of Renewables across the Caribbean

The abundance of unexploited renewable resources across the Caribbean positions the region to become a leader in sustainable development. An overview of RE potential across Caribbean Community (CARICOM) member states can be seen in Figure 1, with estimates for several renewable technologies based upon the 2027 energy capacity projections outlined by the Caribbean Sustainable Energy Roadmap and Strategy [19]. For example, the CARICOM subset of Eastern Caribbean islands from St. Kitts & Nevis to Grenada collectively accounts for a potential of 6280 MW of exploitable geothermal power [19]. Interestingly, and although not currently planned, a collective approach to exploit this resource could further increase its efficacy; for example, between the islands of St. Kitts and Nevis (approximately 3.5 km from coast to coast), or between Dominica, Guadeloupe and Martinique through inter-island grid connectivity [20]. On the other hand, geothermal resources have been widely explored but often run into implementation difficulties and delays (e.g., Grenada, Saint Lucia).

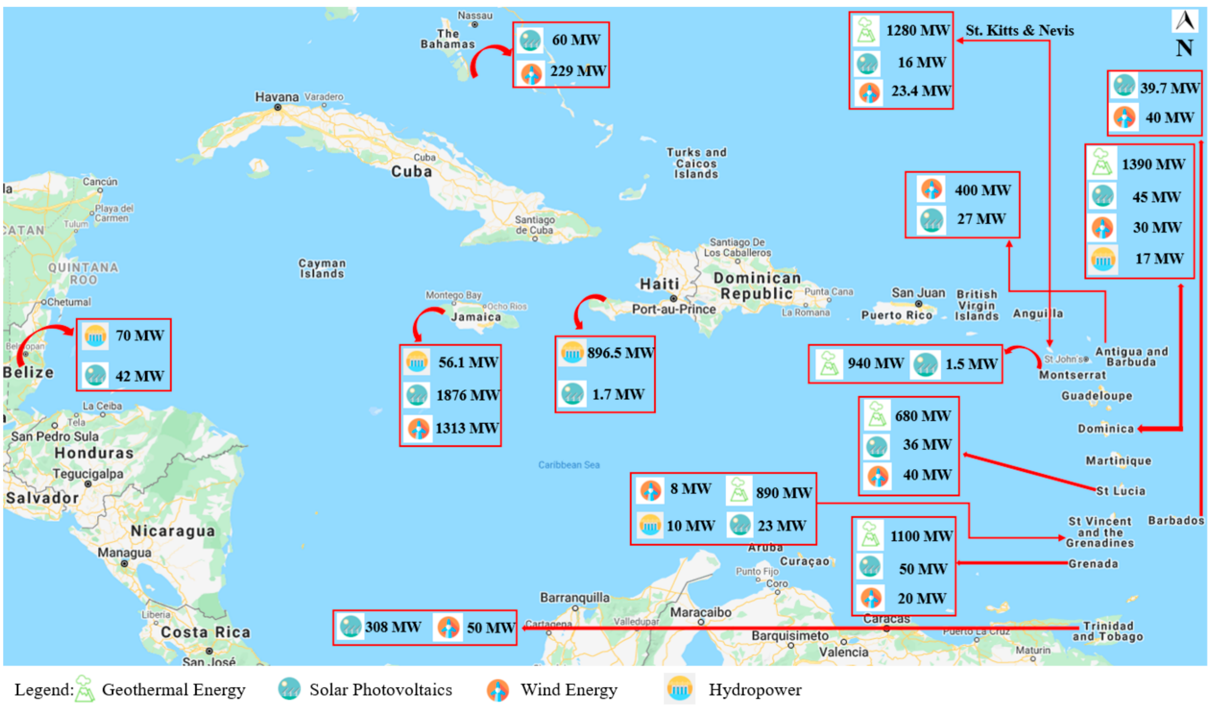

Figure 1. Renewable energy distribution across the Caribbean Community (CARICOM) nations. Map created based on data from Ochs et al. [19].

It should be noted that SIDSs, in addition to their energy needs, are acutely focused on climate adaptation measures that can be supported by ambitious RE integration plans. In the Caribbean, the primary focus will be on increasing penetration rates of solar photovoltaics and wind energy. The variable nature of wind and solar power mandates that there be an additional source of energy or storage of energy to complement these two resources. Battery storage is an increasingly viable option for storing energy, whereby utilities operate load shifting methods to "transfer" energy from times of plentiful sun and wind to those times without [21]. The other available avenue to complement variable renewable power generation is through the use of a dispatchable (controllable) source of power. If fossil fuel sources and nuclear energy are not considered, a limited number of technologies are available (e.g., hydropower, geothermal, biomass, waste, tidal, wave, and OTEC).

Worldwide, hydropower has long been the dominant renewable electricity source; however, hydropower plays a fairly insignificant role in the region (with few exceptions such as Suriname and Belize, neither of which are part of the present analysis). As shown in the summary in Table 1 as well as in Figure 1, some countries have hydropower resources that may be either very small (Grenada) or already at maximum capacity (Dominica and St. Vincent and the Grenadines). In very few cases in the region, pumped hydropower storage, and the increasingly viable conversion of renewable electricity to hydrogen through hydrolysis are also being explored. Hydrogène de France (HDF), for instance, has recently invested in developing a 55 MW/140 MWh hydrogen-based solar-plus-storage plant in French Guiana in 2018 [22], for which work was expected to begin in 2020.

Table 1. List of Caribbean countries with yes (green) or no (light red) filters for potential hydropower, geothermal and ocean thermal energy conversion (OTEC) technologies as dispatchable renewable energy. For OTEC in this table, no filtering has been done for resources to determine proximity to population centers or other infrastructure. In some cases (yellow), hydropower resources may be small, either in absolute terms or in comparison to the overall system capacity. Additional information for reference purposes on peak demand and electricity price by country, the latter adapted from NREL [23].

Country	Hydropower	Geothermal	OTEC	Peak Demand (MW)	Residential Electricity Price (USD/kWh)
Bahamas				308	0.32
Cuba					
Turks and Caicos				34.7	0.26
Jamaica				644	0.28
Haiti				500	0.13
Dominican Republic				2506	0.13
Puerto Rico				3685	0.22
British Virgin Islands				32	0.24
U.S. Virgin Islands—St Thomas and St John				88	0.40
U.S. Virgin Islands—St Croix				55	0.40
Anguilla				14	0.23
Sint-Maarten/Saint-Martin				42.6/32	0.30
St Kitts and Nevis				20.4 and 10.4	0.26
Antigua and Barbuda				50	0.40
Montserrat				2	0.50
Guadeloupe				254	0.19
Dominica				16.8	0.21
Martinique				235	0.11
St Lucia				60.3	0.28
St Vincent and the Grenadines				21	0.19
Barbados				168	0.25
Grenada				30	0.32
Trinidad and Tobago				1322	0.05
Bonaire				12	0.22
Curaçao				130	0.35
Aruba				135	0.17

Another potential energy source, biomass use for power generation, can largely come in two forms: either using waste from crops, such as sugar cane, or from purpose-grown bioenergy crops. Biomass electricity can therefore play a niche role in some countries, but especially on some of the smaller islands, a large biomass to electricity capacity is not to be expected due to environmental concerns and climatic risks posed to already strained agricultural systems. These limitations are further compounded by resource competition, because most agri-based biomass systems need a constant supply of by-products which are often more valuable on international markets than being converted into ethanol or burned for electricity.

