A review of wave energy conversion and its place in the Caribbean region

Kevin G. Lemessy, Krishpersad Manohar and Anthony Adeyanju

Abstract—**This study reviews wave energy and the design of various wave energy conversion systems, to assess the state of the industry, identify the limitations, challenges and barriers developers face and determine the applicability of it to the Caribbean region. The use of an energy dense and accessible renewable resource like wave energy in the Caribbean region is important since most of the nations are small island developing states with limited or no natural conventional energy resources. As such, their economy, safety and security is often impacted significantly by decisions from the world's major energy producers and trade markets. The advancement of wave energy conversion within the region will also contribute to the reduction of green-house gas emissions as dictated within the Paris Agreement. This study was conducted via a detailed research of literature related to the topic and an analysis of key metrics. It was identified that though the Caribbean possesses some of the lowest levels of ocean wave energy in the world, due to other factors it can still be considered as one of the most practical destinations for wave energy harvesting.**

***Keywords*— Caribbean region, Energy security, Marine energy, Small Island Developing States, Sustainability, Wave Energy Conversion.**

I. Introduction

ENERGY is a unique property of the universe which can "neither be created nor destroyed, but can be transferred from one system to another and converted from one form to another" [1]. This "mystical" substance called energy is ultimately responsible for all life on the planet earth, as life cannot exist without it. It may come in various forms, which include: electromagnetic, electrical, magnetic, nuclear, chemical, thermal and mechanical [2]. Almost, all forms of energy in the world can fall into one of these categories. Energy is a fundamental property of matter and space, as such it is a fundamental property of existence itself. This is because the structure of any matter or field is energetic (e.g. photon waves in space, atoms, molecules and electrons all possess energy) [2].

As the world's population has risen to over 7 billion people, the demand for energy continues to rise [3]. Modern human societies (an example of a complex physical system) cannot be maintained without high quality energy entering from outside the system [1]. Energy is what powered the industrial revolution in the 1800s to present and is what continues the information technology revolution today. Traditionally, the world's source of energy has been based on fossil fuels, which includes coal, petroleum and natural gas [3]. The stability of the cost of energy has always been uncertain, this was illustrated over the last couple of years when a barrel of Brent crude oil went from over $100.00 USD in April 2014, to around $30.00 USD in October 2015 [4].

When it comes to renewable energy (RE) and sustainable development (SD), energy security and poverty reduction are key objectives that can be achieved. SD expresses the reduction in the abuse of the natural resources (energy) that are afforded to us, as this will lead to a significant reduction in supply for the future generations. Limited energy often reduces the potential for nations to meet basic needs, such as health care, transportation services, agricultural tasks and domestic use. As such, SD advocates the need for us to find and utilise RE resources, for economic activity, social welfare and environmental sustainability on Small Island Developing States (SIDS). This can be done through increased energy access to most of the population while reducing local and global pollutants [5].

II. Wave Energy (WE)

The use of WE devices have been explored since the late 18th century. This is evidenced by a patent filed by Girard and his son in 1799 - Paris. Years later, Bochaux-Praceique used wave power devices to power and provide light to his house in 1910. This feat of engineering was considered to be an early recorded practical application of WE. The industry continued to gather attention in 1973 - motivated by the oil crisis of the day. As the price of oil reduced later that decade, so did the funding towards the development of this type of technology. Some years later a resurgence occurred, this time due to the threat of global warming and climate change [6].

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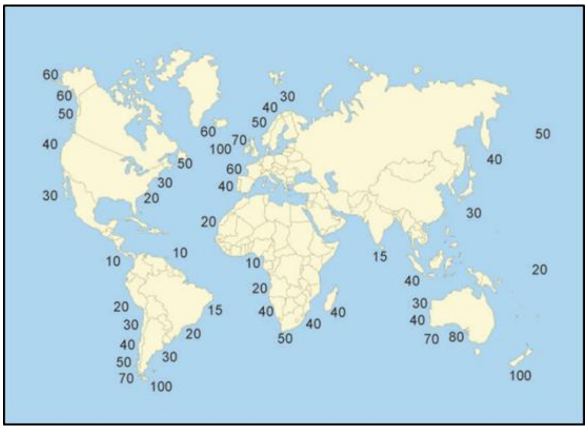

Fig. 1. Global average wave energy flux in kW/m [7]

The WE potential of an area can be determined by mapping the significant wave heights within that area. The largest significant wave heights globally are focused between the 30-60° North and South latitude. As such, these regions host the greatest intensities of ocean wave energy. In the regions above 30° North, the monthly median wave power ranges from around 35-130 kW/m in the Atlantic and Pacific oceans from November to March (winter period), while below 30° south, the monthly median wave power ranges from around 50-100 kW/m throughout the year. WE from the trade winds reach a maximum value of 20 kW/m in the Pacific Ocean and around 13.5 kW/m in the Atlantic Ocean [8].

In the Caribbean, waves are powered by the Atlantic trade winds. Fig. 1 shows that the average WE flux in the Caribbean region to be 10 kW/m, a value approximately similar to what was described by reference [8]. As such the Caribbean region has been described as having one of the lowest levels of WE resources globally.

III. Wave Energy Conversion (WEC)

There are over one thousand patented WEC techniques globally. Most of them are in the research and development stage (with the exception of a handful that have been tried commercially) and are designed specifically for higher WE climates like those in the high latitude regions. In 2015 there were approximately 170 different WE devices being actively developed globally at a noticeable level [9]. The following are examples of the most popular concepts used worldwide.

A. Point Absorber

This WEC technique involves the use of a floating structure (e.g. a buoy) that absorbs the energy from waves in all directions. Design details of the Point Absorber show that it is symmetrical about an axis and of a small horizontal dimension when compared with the wavelength of the passing waves [10]. This resulted in a significant advantage as the direction of the waves does not impact the amount of energy to be harvested [11]. The relative motion of the device is also key to the operation of the Power Take-off (PTO) unit; for this to be facilitated the device must be connected to a stationary point (e.g. the seabed).

As a wave passes, the buoy part of the point absorber rises with the crest and drops with the trough. This in turn generates electricity by either using a directly connected linear generator or by pumping hydraulic fluid to a hydraulic motor using a hydraulic piston cylinder. The piston rod on the hydraulic cylinder is driven by its direct connection to the buoy above. Suction occurs when the buoy rises due to the crest of wave and pushes forward due to the trough of the wave. This action, pumps the fluid forward through the hydraulic motor, which in turn drives a rotary generator. Examples of point absorber WE devices are the OPT Powerbuoy, Wavestar and the Wavebob [10]. This type of technology is best suited for offshore or nearshore applications. This design concept possesses a high conversion efficiency with low construction costs but difficult maintenance operations due to corrosion [12]. Fig. 2 shows a schematic of a point absorber system [13].

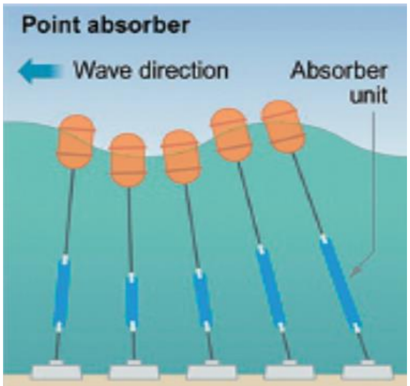

Fig. 2. Illustration of the Point Absorber concept [13]

B. Submerged Pressure Differential

This WEC system is similar in operation to the point absorber. The only salient difference is that the submerged pressure differential technology operates completely submerged in the water. The motion of the ocean waves passing creates a pressure difference, causing the body to heave and drive the PTO unit due to its relative motion [10].

When the crest of the wave is over the device, the hydraulic fluid trapped in the cylinder compresses due to the pressure forces acting downward on the cylinder by the water. As the crests passes and the trough is now over the device, the pressure acting downward is reduced because the volume of water over the device has lessened. This reduction in water volume over the device, leads to a decompression of the fluid trapped in the cylinder [11]. The continuous up and down motion can be used to produce electric power through the use of a linear generator or by a hydraulic motor powered by compressed fluid.

Advantages of this concept is that they can survive in extreme storms and they reduce the visual impact of wave energy harvesting farms. An example of such a device is the Archimedes Wave Swing (AWS) [10]. Developed by the Netherlands company, Teamwork Technology. A 2 MW prototype was constructed and tested offshore of Portugal in 40 meters of water, for demonstration [14]. Fig. 3 shows a schematic of a submerged pressure differential device.

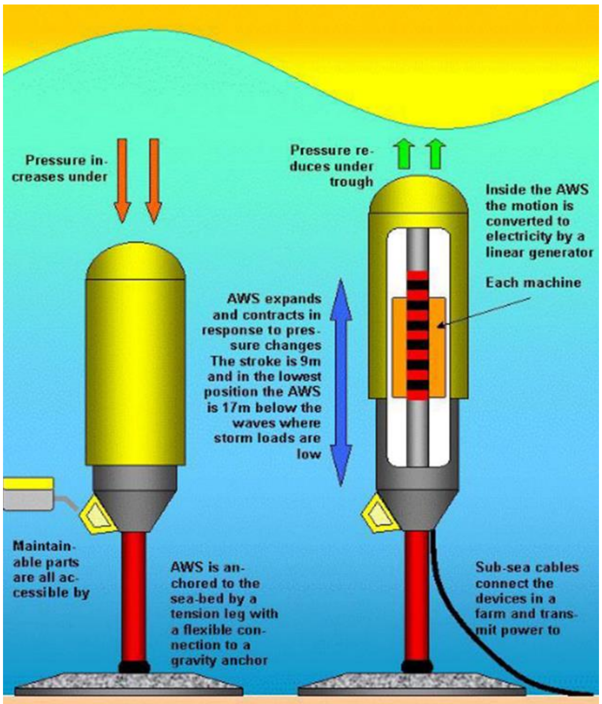

Fig. 3. Submerged Pressure Differential concept [10]

C. Attenuator

These WEC floating devices, are distinguishable by their significant dimensions that is relative to the wavelength. They are able to span across varying wave crests, riding it as they orientate parallel to the direction of the largest passing waves [11]. They utilise the relative motion created when the device flexes as a wave passes to generate power [10].

At the joints, hydraulic cylinders connected to hydraulic systems are housed. The bending of 2 segments towards each other connected by the joints, pressurises the hydraulic fluid by forcing the rod down the bore. This pressurised fluid travels through tubes and valves to drive a hydraulic motor which turns the rotor in a generator, thus creating electricity. The highest efficiency of the device occurs when the natural frequency is close or equivalent to that of the passing wave [13]. An example of this technology is the Pelamis [10].