Finally, waste-to-power generation could play a marginal role in some countries, either from solid waste combustion or capture of landfill methane; although countries in the region do have waste disposal challenges, the overall amount of waste generated in 2010 was ~1 kg/person/day) [24], with estimates of the combustion value and the resulting electricity generation from municipal solid waste [25] leading to an energy production of approximately 90 kWh/capita/year; a relatively small contribution compared to typical island electricity consumption of ~2000 kWh/capita/year.

Beyond the critical issue of carbon emissions reductions, there are other reasons for Caribbean SIDSs to transform their energy systems to domestic renewable resources. Caribbean member states are vulnerable to the volatile nature of the oil and gas industry; hence, a continued reliance on fossil fuel imports hinders energy diversification and economic security. Collectively, the average price of the domestic retail rate of electricity across Caribbean islands states is ~USD 0.30/kWh [23]. Therefore, there is a continued need for RE integration to mitigate trade imbalances due to fossil fuel imports. In addition, Caribbean countries tend to rank in the middle of the Notre Dame Global Adaptation Initiative Index [26], a measure of a country's vulnerability to climate change and its readiness to improve its resilience. The combination of vulnerability, economic stress and climate change mitigation commitments motivate the present work.

Ocean energy technologies such as wave, tidal and OTEC are not represented in Figure 1. Of these, the first two have very low potential in the Caribbean [4], whereas OTEC has much more favorable potential in some localized areas. In the next subsection, the available dispatchable RE technologies in the region are explored in more detail, assuming that solar PV and wind will form the backbone of the power system.

1.2. Summary of Dispatchable Renewable Technologies and OTEC Potential

The analysis presented in this paper is multi-faceted, looking at OTEC resource potential in all Caribbean island states, some ancillary advantages of OTEC as both a supporting technology for variable renewable systems as well as in terms of seawater desalination as an additional adaptation and resilience measure, and finally, at the economics of OTEC as part of a 100% RE system. The International Renewable Energy Agency (IRENA) surveyed ocean energy resources around the world [4], and for the Caribbean region, both tidal and wave power are poor resources due to limited tidal channels to harness energy; therefore, these technologies are not considered within this study. Table 1 gives a summary of potential resources for hydropower, geothermal and OTEC, summarizing the discussion in the previous section and with the latter based on the results to be shown in Section 3. The comparison is then used to motivate the results of this paper and look in more detail at OTEC as a potentially viable and alternative complementary power source for high VRE penetration, and as a technology that can also provide other co-benefits for those regions in which it is viable. Geothermal and OTEC as listed are really either available or not, depending on geological conditions. Hydropower in some cases may be available on a small scale, either in absolute terms or relative to system size. In addition, peak demand for each of the islands is listed to provide a sense of the system size [23]. This will become more relevant in the discussion below on complementing VRE with dispatchable renewables.

1.3. OTEC, SWAC and Desalination

OTEC, a concept that has been around for over a century, takes advantage of the temperature difference between warm surface ocean water and constant temperature deep ocean water; typically, the difference is ~20 °C for useful energy harvesting to drive a thermodynamic engine cycle [3]. At depths of approximately 1000 m, ocean temperatures are nearly uniformly at ~4 °C. For a temperature difference of 20 °C and constant year-round availability, low-latitude regions are most promising, with surface water temperatures of 25 °C or more [3]. The approach of OTEC is to take advantage of effectively infinite hot and cold reservoirs with a small temperature difference, and therefore low thermodynamic efficiency, but with a resource base that is theoretically inexhaustible given the persistent thermal gradients.

There are three main strands of literature concerning OTEC and the related technologies. A series of papers has initially mapped global, and some regional, potentials based on sea-surface temperatures [7,27] In addition, whether for OTEC, SWAC or desalination work, analyses of bathymetry have been undertaken to a somewhat lesser degree [28]. Sections 2.1 and 3.1 of this paper explore regional variations in more detail, which is one of the main contributions of this work.

The second and larger area of research is focused on the thermodynamic efficiency and optimization of technological system components for OTEC, usually with much less or no attention given to the geographical location of the potential systems. Two main categories of OTEC are the closed-cycle (CC) and open-cycle (OC) OTEC systems. CC-OTEC uses a high vapor pressure working fluid together with heat exchangers where the warm surface ocean water vaporizes the fluid, which then drives a turbine and a generator. The fluid condenses when coming in contact with the cold reservoir, water coming from the deep ocean. OC-OTEC, on the other hand, takes warm surface water and draws it into a low-pressure chamber in which it is flash evaporated (boiled) which drives a low-pressure turbine and subsequently the generator. Here, the condensed water resulting from heat-exchanger contact with the colder, deep-ocean water, is also desalinated in the process, a co-benefit of this process cycle [29–39].

For both processes, there is potential for using the circulating cold water for SWAC, essentially a low-carbon and low-cost replacement for utility-scaled and chiller-based cooling. However, in all of these technologies, two of the most critical and expensive components are the heat exchangers and the necessary piping to reach deep, cold ocean water, and subsequently, coastlines. Having both warm and cold-water reservoirs near the generation facility and for SWAC, near-demand for cooling becomes one of the most important criterion for site selection [28].

The third area of research, usually in conjunction with one of the first two, is to analyze the economic feasibility, or at least, the system costs of OTEC, desalination, and accompanying SWAC outputs. Sections 2.2 and 3.3 explore these aspects in more detail, highlighting the main economic considerations where the emphasis is placed on the economics of both OC- and CC-OTEC, showing that costs decrease when moving to the CC-OTEC technology, due in part to the overall larger size (>10 MW) of these systems compared to smaller OC-OTEC plants [6,8,10,29,40,41].

2. Materials and Methods

The following three sections present the methodologies used in this paper. Bathymetry mapping of all Caribbean Island states was used to determine the most promising sites for OTEC (Section 2.1). A summary of economic parameters and approaches is given in Section 2.2. The description of residual loads and the hourly modeling of RE generation and battery storage is provided in Section 2.3.

2.1. GIS Bathymetry Mapping of the Caribbean Region

Previous low-resolution mapping of potential OTEC resources that looked at sites with a temperature difference ~20 °C and within 200 miles of coastlines [15] is expanded upon in the present work. Suitable locations within the Caribbean region, with an emphasis on SWAC, have also been previously investigated [40]. A very recent report explored a specific site in Puerto Rico in great detail, and represents the follow-up stage for any given sites identified here [42].