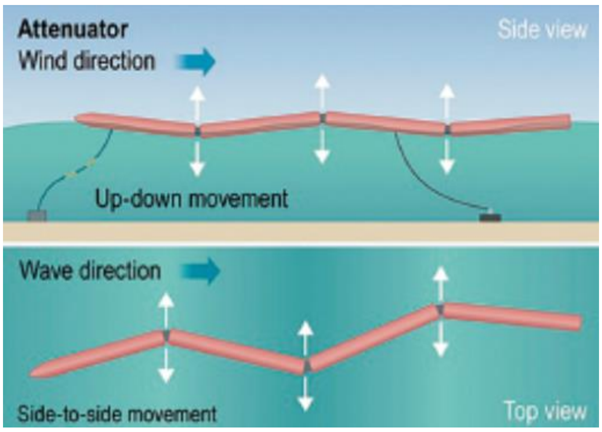

Fig. 4. Attenuator concept [12]

The Pelamis is held in place by a mooring system, that is flexible enough to let the device self-align according to the wave direction [15]. This was done to maximise on the amount of energy harvested. The Pelamis was also designed to be quickly detached from all cables so that it can be transported easily, in the advent of severe incoming weather conditions that may damage it [15].

D. Terminator

This type of WEC system operates by automatically adjusting its main dimension to be perpendicular to the direction of incoming waves. It has a cam like shape and as an ocean wave passes it induces the rotation of gyroscopes [10].

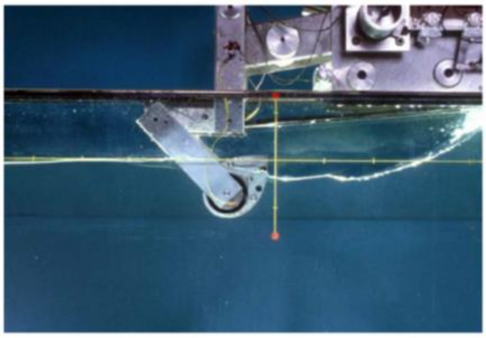
Fig. 5. Terminator concept [11]

As the tail of the device goes up due to a passing wave, the connecting shaft rotates in the same direction at an angular velocity that is directly proportional to the upward linear motion of the tail. However, when the tail comes down as the wave passes and it experiences its trough, the shaft does not rotate in the opposite direction. Its operations are similar to a ratchet mechanism, which allows rotation of the shaft in one direction only, due to a collection of angled teeth along the circumference of the shaft. This shaft is connected to the rotor for a hydraulic motor at the next end. As a wave passes the device, hydraulic fluid is pressurised and using a hydraulic motor, the electrical generator converts the mechanical rotary motion into electricity [13]. An example of such a device is Salter's Nodding Duck [10]. Stephen Salter of the University of Edinburgh, developed a device using the Terminator concept that theoretically is reported to be the most efficient WEC device ever created [11].

E. Oscillating Wave Surge

A device of this kind operates via a flap mechanism (mounted on the seabed) that moves back and forth as a waves pass. Fig. 6 shows a schematic of an oscillating wave surge. The oscillatory motion drives a PTO that is able to extract the energy from the waves that make it move. A known example of this device is the Aquamarine

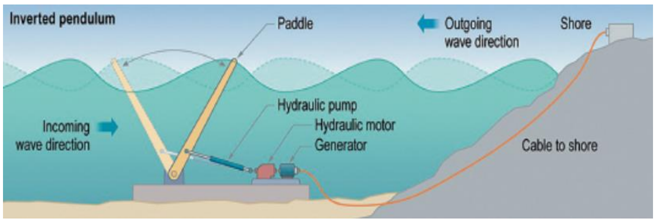

Fig. 6. Oscillating Wave Surge concept [12]

Power Oyster device [10]. The Oyster utilises double acting cylinders to pump water through subsea pipes at high pressures to a Pelton turbine onshore [16]. It's to and fro movement of a flap like device, characterised by a hinge, made from glass-reinforced plastic and carbon steel, harnesses the mechanical energy of ocean waves. This mechanism is used to capture mechanical power [17]. The deflector is placed perpendicular to the direction of incoming waves, so that it takes advantage of the horizontal particle velocities of passing waves [11]. This technology is highly efficient but the maintenance operations are complicated, thus increasing its cost [13].

F. *Oscillating Water Columns*

This hollow WEC system, as shown in Fig. 7, allows trapped air in a structure above the water surface to compress and decompress as the water level rises and falls due to passing waves. The compression and decompression of the air in this column places a force on the blades of the turbine so that it may induce generation of electricity as it turns [10]. The air column is referred to as the collector and it essentially converts the incoming wave power to air power. The PTO is the Well's turbine, a unidirectional air turbine capable of having the blades turn when air is flowing in either direction and thus generating electricity. The collector of the structure account for 85% of the total cost, however if it is joined with a vertical breakwater system the overall cost of the WEC will be reduced as a dual purpose will now be implemented [18].

The shape of the tunnel for air being sucked in towards the Well's turbine allows for an increase in air velocity through the use of the Venturi effect. The increase in air velocity, allows for a higher force to be placed on the blades of the turbine and as such power generation.