The main requirements applied in what follows are having a depth of 1000 m, for consistent ~4 °C temperature, and that potential OTEC sites be near coastal areas to minimize piping lengths and allow land-based infrastructure for the OTEC power plant. Coastlines were defined using the National Oceanographic and Atmospheric Administration (NOAA) high-resolution shoreline database, and then extended out to a distance of 10 km. The primary bathymetry dataset used was the General Bathymetric Chart of the Oceans (GEBCO) [43], which covers the complete extent of the study area at a 15 arc-second resolution. Information on bathymetric source data types is provided with the downloaded grid, with examples including single and multibeam bathymetry, and seismic and sounding surveys. The 10 km study area extending from coastlines was further refined with 2.5 km shoreline buffer increments symbolized to emphasize proximity to the coast. Particular areas of interest within the study area were located by identifying the gridded areas of the GEBCO bathymetry dataset at depths greater than 1000 m. Over the extent of the study area, the horizontal resolution of the GEBCO 15 arc-second depth data was approximately 400 m (range 385–460 m).

For purposes of organization, two sub-regions within the Caribbean region are considered (Figure 1). The Greater Antilles consisting of larger islands such as Cuba, Jamaica, Hispaniola (Haiti and the Dominican Republic), and Puerto Rico; The Bahamas and Turks and Caicos Islands are also taken as part of this group. The Lesser Antilles are the islands ranging from the U.S. and the British Virgin Islands and Anguilla southward to Trinidad and Tobago, including Barbados and islands near the coast of South America (Aruba, Curaçao, Bonaire and Isla de los Roques). Each of these is examined in turn to identify candidate areas within these regions for OTEC implementation based on the chosen criteria. Detailed maps of the bathymetry and distances to the coast for all islands are shown statically in the Supplementary Information online as well as being available as an interactive mapping tool at https://tinyurl.com/8hkznwxr (accessed on 13 April 2021).

2.2. Summary of Economic Parameters for OTEC and Desalination

As referenced above, a number of studies have attempted to determine the costs for coupled OTEC and desalination and SWAC systems. The typical view as been that (i) these technologies are not yet ripe, (both technologically and economically), being only in the pilot-project stage, but that (ii) with enough research and deployment, economies of scale will drive costs down, with one of the reasons for examining the feasibility of these coupled systems stemming from the hope for better energy economics with these dual-use technologies. However, as shown by the specific cases highlighted here with the filtering of likely areas for OTEC, the feasible sites dwindle in number to very few.

Relatively few detailed economic estimates are available in the literature. The most complete recent accounting for costs is for a CC-OTEC system [29]. A detailed study of both CC and OC systems was carried out in Vega [8]. In this paper, the large degree of uncertainty in OTEC cost estimates is recognized, but literature results are used to guide the analysis. Earlier work assumed an offshore platform for hosting the OTEC system, with the platform, moorings and undersea power cable representing a significant fraction of the total cost. These previous analyses also assumed a relatively large, generically placed (geographically) OTEC plant of 50 MW capacity, having determined that a strong cost advantage arises in moving from plants of 10 MW or less to this larger size due to scale effects [8]. For the proposed applications discussed in the present work, smaller plants or units in the order of 5–10 MW capacity are more appropriate. Based on Vega [8], the specific (i.e., per kW of capacity) capital cost of a 5–10 MW plant would be approximately three times that of a 50 MW plant [8]. One key assumption, following Vega [8], is that overall component costs for the CC and OC plants will be approximately equal [8]. Using these scaling factors and assumptions, the capital cost for a 5 MW OC-OTEC plant would be approximately USD 13,500/kW (also converting 2009 USD to 2018 USD with a producer price index factor of 1.2).

A more recent analysis examined an OC-OTEC plant with a net capacity of 2.3 MW (after self-consumption was taken into consideration) in which multiple such units could be combined for a power plant of larger total capacity [29]. Those authors estimated a levelized cost of electricity of EUR 269/MWh (~USD 300/MWh or USD 0.30/kWh) in their base case, with a capital cost of EUR 16,000/kW (EUR 14,000/kW in a low-cost case). Finally, another recent paper estimated capital costs for a 10 MW OC-OTEC system to be USD 15,000/kW [44]. This result is somewhat higher than that of the earlier work [8], but within any reasonable estimate of uncertainty and will be used as a best-estimate baseline in the analysis, with sensitivity tests for lower and higher costs being applied.

As far as the production of desalinated water and electricity is concerned, an estimate gives daily production of 118,000 m^3 and an annual output of electricity (assuming an overall 92% capacity factor) of 414,415 MWh [8]. For operation of a smaller system with 0.5 MW net capacity and 80% capacity factor, a freshwater production of 1175 m^3/day was found in Kim et al. [33], in very good agreement with Vega [8]. More realistically, especially given the grid integration potential considered here, a capacity factor of ~70% should be taken if sized reasonably for the system, which increases the LCOE. This co-benefit of desalinated water will be considered in the analysis as well. Estimating the cost of water from an informal survey of the websites of regional water agencies, a value of USD 1.5/m^3 was used and sensitivity to lower (USD 1/m^3) and higher (USD 2/m^3) water prices was tested.

2.3. Load, Residual Load and System Benefits of Dispatchable Renewable Energy

According to the best available science as summarized by the IPCC, compliance with the Paris Agreement will require a near-total phase-out of fossil fuels by about 2050 globally [2]. In support of the need to understand this transition, modeling integrated systems of 100% RE has become an increasingly active field of research [45–48]. The strong decrease in the past decade in the cost of solar PV, wind power and batteries, and in the near future, of electric vehicles, outlines a pathway forward to the elimination of fossil fuels and reliance on sustainable, renewable sources of energy [16,49–51].

In general, there is a trade-off between the possibility of integrating high percentages of variable renewables and the use of either storage or a dispatchable power source. As will be shown, adding a relatively small amount of dispatchable capacity, even if expensive when considered in isolation, can enable a significantly increased uptake in much cheaper wind and solar energy. Thus, when an overall system LCOE is considered, there can still be a benefit of the apparently expensive technology [52,53].

To investigate trade-offs, a Python-based model was constructed (available at https://github.com/RJBrecha/OTEC-Caribbean, accessed on 13 April 2021), and a fictitious but representative Caribbean island was assumed, with a yearly electricity generation of 250 GWh and a peak demand of 37 MW. Here, proprietary hourly demand data have been used, but scaled from an actual country to the total generation for this fictitious island. Load curves tend to be very similar for smaller Caribbean islands except for the overall amplitude, and at the level needed for this demonstration of principle, these data are deemed sufficient. Hourly demand data can alternatively be taken from data available for synthetic demand curves generated as part of 100% RE modeling efforts [54]; comparison with real data shows a somewhat exaggerated secondary evening peak for the synthetic data.