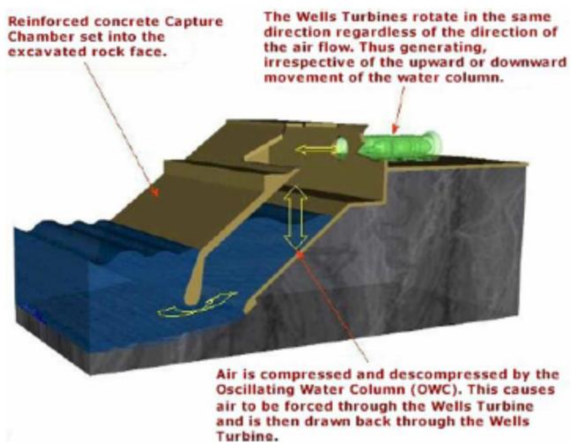

Fig. 7. Oscillating water column concept [11]

G. *Overtopping*

This type of WEC device operates by capturing water in a reservoir above sea level from waves passing and allowing it to drain back into the sea using gravity to power turbines in the structure. The waves are focused and allowed to crash into the device permitting wave run up to take place and eventual overtopping. As this occurs the water overtopped is collected in a reservoir or catch basin where it is channelled through some turbines which utilize hydro power similar to a hydro powered dam [13]. This type of technology is limited to locations with a sustained wave climate. An example of a wave overtopping device is the Wave Dragon. (Fig.8)

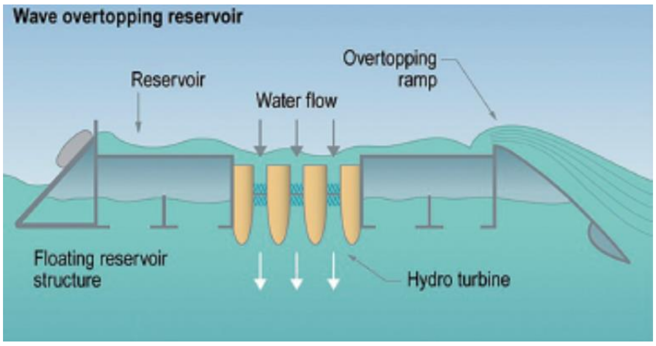

Fig. 8. Wave overtopping concept [12]

The reservoir on the wave dragon acts as an energy storage device that smoothens the power generated by regulating the flow of water through the turbines. The generator in the Wave Dragon device is a permanent magnet synchronous type with variable speed [19]. The efficiency of the prototype's power conversion system (water from the reservoir to electricity supplied to the grid) was approximated to be 50% while the full scale version is estimated to be 85% [20]. The wave dragon was designed to operate in water depths of 20m [21].

IV. IMPACT, BARRIERS AND CHALLENGES OF WEC

H. *Environmental Impact*

Conventional electric power generation has resulted in varying levels of environmental hazards [22]. The use of nuclear power plants possesses the inherent hazard of radiation leakage, dams for hydropower can cause ecological imbalances via the alteration of the natural course and fossil fuels pollute the atmosphere with carbon dioxide or various other greenhouse gases. All accounts thus far, have attributed WE to be renewable, clean and kind to the environment. To date one cannot find any solid academic studies to suggest otherwise [23]. Some other concerns that are being looked at are [23]:

- Floating wave power structures (e.g. buoys) may attract migrating birds and entrap marine mammals in rough sea conditions.
- Wave farms may reduce the effects of the local wave climate by stripping too much energy and thus impact the natural sediment transport at the shore. This may be ideal if the WEC devices acts as a breakwater and

helps reduce coastal erosion where needed or may be negative if devices hinder the natural flow and spreading of sediment along a beach if there are little hydrodynamic forces.

- Construction noises and noise distributed from subsea cables may stress the aquatic life in the area. In addition to this, dredging of fine sand can clog the gills on fishes, reducing their survivability.
- Electromagnetic interference from subsea cables can be identified from animals such as eels and sharks, disorienting them and their natural behaviours.

Also, newly installed devices will be sought after by marine life for colonisation as their hard structure will present itself as an artificial reef [24]. Animals living on or around these devices are prone to hazards from the leakage of lubricants, as the fluids utilized in these equipment can be toxic to the marine ecosystem [24]. Fishing operations can also be negatively affected, either by restricted access to fishermen, or disturbing the migratory patterns of fish life [25].

I. Barriers

One of the major barriers affecting the advancement of the WE industry is the lack of investment. Kempener and Neumann detailed in their report that the wave energy market is still primarily driven by start-up companies and university researchers [26]. As such, most of the research has been on pre-commercial status since its beginning. Investment in scaling up devices and the development of wave farms is highly needed for the industry to progress.

Key requirements for advancement are public policies developed by governments to attract and promote private investment and grant funding for research and development. An overall economic view may be beneficial to catapult the WE industry. An example may be the restructuring and repurposing of ship yards to become manufacturing hubs for wave energy devices and retraining local fishermen to become operating and maintenance personnel. This view may allow the marine energy concept to become an industry that can diversify and transform small economies like those in SIDS. Planning of zoned marine areas and licensing of operators are important aspects that is currently restricting development and also needs to be addressed. The lack of these processes presents risks of project failure for those with interests in energy, tourism, fisheries and transport [26].

Tao et al. presented the following additional barriers of the industry [12]:

- Details of the wave energy resource needs to be determined for most countries (especially SIDS) for there to be any real financial investment to key projects. Without this information financiers will be asked to invest blindly - this is highly unlikely.
- Improvement in the reliability, survivability, and installation capability of WE devices is paramount for the technology to take off. The extreme forces presented by ocean waves make these 3 areas difficult.
- The levelised costs of ocean energy technologies are significantly higher than those of its conventional counterparts. On the open market, wave energy needs to be comparable in order to compete for usage preference. The difficulty in determining the lifetime of energy devices hinders the reduction of this cost. WE devices vary in costs and life span as they vary in operating principles. Also, the amount of power producible and cost of operating/maintaining is not only incumbent on the design but varies due to site.
- Determination on which regulations to comply with confuses investors. For a new industry it may be very vague on which regulations take precedence, e.g. regulations for marine affairs, regulations for energy production, etcetera. There will be a lot of overlap that can have investors bewildered.
- Proximity to the grid is important as distance reflects in the construction and maintenance costs.
- Underdeveloped supply chain due to the infancy nature of the WE industry.

J. Challenges

WE devices possess inherent challenges based on their nature of source and its operations. One such challenge faced is the visual impact of devices. This impact is based on the type of device used, its distance from shore (e.g. oscillating water column, point absorbers, etc.) and the geographic location. Wave farms placed nearshore in areas that are not visited or cannot be viewed easily will have very little visual impact [27]. Similarly, when some WE devices are fully operationally they produce noise levels that are generally lower than that of a ship but louder than the winds and waves surrounding it. Noise generated offshore will have little impact on pedestrians by the shore. Underwater however, noise travels long distances and can impact marine life [27].

Another major challenge is the intermittent nature of marine energy. Waves can be predicted but not controlled [7]. This is one of the biggest hindrances to commercialisation. There will be a need for an energy storage capability to provide a practical supply of energy to society. This is why the power quality from WE devices is traditionally considered to be low, because of the variable nature of ocean waves. Specific mechanisms are required to circumvent this and make the power output more constant for grid connection [27].

Finally, WE development is extremely site specific and dependent. This is a trait that all RE sources have in common. Devices must not be sited only where they can capture the greatest wave but also where logistics are capable for maintenance and operation of the farm, little impact on the environment, no challenges on territorial waters, etcetera [27]. The site itself can be a troubling issue if power transmission is to come from offshore. There is a strong need for quick access to the grid or the use of a small power plant offshore to overset this grid extension to secluded areas [27].

V. ANALYSIS OF CARIBBEAN SIDS

The Caribbean Community (CARICOM) is a collection of Caribbean based nations, that are largely made up of island state economies. It is essentially surrounded by the Caribbean Sea, Gulf of Mexico and Atlantic Ocean. In addition to culture, CARICOM members share similar economies with the exception of a few. To support these economies, the supply of energy plays an integral role.

K. Energy in Caribbean SIDS

The CARICOM is primarily made up of SIDS. Their membership comprises of 15 full members, 5 associate members and 8 observer nations. With regards to energy, CARICOM's full members are described as [29]:

1. Major hydrocarbon energy producer/ Net Energy exporter - Trinidad and Tobago (T&T).
2. Minimal hydrocarbon energy producer / Net energy Importers- Suriname, Barbados and Belize produce crude oil for some domestic use. Barbados also produces natural gas for similar activities.
3. Non hydrocarbon energy producer / Net energy Importers - All other members (Antigua and Barbuda, The Bahamas, Dominica, Grenada, Guyana, Haiti, Jamaica, Montserrat, Saint Kitts and Nevis, Saint Lucia and Saint Vincent and the Grenadines) import hydrocarbon energy for their domestic operations.

In the Caribbean, T&T is the primary consumer of energy within the region. In 2007, T&T consumed roughly 67.5% of the barrel of oil equivalent entering the region [29]. Indicating that the rest of the regional countries consume very little energy in comparison.

Most CARICOM members have few or no fossil fuel reserves, so they rely heavily on importation to fulfil their energy demands [28]. This over reliance on imported fossil fuels is a great risk to their energy security and exposes them to the unstable operations of the international oil markets. In addition to this, the use of valuable foreign exchange could be better utilized for the domestic investment in the CARICOM countries provided their energy demand is secured. CARICOM countries traditionally experience high electricity tariff rates which discourage economic development and foreign investment. Trinidad and Tobago is the only exception to this in CARICOM, as they generate electric power from their domestic supply of natural gas [28]. RE investment in the Caribbean have been progressing slowly with varying levels of interest indicated through the amount of funds spent.

TABLE I
THE MAJOR ENERGY CHALLENGES TO CARICOM MEMBERS

Technical	Socioeconomic	Environmental
Isolated grid networks	High electricity tariffs	Local air, freshwater and ocean pollution
Small overall generation capacity	Vulnerability to rising volatile fuel prices	Deforestation
Inability to meet existing and future demand	Missed opportunities for domestic investment and jobs	Degradation and depletion of natural habits, ecosystems and resources
Outdated equipment	Energy poverty	Global climate change
Low efficiency		

[28]

A study of new investment made in RE by technology globally in 2014, showed no information towards the Caribbean region on this topic [30]. However, it is worthwhile to note that in terms of investment, solar and wind energy continues to lead the charge globally. This level of investment has resulted in these technologies being the most developed within the RE group [30].

In the Caribbean, SIDS have relatively small landmasses, which limits the use of solar and/or wind farms for significant RE supply. Approximately 50% of CARICOM nations possess active volcanoes, as such geothermal energy can be considered viable within them. However, not all countries maintain this natural resource. Agricultural land is also very precious as they play a major role in the economy of most CARICOM nations. Therefore, there is very little additional agricultural land space for growing crops sustainably to be used a biofuel. This leaves marine energy as the most practical form of RE that all CARICOM nations can tap into without negatively affecting their economy.