To a first approximation, solar and wind energy generation at an hourly time resolution for a given modeled installed capacity can be obtained from https://www.renewables.ninja/ (accessed on 13 April 2021) based on reanalysis data [55,56]; before embarking on a large-scale transformation it would be necessary to undertake actual in situ measurements. With these three datasets, each of which can be scaled in amplitude to represent different levels of production of wind and solar power, as well as for different overall demand, an hourly time series can be constructed that shows the residual load after VRE has been taken into account, i.e., load minus solar and wind power. For an assumed installed capacity of a dispatchable source (OTEC is the assumed technology in this case, but this could be made up of different sources), if the residual load from VRE is positive, i.e., demand is not satisfied, then the dispatchable source is used to fill in the gap up to its maximum capacity. In the model, the dispatchable source is also assumed to have a minimum output that is chosen to be 25% of the maximum capacity. Finally, storage is integrated into the model with a given capacity (MWh) and power output (MW) (batteries, either at utility-scale or in an integrated grid with electric vehicles, or perhaps hydrogen with fuel cells), such that an oversupply of VRE can charge the storage, or undersupply of VRE with dispatchable source results in the discharge of energy storage; the dispatchable renewable source can also be used to charge the battery up to its maximum capacity as needed. This process is modeled for each hour of the year with the goal of satisfying demand at each hour while keeping track as well of the capacity factor of the dispatchable source, the state of charge of the storage, and the total curtailed amount of VRE during the year. A convenient way to visualize the various trade-offs that arise, including that of meeting demand versus curtailing VRE (which can in some cases be part of an optimal solution) is through the use of residual load duration curves [57]; this approach is presented in the Supplementary Information online.

A variety of combinations of dispatchable renewable source, storage capacity, and VRE (wind + solar PV) can meet the demand for all hours of the year. Using this model, it is possible to find the amount of storage (in MWh) needed for a given combination of wind, solar PV, and dispatchable renewable power (e.g., OTEC) capacities such that demand for all hours of the year is met. Table 2 summarizes input parameters and assumptions used for the scenarios and to determine the total system levelized cost of electricity (sLCOE). Whereas the exact nature of the dispatchable source is of less importance here, for several of the Caribbean islands under consideration, OTEC may be the best or only dispatchable renewable technology potentially available. Indicative costs are based on storage and renewable energy costs [51,58,59].

Table 2. Parameters for the evaluation of system levelized costs of electricity (sLCOE) for different combinations of solar photovoltaic (PV), wind, dispatchable renewable and storage.

Peak power	37.7	MW
Yearly energy	250	GWh
Levelized cost of wind	USD 100	/MWh
Levelized cost of solar PV	USD 100	/MWh
Levelized cost of dispatchable renewable source (OTEC)	USD 300	/MWh
Levelized cost of storage	USD 300	/MWh
Lifetime of storage	15	years
Lifetime of system	20	years

With these data and parameters as background, the main results of this paper are presented in the following section.

3. Results

Results are presented in the following three subsections. First, examples of the results of GIS mapping for near-shore OTEC potential are given in Section 3.1 with more details in the Supplementary Information. System integration of variable and dispatchable renewables with battery storage are shown in Section 3.2 and example system LCOE results are given in Section 3.3 showing estimated costs both with and without the inclusion of desalination.

3.1. GIS Mapping of Deep Water at Different Distances from the Coast

Example results of GIS bathymetry and coastal distance mapping are shown in the following two sections for the Greater and Lesser Antilles; a summary of promising locations for OTEC near towns or other facilities is shown in the final subsection.

3.1.1. Greater Antilles (with The Bahamas and Turks and Caicos)

As an example, a map of Jamaica is shown in Figure 2. On this map, the blue area shows the regions of >1000 m depth, and the gray area those with depth <1000 m. The additional contours are for distances of 2.5 km (green), 5.0 km (yellow), 7.5 km (orange) and 10 km (red) from the coast. The interpretation of the map is that any area for which the blue 1000 m depth contour is closer to the coast than a given distance contour will represent cold, deep water at a constant temperature. For the sake of the evaluation, the most promising locations are those closer than 5 km (yellow line) and preferably (in the sense of the cost of construction) closer. In the case of Jamaica, the best locations from the point of view of a near-coastal resource for OTEC would be near Negril, Lucea, southeast of Kingston, and near Port Maria and Port Antonio in the northeast. A more detailed list of potential sites in the Greater Antilles is given in Table 3.

Table 3. List of sites with OTEC potential (1000 m depth at closer than 5 km to the coast) as well as being near towns or other infrastructure.

Jamaica	Western	Negril (hotels, airport)
	Northwestern	Lucea
	Northwestern	Montego Bay
	Southeast	East of Kingston
Grand Cayman	All areas	George Town, Bodden Town, East End, West Bay
Cuba	Southeast	Santiago de Cuba
	Northeast	Guardalavaca (tourist resorts)
	Northeast	Playa Uvero, Playa La Playita (tourist resorts)
	Northeast	Havana
Bahamas	Central	Nassau
Turks and Caicos Islands	East	Cockburn Town
Haiti	West	Canal de St.-Marc, Canal de la Gonâve
Dominican Republic	South	Barahona, Paraíso, Los Patos
Puerto Rico	Southeast	Guayama
Guadeloupe	Northeast	Le Moule
Dominica	West coast	Roseau, Portsmouth
Martinique	West coast	Fort-de-France, St Pierre
St Lucia	Southwest	Soufriére
St Vincent and the Grenadines	West coast	Kingstown

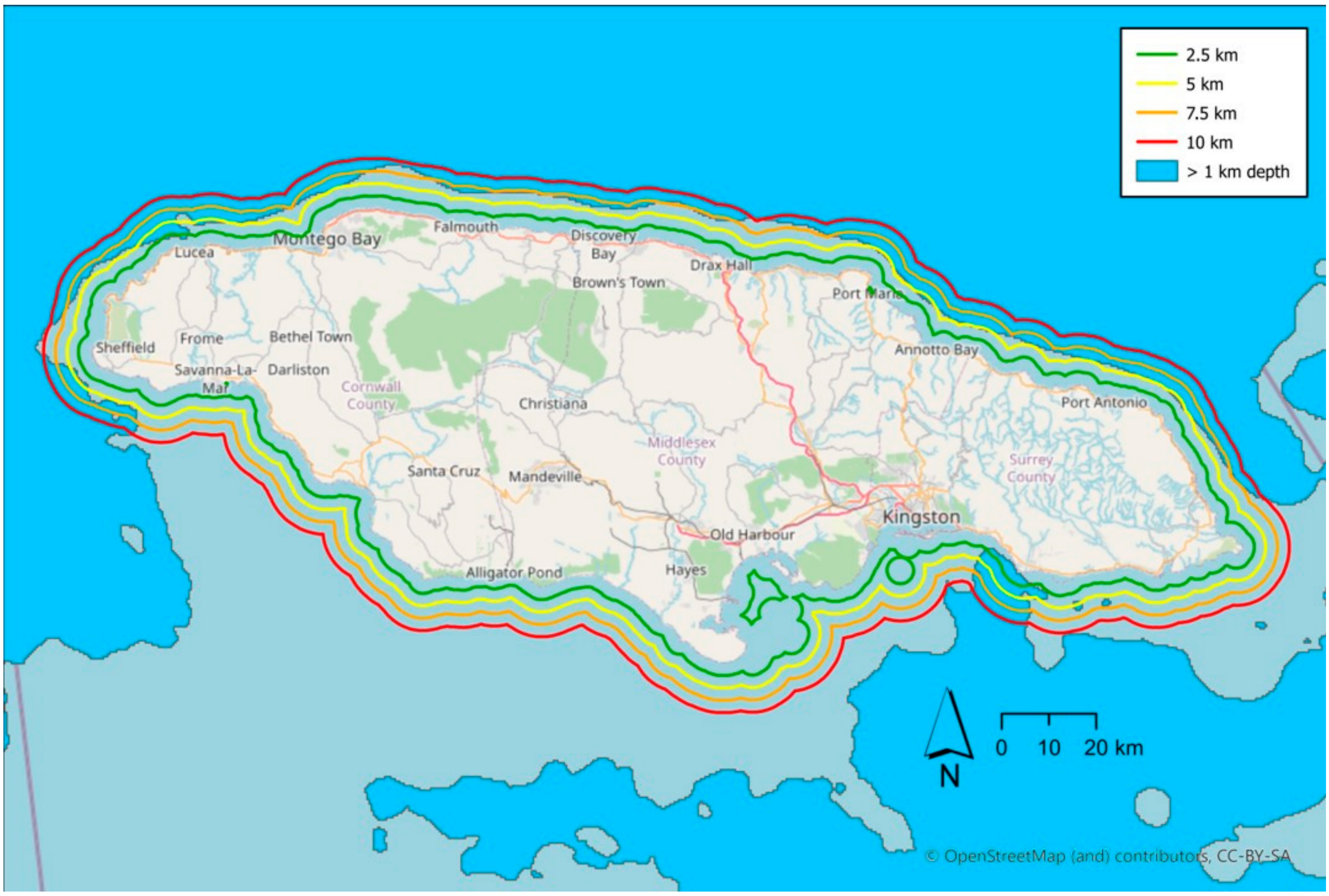

Figure 2. Map of Jamaica with a bathymetry contour representing the boundary between depths of greater than 1000 m (blue) and less than 1000 m (gray). Other contours are equidistant from the coast at 2.5 km (green), 5.0 km (yellow), 7.5 km (orange) and 10 km (red).

3.1.2. Lesser Antilles

Two examples of islands with promising OTEC locations for the Lesser Antilles are shown as examples in Figure 3, for Martinique and for Saint Lucia. Several of the Eastern Caribbean islands have deep water within 10 km of the coast. Again, the areas enclosed in red are distances of 10 km and distances from the coast of 5 km are shown in yellow. Depths of 1000 m and greater are outside (i.e., farther from the coast than) the gray area and represented in blue. It can be observed that several areas off the coasts of islands appear to be viable sites for OTEC, with deep, cold ocean water at distances of 2.5–5 km or less. A more detailed summary of mapping and potential sites is shown in the SI online, but also explicitly includes those islands with no likely OTEC potential according to these criteria, for example, St. Kitts and Nevis, Antigua and Barbuda, Aruba and Trinidad and Tobago.

As an additional example of an island without potential OTEC resources according to the criteria that have been set here, in Figure 4 a map of Antigua is shown in the same format. The gray area is at depths of less than 1000 m, and the contours out to 10 km and beyond all lie within that relatively shallow area. Thus, to reach sufficient depths around Antigua for OTEC, there would have to either be very long pipes, or the system would have to be set up on a floating platform. The area off the northeast coast of Antigua, nearest to the deep water, also encompasses a Marine Protected Area, which would present an additional hurdle to implementation and represent a potentially negative impact in the broader sense of sustainability for energy system infrastructure.

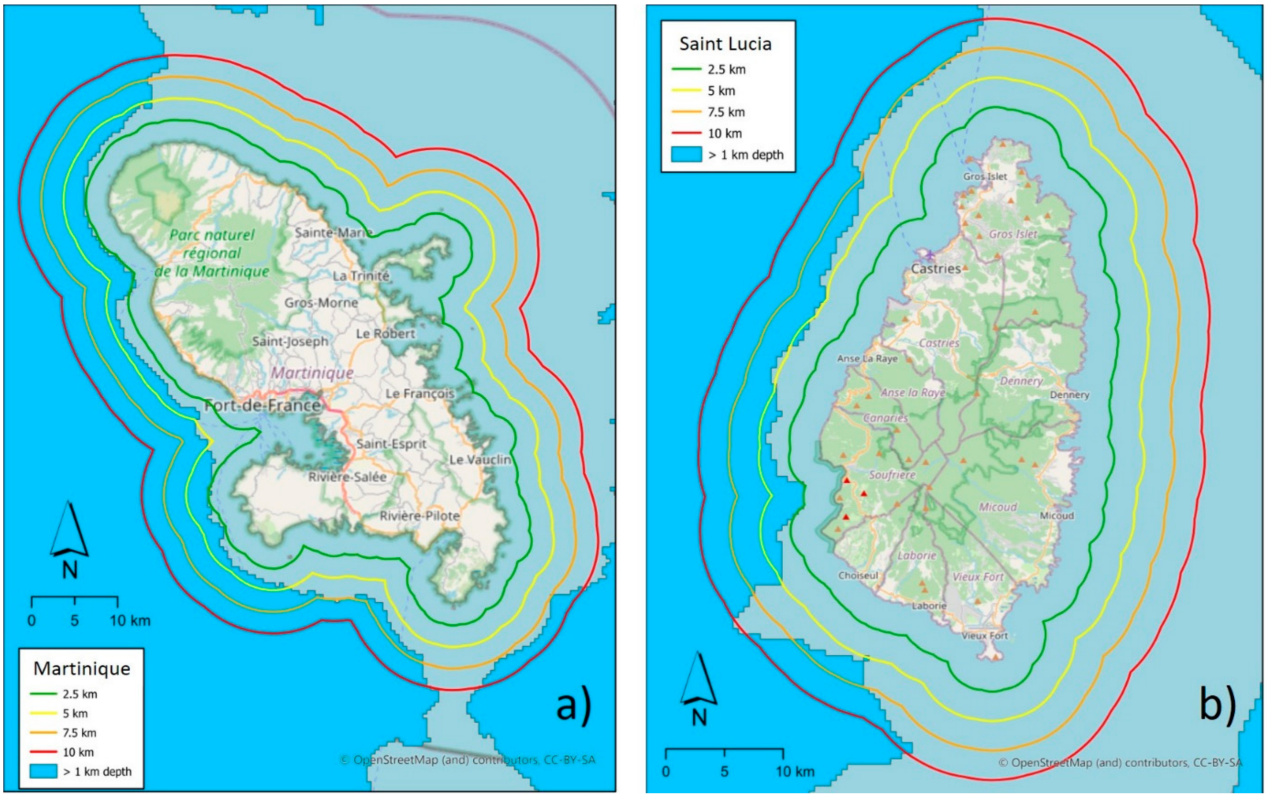

Figure 3. Maps of two example countries in the Lesser Antilles, (**a**) Martinique and (**b**) Saint Lucia. Bathymetry contour (gray/blue) represents the boundary between depths of greater than and less than 1000 m. Other contours are equidistant from the coast at 2.5 km (green), 5.0 km (yellow), 7.5 km (orange) and 10 km (red).