A regional approach towards renewable energy projects in the Caribbean can circumvent the problem of low investment due to the small scale operations that is expected by individual countries [28,30]. This regional approach can lead to the development of supply chains, sharing of information and capacity building which ultimately will advance the region's economy.

Most of the CARICOM member states economy, is based on food processing, agriculture and tourism [28]. This explains the low levels of energy consumed per capita (excluding Trinidad and Tobago). Due to the high operating cost based on imported fuel, poor transmission/distribution systems and low economies of scale, Caribbean electricity prices are considered amongst the highest in the world. Suriname and Trinidad and Tobago, however, has very low electricity costs due to government policies [28]. For other nations in the Caribbean, RE sources specifically geared to their unique situation (relatively small land masses that are constantly greeted by waves on their coastlines) may provide a means to improve their general standard of living. These waves would have travelled for miles across the Atlantic Ocean, bringing with them a renewable supply of energy that is ultimately powered by the sun [31]. Theoretically the global wave energy resource is 8×10^6 TWh per year.

Based on 30 year wave hindcast, the WE potential in the Caribbean Sea under the influence of the Caribbean Low-Level Jet is 8-14 kW/m [32]. The best months for WE extraction are considered to be from December to March and June to July [32].

VI. Comparison of Caribbean SIDS To Notable Wave Energy Countries

Key metrics were examined by countries considered to have a recognizable presence in the WE industry and they were compared with those of Caribbean SIDS. The criteria examined amongst the nations include:

1. Electric power consumption
2. Population size
3. CO_2 emissions
4. Coastline per land area ratio
5. Maritime economy activity
6. Openness to RE

The countries or groups identified as having a recognizable WE industry currently or in the past are: Australia, Belgium, Brazil, Canada, Chile, China, Denmark, European Union, Finland, France, Germany, Greece, India, Ireland, Israel, Italy, Japan, New Zealand, Norway, Portugal, Russia, South Africa, Singapore, South Korea, Spain, Sweden, The Netherlands, Turkey, United States of America (USA) and the United Kingdom (UK) [33]. They were identified as countries with at least one recognisable level of wave energy development as of 2013. It should be noted that 20 out of the 30 nations/groups identified, are situated in the top 50 nations in the world with respect to Gross Domestic Product (GDP) per capita. As such, they can be described as some of the wealthiest nations globally [34].

The countries identified as Caribbean SIDS according to United Nations Educational, Cultural and Scientific Organisation (UNESCO) are: Antigua and Barbuda, Bahamas, Barbados, Belize, Cuba, Dominica, Dominican Republic, Grenada, Guyana, Haiti, Jamaica, St. Kitts and Nevis, St. Lucia, St. Vincent and the Grenadines, Suriname, Trinidad and Tobago (T&T), Anguilla, Aruba, British Virgin Islands (BVI), Cayman Islands, Curaçao, Montserrat and Sint Maarten. Puerto Rico, St. Martin, United States Virgin Islands (USVI). The Turks and Caicos Islands (TCI) were added to the list for analysis, but they are not formally recognized as SIDS according to UNESCO [35].

L. *Assessment of Electric power consumption (kWh per capita)*

The top 10 wave energy identified countries (WEIC) with the highest electric power consumption (kWh per capita) are Norway, Canada, Finland, Sweden, USA, South Korea, Australia, New Zealand, Singapore and Japan- in that order. The values used were based on an average from the years 2012, 2013 and 2014 [36].

The top 10 Caribbean SIDS with the highest electric power consumption (kWh per capita) were identified as BVI, Cayman Islands, Aruba, T&T, Puerto Rico, TCI, the Bahamas, Curacao, Montserrat, St Kitts and Nevis- in that order. The values used were based on an average over the years 2012, 2013, 2014 and 2015 [36].

M. *Assessment of Population size*

The top 10 WEIC with the lowest population size are New Zealand, Ireland, Norway, Finland, Singapore, Denmark, Israel, Sweden, Portugal and Greece- in that order. The values used were based on an average over the years 2015, 2016 and 2017 [37, 38].

The top 10 Caribbean SIDS with the lowest population were identified as Montserrat, Anguilla, St. Martin, BVI, TCI, Sint Maarten, St. Kitts and Nevis, Cayman Islands, Dominica and Antigua and Barbuda- in that order. The values used were based on an average over the years 2015, 2016, 2017 and 2018 [37, 38].

N. *Assessment of Carbon dioxide emissions (metric tons per capita)*

The top 10 WEIC with the highest carbon dioxide emissions (metric tons per capita) are USA, Australia, Canada, Russia, South Korea, Norway, The Netherlands, Japan, Germany and Singapore- in that order. The values used were based on an average over the years 2012, 2013 and 2014 [39].

The top 10 Caribbean SIDS with the highest carbon dioxide emissions (metric tons per capita) were identified as USVI, Curacao, T&T, Sint Maarten, Montserrat, Aruba, Cayman Islands, the Bahamas, BVI and TCI- in that order. The values used were based on an average over the years 2012, 2013 and 2014 [39].

O. *Assessment of Coastline per area ratio*

The top 10 WEIC with the highest coastline per land area ratio are Singapore, Denmark, Greece, Japan, Norway, New Zealand, UK, Italy, South Korea and Ireland- in that order. The values were developed by dividing the individual country's coastline length in km by the land mass size in km^2 [40, 41].