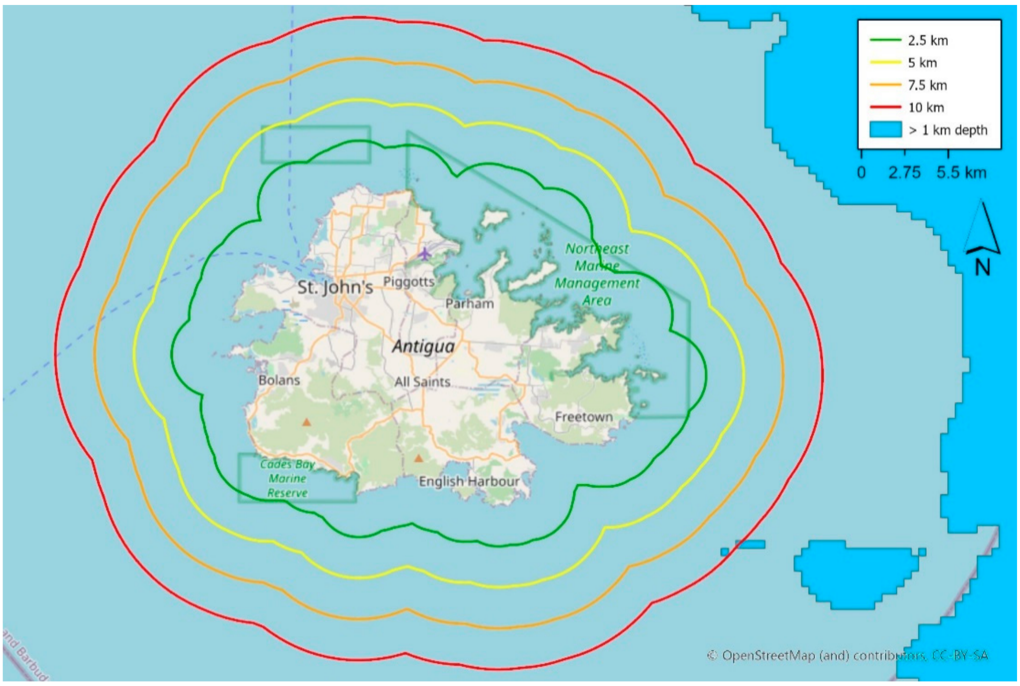

Figure 4. Map of Antigua with bathymetry contours and the blue area representing depths of greater than 1000 m and gray for less than 1000 m. Other contours are equidistant from the coast at 2.5 km (green), 5.0 km (yellow), 7.5 km (orange) and 10 km (red). Marine protected areas are shown within the light green polygons.

3.1.3. Summary of Promising OTEC Sites

While this study provides a more detailed mapping analysis than has been previously published, precise evaluation of potential projects will rely on a number of additional important details, such as the presence of Marine Protected Areas coincident with near-shore deep water, the location of towns or tourist areas, as well as convenient roads and transmission infrastructure. As a first approximation, only areas that were within the 5 km buffer were chosen, and also near infrastructure as described. Thus, the results presented in Table 3 are not exhaustive, but rather provide examples of potential sites for OTEC. At this first level of approximation, several islands can fulfill this latter criterion as well. For example, Dominica (near the capital city Roseau), the west coast of Martinique, and St. Lucia (near Soufrière) are among the most promising sites, along with several areas in Cuba and Jamaica, amongst others.

Below OTEC capacities of 10–25 MW will be considered; this amount of capacity can have the greatest impact in terms of energy generation across the islands with smaller overall power capacity (as shown in Table 1), notably, the islands of Dominica, St. Vincent and the Grenadines, Saint Lucia, and Grenada. Of the larger islands, Jamaica in particular is aggressively pursuing increased rates of RE penetration and could potentially adopt OTEC technology to supplement the intermittent nature of the dominant renewables of solar and wind. Islands such as Grenada and Saint Lucia have long included geothermal technology with capacities of 10–30 MW in their energy system planning, but have had challenges in seeing these plans come to fruition; OTEC could be an alternative and these islands (together with others) and the potential OTEC locations are summarized in Table 3.

3.2. Results for Balancing Dispatchable OTEC Technology with Variable Renewables and Battery Storage

In Figure 5, two cases are shown in which the dispatchable OTEC technology capacity is set at 10 MW (Figure 5a) and at 20 MW (Figure 5b), and the capacities of the VRE technologies are varied from 0 to 200 or 100 MW (x- and y-axes). The amount of storage capacity is capped here at 2000 MWh and at 1000 MWh, respectively, for clarity of presentation. The main point to note is the relationship between a decrease in dispatchable power capacity and an increase in necessary storage capacity, becoming more pronounced at lower wind and solar PV capacities. Essentially, for low dispatchable capacity, large amounts of storage are needed, mainly to make up for a relatively small number of extended periods during which wind and solar PV power are both not available. In Figure 5, there is a very sharp rise in battery capacity at low levels of wind and solar capacity; this feature is an artefact of the problem definition and represents the fact that not enough overall capacity is available in the system to cover demand during a significant period of time during the year.

Table 4 shows the results for a selection of cases with differing amounts of VRE and dispatchable RE, effectively representing points on the surface of the plots in Figure 5 when combined with the storage capacities. One feature not visible in Figure 5 is the amount of curtailed variable renewable power, which becomes significant as the VRE capacity increases, and thus represents an additional trade-off to be considered. Table 4 shows the curtailment amount in GWh per year for each selected case. The combination of all these factors contributes to the total system cost.

3.3. Results for System Levelized Cost of Energy

Table 4 also shows the sLCOE for each of the eight cases. In Figure 6a, a further comparison is made for these eight cases, with the blue and orange bars representing the sLCOE both without and with the inclusion of benefits of desalinated water that would be produced by an OC-OTEC system. Additionally, displayed in Figure 6 is a shaded region that represents the estimated LCOE for a diesel reciprocating engine system that has, until recently, been the power source of choice for many countries [51]. One feature not included here is costs incurred due to grid extensions and other system costs often associated with the higher penetration of renewables [60]. These costs will be very dependent on individual system configurations and would require further investigation within the context of a given country.

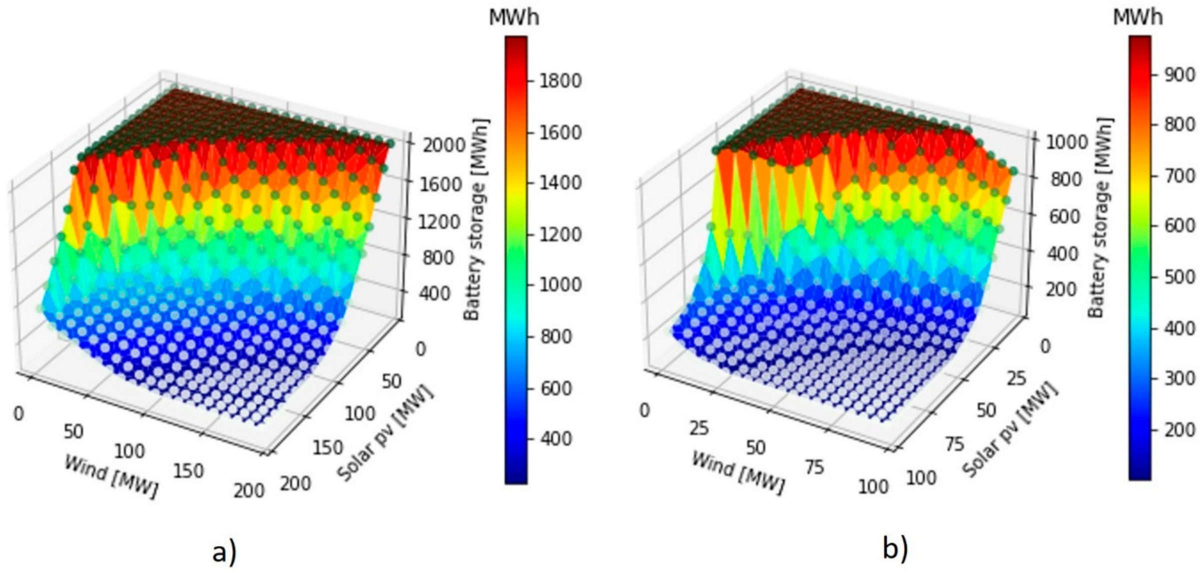

Figure 5. Necessary amount of storage capacity (in MWh) to allow demand to be satisfied for every hour of the year, and as a function of the installed wind and solar PV capacity. (**a**) With 10 MW of dispatchable renewable capacity and (**b**) with 20 MW of dispatchable renewable capacity. Peak system demand is 37 MW in this example. Note the difference in scale of a factor of two between the plots.

Table 4. Sample results for sLCOE (USD/MWh) for different system configurations (solar PV, wind, dispatchable renewable, storage). Comparison is made with and without including the co-benefit of desalination. Dispatchable (Disp.); Desalination (Desal.); Curtailment (Curtail.) For the sLCOE with desalinated water, sensitivity to water price is included in parentheses, with the base case being USD 1.5/m^3 and in the range USD 1/m^3 to USD 2/m^3.

Case	Solar (MW)	Solar (GWh)	Wind (MW)	Wind (GWh)	Disp. RE (OTEC) (MW)	Disp. RE (OTEC) (GWh)	Storage Capacity (MWh)	Energy from Storage (GWh)	Curtail. (%)	sLCOE (USD/MWh)	With Desal. Water (USD/MWh)
1	200	335	73	204	0	0	2000	42.5	53	424	424
2	140	234	73	204	10	40	1000	17.8	48	326	300 (292, 309)
3	120	201	53	150	10	46	1500	24.5	37	351	322 (313, 332)
4	100	167	44	122	15	71	1000	15.8	30	304	259 (244, 274)
5	90	151	34	95	15	79	1500	20.3	23	349	3299 (283, 316)
6	80	134	17	48	20	117	1000	15.7	16	316	242 (218, 267)
7	90	151	24	68	20	108	500	11.3	23	267	199 (177, 222)
8	60	100	29	82	25	115	200	2.37	16	229	156 (133,181

There are several points to note about these summary results. Firstly, costs for solar and wind have been set at USD 100/MWh; a conservative estimate in that there are many examples around the world of far lower LCOE for these technologies, and in fact in more mature markets, power purchase agreements have been tendered with costs of only USD 30–40/MWh for systems of solar PV or wind energy, even including battery storage in some cases. On the other hand, Caribbean islands have not yet shown the cost decreases to these lowest levels. A second point is to emphasize that USD 300/MWh is used to represent relatively untested OTEC costs; with other technologies such as geothermal or hydropower, the dispatchable source would be expected to have significantly lower LCOE, thus lowering the sLCOE cost with respect to those shown here, even without the added benefit of desalinated water, as illustrated in Figure 6. Even with these caveats and relatively conservative assumptions, the system LCOE for OTEC with the co-benefit of desalinated water, and in some scenarios even without this advantage, is less than it would be for diesel power generation.

To represent potential and likely future developments, Figure 6b shows the same analysis but with an assumed cost of solar PV and wind each of USD 50/MWh, and storage costs of USD 150/kWh, keeping the uncertain cost of the dispatchable OTEC source constant at USD 300/MWh. This situation might represent expected costs by 2030, which is when many Caribbean islands will have increased the implementation of variable renewables and will be looking at options for complementing variable renewables with a dispatchable source of RE. It is seen that with these costs decreasing, even with the relatively expensive OTEC technology as a backstop, the total system cost of electricity is less than what would be expected for diesel generators in nearly all cases. Taking into account the added benefit of desalinated water, the difference is even larger.