The top 10 Caribbean SIDS with the highest coastline per area ration were identified as Curacao, Anguilla, Cayman Islands, BVI, St Kitts and Nevis, TCI, Montserrat, Aruba, Grenada and Antigua and Barbuda- in that order. The values were developed by dividing the individual country's coastline length in km by the land mass size in km^2 [40, 41].

P. *Assessment of Maritime Economy Activity (Port container traffic)*

The top 10 WEIC with the highest maritime economy activity are China, European Union, USA, Singapore, South Korea, Japan, Germany, Spain, The Netherlands and India- in that order. The values used were based on an average over the years 2015, 2016 and 2017 [42, 43].

The top 10 Caribbean SIDS with the highest maritime economy activity were identified as Jamaica, Dominican Republic, The Bahamas, T&T, Cuba, Haiti, Suriname, Barbados, Curacao and the Cayman Islands- in that order. The values used were based on an average over the years 2015, 2016, 2017 and 2018 [42, 43].

Q. Assessment of Openness to RE (Percentage of energy needs supplied by RE source)

The top 10 WEIC with the most openness to RE are Norway, New Zealand, Sweden, Brazil, Canada, Portugal, Denmark, Germany, Turkey and European Union- in that order [44, 45].

The top 10 Caribbean SIDS with the most openness to RE were identified as Dominica, Belize, Suriname, Dominican Republic, Haiti, St Vincent and the Grenadines, Jamaica, Guyana, Aruba and Barbados- in that order [44, 45].

VII. Discussion

The purpose of this paper was to illustrate why the Caribbean can be considered one of the more practical destinations for WE harvesting. One reason is the low range of WE resource.

The WE resource in the Caribbean is one of the most sustainable in the world. The Caribbean operates with WE magnitudes of 8-14 kW/m [32]. This is represents an operating range of 6 kW/m compared to ranges of 95 kW/m and 50 kW/m in regions above 30° North and below 30° South respectively [8]. As such, a WEC devices designed for the Caribbean will capture a greater percentage of the WE resource than its high latitude region counterparts. Larger devices are required for large wave heights but they will be ineffective when a smaller waves pass. Similarly, smaller devices are required for small wave heights but they will be ineffective when a larger waves pass. Thus, devices operating in regions with small ranges (e.g. Caribbean) will be more effectively utilised. Another reason to consider Caribbean WE harvesting is the high levels of availability of the devices for operations and accessibility of them for maintenance [47].

Availability is defined as the percentage of time that a device is ready or capable to produce energy. It is ultimately dependent on ocean conditions and the type of conversion system used. All WE devices have an operational range in which they can begin to harvest energy and when they can no longer gather energy, because they have reached their maximum capacity. Though some sites are very rich in WE, the device used must be designed specifically for it because if it is not, it will spend majority of the time uneconomically in survival mode [47]. Accessibility is defined as the percentage of time when the device could be accessed for maintenance operations. It depends on the ocean conditions, as well as the device itself and type of vessels used in operations. [47] When these practical

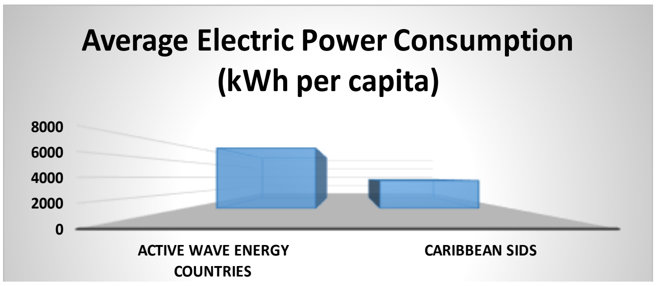

Fig. 9. Electric power consumption comparison

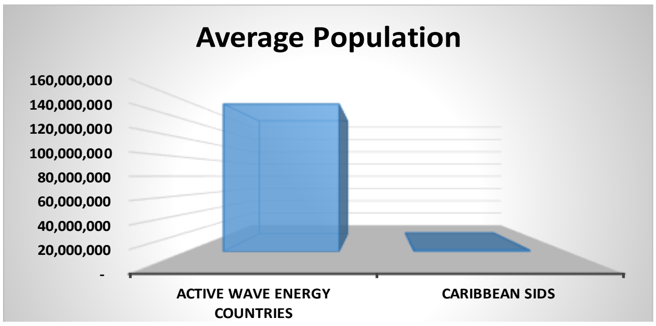

Fig. 10. Population comparison

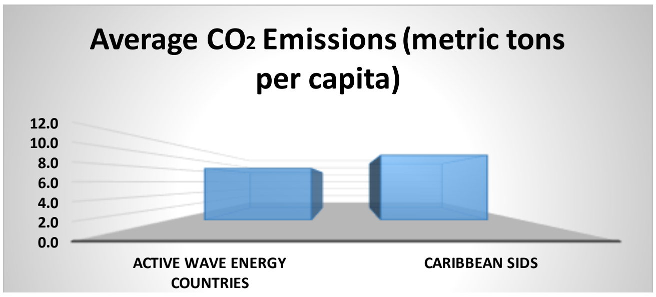

Fig. 11. CO_2 emissions comparison

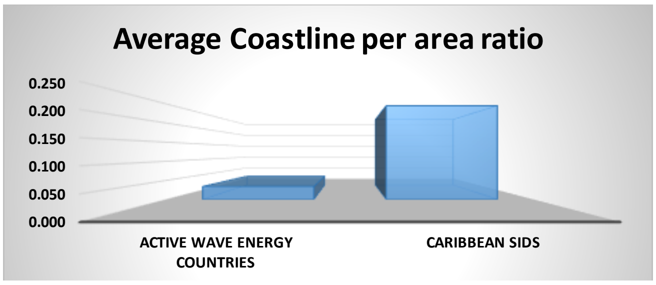

Fig. 12. Coastline per area ratio comparison

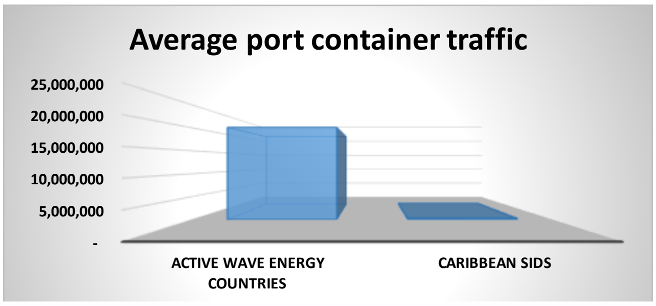

Fig. 13. Port container traffic comparison

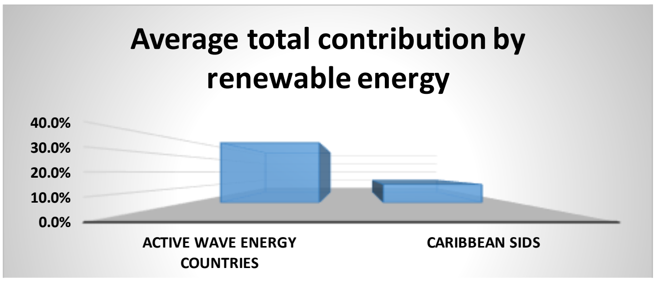

Fig. 14. Total renewable energy contribution comparison

requirements are analysed, the high WE regions with their rough sea conditions make it very difficult for the implementation of devices, running operations and performing maintenance activities. The International Energy Agency cited this as one of the key reasons for unsuccessful marine operations in the WE sector. Most WE devices that were tested at sea, experienced long wait times (weather windows) for maintenance operations as the inherent danger and inability to perform maintenance tasks increases exponentially in very rough sea conditions [47]. The low WE resource in the Caribbean could be considered advantageous in this regard as high levels of accessibility and availability is expected [7, 8].

In identifying relevant technology that could be useful in the Caribbean context, two seemed to be the most suited - the Submerged Pressure Differential and the Oscillating Wave Surge. This is because:

- Tourism in the Caribbean is integral in their economy [28]. The scenic view of beaches is a major part of the region's tourism product. Wave harvest farms above the surface and on beaches is expected to be a deterrent to tourists [27].
- Subsurface technology may yield greater longevity in this region as it is protected from the violent winds of storms that visit the Caribbean annually. The National Oceanic & Atmospheric Administration (NOAA) indicated that an annual average of 12 and a maximum of 28 hurricanes have visited the Caribbean in the past [46].
- The WE resource range is too small for Attenuator, Oscillating Water Column or Overtopping WEC to be effective [10, 13].

Another reason for successful WE harvesting is the indication that an industry can be maintained by an analysis of selected criteria. Successful WE harvesting in a region not only depends on a sustainable and worthwhile wave resource, but also the ability of the region to support maintenance activities, provide adequate maritime services and others. The rationale for the criteria analysed in section IV were as follows:

- The lower the electric power consumption (kWh per capita) of a nation the more feasible a RE sector will be as the technology can have a greater level of impact. For example, a WE farm producing 100 MW of electricity will have a greater impact to a country utilizing 200 MW as opposed to one that demands 20,000 MW.
- The smaller the population size, the lower the overall energy demand, and as such the greater impact a RE resource can make to the nation.
- The higher the carbon dioxide emissions (metric tons per capita) of a nation, the greater priority should be set by governments for it to be reduced in order to ratify the Paris Agreement.
- The higher the coastline per land area ratio the increased probability of that nation being able to support a marine economy (e.g. WE harvesting). It follows the assumption that these type of nations already engage in fishing, ship repairs, water transport services, marine construction and maritime security. All services with transferrable skills to support a WE farm.
- The larger the amount of large sized containers passing through a country's ports of entry, the more developed the maritime services sector is expected to be. Services such a dry docking, welding and fabrication, the use of ports/harbors would be beneficial for industry sustainability.
- The higher the percentage of electricity already supplied from RE, the more open the population is to introduce another form of RE and the greater emphasis placed on RE from a government's policy standpoint. It is expected that they are cognizant of RE and appreciate the significance of incorporating it.

VIII. CONCLUSION

Based on the criteria examined in Figures 9 – 12 and what it suggests, coupled with a small WE range and the high levels of availability and accessibility, WE can be considered a significant source of RE in the Caribbean. Further development in maritime services and more emphasis by policy makers will be required for increased chances of commercial success. To date, no major effort has been made to the development of a WE industry, this may be due to lack of capital funding, low levels of research and development in the jurisdiction, or little attention given by WE developers globally. It is recommended that research into a WE converter specifically for the Caribbean be developed.

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