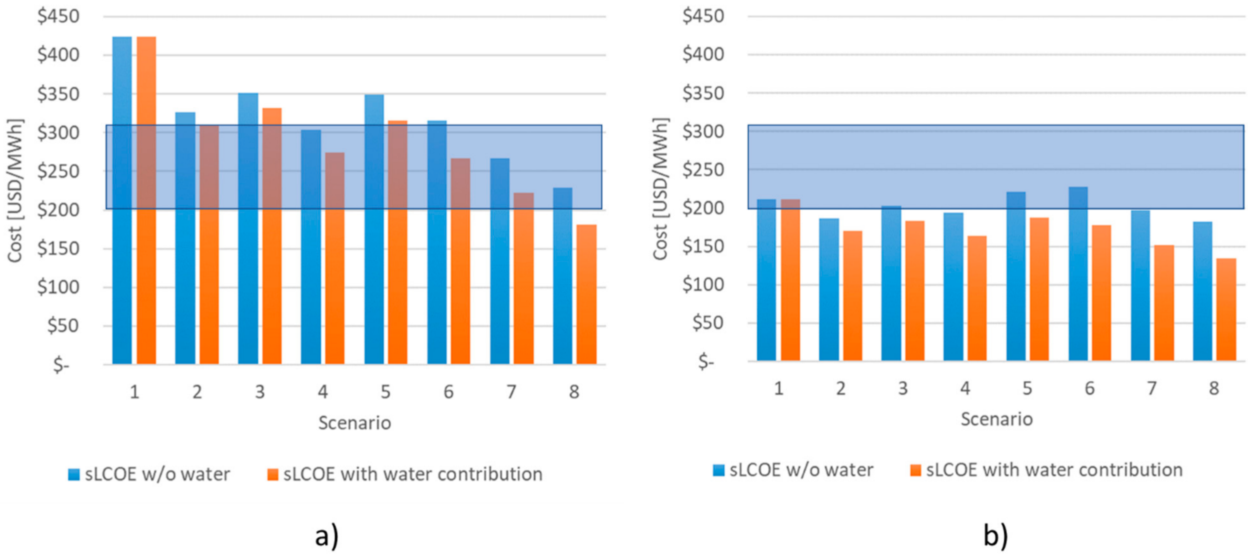

Figure 6. Comparison of the sLCOE for eight example cases as described in the text and in Table 4: (**a**) with estimated current costs of each technology, and (**b**) with estimated costs in 2030, when deep renewable energy penetration will likely be starting to make dispatchable technologies a necessity to complement variable renewable energy sources.

4. Discussion

OTEC has been presented here as a potential niche solution for high-penetration renewable energy systems in Caribbean island countries. OTEC has been in discussion as a power source, together with co-benefits such as seawater air conditioning and desalination, for many decades. The principles of OTEC are well known, but in many situations there are other technologies with better prognoses for large-scale adoption. However, as described here, for island nations with large amounts of solar and wind energy potential, either energy storage or a dispatchable energy resource is necessary as a complement to variable renewables. Many studies have looked at OTEC, focusing on the technology itself and understanding how to make OTEC more economically competitive. In the present work, a different starting point has been taken, namely, that of considering OTEC as one part of a system and looking at the advantages of even a relatively expensive (in the sense of LCOE) technology in enabling a higher penetration of inexpensive variable renewables. The key is then to look at the electricity system as a whole and not at each technology independently—the system LCOE is the important parameter, and OTEC can contribute to a system with an economically competitive LCOE dominated by solar and wind.

OTEC technologies present many challenges, mostly infrastructural, both because they are relatively untested on a larger scale and due to the partial location of structures in ocean waters. Caribbean systems are particularly vulnerable to extremes in weather owing to the pronounced hurricane season and deep convective atmospheric conditions that often result in storm surges and inclement weather during the rainy seasons.

OTEC systems are governed by basic principles of vertical ocean thermal gradients and are relatively simple in their operation, excluding more advanced hybrid and electrolysis complementary operations. Both floating and shelf- or land-based systems involve extensive lengths of piping which can be easily disrupted by turbulent ocean surfaces. Here, the focus has been on land-based systems because the foreseen application is that of a dispatchable power source that complements variable wind and solar PV, and therefore provides an important stabilization role in the grid for which risks of disruption should be minimized. Although having these systems at some distance offshore would provide the advantage of tapping into greater and less variable thermal gradients, this would come at a greater infrastructural cost and capital risk. The Caribbean basin is already seeing more weather extremes in recent years, and meteorologists have shown through extensive climate models that climate change is making hurricanes more frequent and powerful over the Atlantic Ocean, where they eventually cross the Caribbean Sea via various paths. In a recent extreme example, the 2017 hurricane season cost Caribbean countries and the United States USD 200 billion, with Harvey, Irma, María and José leaving islands such as Barbuda, Dominica and Puerto Rico completely incapacitated by their passage [61]. Thus, sea-based OTEC systems are considerably more vulnerable to these climatic changes given their operation and offshore siting. The increased variability in the tracks of hurricanes is also adding new challenges for the region when viewed in the light that new countries and economies, once at low risk to these systems (Guyana and Trinidad and Tobago for instance), may become increasingly vulnerable to these weather extremes.

5. Conclusions

In this work, a set of observations relevant to achieving the challenging goal of 100% renewable energy systems in the Caribbean Island States has been presented. By their very nature, these countries and territories have limitations in both resources and interconnections that would otherwise ease the transition to fossil-free energy systems.

The positive side of this scenario of transformation is that Caribbean islands are wealthy in the inexhaustible natural resources of solar and wind power; however, dispatchable RE resources are more unevenly distributed among islands, even within a small region. While there has been a dramatic reduction in the cost of wind turbines and solar PV panels over the past decade, bringing the cost of these technologies to a level competitive with the existing fossil-fuel generation used by most Caribbean islands, the same is not necessarily true for other renewable resources such as geothermal power and ocean technologies such as OTEC and wave power. In power systems dominated by variable renewable sources, complementary technologies are necessary to ensure grid reliability. As has been shown here, there is a significant tradeoff in islanded systems between the availability of storage and dispatchable renewable resources. Implementation of an OTEC system with a capacity in the order of several MW for a system with a peak demand of a few tens of MW serves to significantly reduce the battery storage capacity necessary for satisfying hourly demand throughout a representative year. OTEC itself is unique in that it can provide more than just electricity services, i.e., desalination and seawater air-conditioning (only mentioned here), each of which can help make the system costs more favorable.

There remains the crucial question of up-front capital costs, which would be relevant one way or another as fossil-fuel generation capacity will be either replaced or phased out with increasing pressure in the coming decade. Oil-based power generation will certainly remain as one option; however, given the cost advantages of RE, there is also the increased risk of new investments either becoming stranded assets or that they will block investment in RE. As has been shown, there are various options on different islands for complementing the wealth of solar and wind potential with other technologies, including OTEC. In the end, a tradeoff exists between the relatively higher capital costs of wind and solar, followed by near-zero operating costs, versus the lower and more familiar cost of purchasing diesel engines that are then accompanied by high yearly fuel and operating costs. Detailed energy system planning will be necessary to demonstrate the lifecycle benefits of renewables, but financial resources must also then be made available to set countries down the pathway to renewables.

Long-term system planning will also be necessary for each island to take advantage of its domestic resources; 100% RE systems are feasible but having some fraction of the system capacity in the form of a dispatchable resource is advantageous, and some islands are strong candidates for the implementation of OTEC as a supporting technology. There are challenges to rebuilding energy systems, whether in the Caribbean or elsewhere. Islands in tropical regions offer large hurdles but also significant advantages, and are opportunities to serve as models for how to diverge from a business-as-usual path of fossil-fuel dependence and move toward a sustainable, renewable energy future.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/en14082192/s1, Part I—GIS mapping details and procedure outline; Part II—Additional results of mapping and preliminary site selection; Part III—Residual load duration curves for the visualization of hourly supply and demand.

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