Background

* Small Island Developing States

Small Island Developing States (SIDS) are a distinct group of developing nations defined at the first UN Conference on Environment and Development in 1992, as geographically located islands in the Caribbean, Atlantic, Indian and Pacific Oceans. These nations are significantly impaired by small size and local populations; insularity and remoteness relative the rest of the developed world; with a proneness to natural disasters and more recently climate change. In particular, the developed world has committed to combat the impact of climate change by increasing the share of renewable energy in the power mix. In contrast the contribution of SID states to global warming is miniscule, despite being the most vulnerable to impacts of climate change (UNDP 2019). For example, in Barbados greenhouse gas emissions accounted for an average of 0.008% of global emissions (USAID, 2017 ). The primary motivation for most SIDS to pursue renewable energy technologies are the savings in foreign exchange incurred by purchase imported fossil fuels.

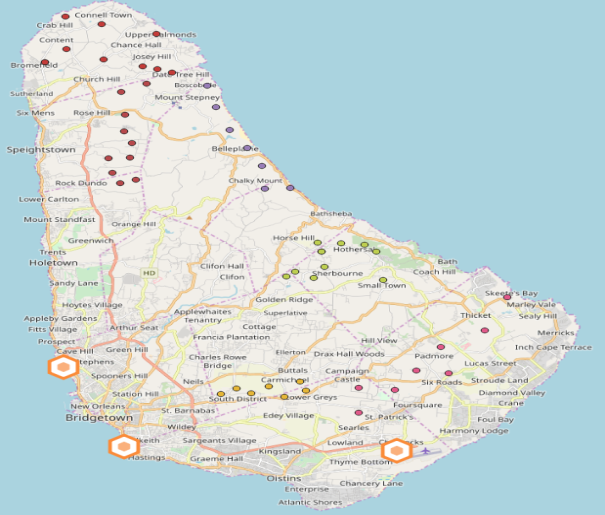
Small Island Developing States have small markets and erratic domestic revenues, which is further compounded by high costs of public services, increased vulnerability to the fiscal impacts of natural disasters. Therefore, SID nations have a limited ability to diversify economically and have high import requirements on strategic goods such as food and fuel, making them economically vulnerable to external forces that are outside of their control, which threatens their economic survival (Briguglio, 1995 ). None-the-less, most SIDs have attractive natural environments making them competitive in the tourism industry. Consequently, tourism is usually the most substantial contributor to GDP growth, followed by other service industries such as ICT-enables business process outsourcing and financial services (UN DESA, 2014).

Following the global, economic and financial crisis and more recently, the Corona-19 pandemic most SIDS have been devastated by rapid growth of debt burdens and high increase in trade deficits (Lee, 2014 ). For example, most SIDs were already heavily indebted as concessional financing in the form of bilateral, multinational loans or grants are the most vital source of for 3 out of 5 SID nations (OECD, 2018 ). The Corona pandemic further disadvantaged many SID nations, as for most, tourism is the most significant contributor to GDP. However, the implementation lockdowns and travel restrictions for health requirements have left many states devasted economically and the estimated time for recovery is unknown. These economic and fiscal challenges are further compounded by high dependence on imported fossil fuel resources for electricity generation and transportation uses, which is a significant financial burden. In some cases, more than 30% of the foreign exchange is used to cover fuel costs, which is particularly devastating due to oil price volatility (Dornan, 2015). The purchase of international oil drained the Barbadian economy of 377 million BBD, resulting in high electricity costs that are passed to the public (Hohmeyer , 2015). This trend will continue without a concerted effort to diversify the energy sector by using renewable energy resources. Although the price dropped in 2013, estimates show the fuel cost alone comprised 0.413 BBD/kWh of the total electricity production costs out of 0.566 BBD/kWh (Hohmeyer , 2015, pp. 3-4). Freeing these resources for other uses will significantly improve the financial position Barbados as is the case for other SIDS. To-date renewable energy technologies have been shown competitively viable to fossil fuel technologies for electricity generation, and many SIDs have made ambitious renewable energy targets with Barbados being one of the few to commit to a 100% renewable energy system by 2030.

* Profile of Barbados

Barbados is the most easterly of several islands in the lesser Antilles island group of the Caribbean located at 13°10' N latitude and 59°30' W longitude. A summary description of the island cane be seen in Table 1.11, the island is relatively flat with the highest point located in the centre at 340 metres and is divided into 12 districts, as shown in Figure 1.11. The population density is one of the highest in the world, estimated to be 663 inhabitants/km2 (UNDP 2019). However, as seen in Figure 1.11, most of the population is located around the urban corridor along The west and south coasts shown as grey areas (FAO 2015).

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| Information | Numerical data |
| Size | 431 km |
| Population | 282,000 (2019) |
| Districts | 12 |
| City | Bridgetown |
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* Climate

The climate is tropical with a constant temperature that rarely descends below 21 degrees Celsius. The wet season lasts from June to November, with the dry season extending from December to May (Humphery, 1997). The average rainfall is about 60.24 inches, which varies significantly on an annual basis, which is a leading climatic factor limiting crop growth (UNDP 2019).

* Solar Resource

The solar resource was one of the first renewable energy technologies in modern times to be used on a large scale on the island. The average daily solar insolation is 5.7 kWh/m² (Moseley & Headley, 1999). Therefore, the solar resource is nearly double to other sites in Europe such as London (2.61 kWh/m²), Dublin (2.39 kWh/m²) and Hamburg (2.52 kWh/m²) (Whitlock , 2000). Many of these countries have significantly larger installed capacities of solar photovoltaics, which serves to demonstrate potentially useful solar resources on the island. The solar irradiance peaks during the five months of April through August but falls off slightly from August through to December (Alleyne , 2014). This trend is in keeping with the rainy season that would be characterised by partly cloudy skies and a slight reduction in the solar irradiance (Harewood , 2019). By the latest estimates, one out of every five homes on the island uses solar water heaters in addition to most commercial and tourism businesses (Haynes , 2019). Presently, more than 95% of the 30MW of renewable energy in grid-connected systems is comprised of solar photovoltaics (Haynes , 2019). In assessing a 100 % renewable energy system, an estimated installed capacity ranging between 200MW – 270MW was recommended in various scenarios (Hohmeyer , 2017). Similarly, the Barbados National Energy Policy analysed a 75% renewable energy mix using 195 MW of installed solar capacity, based on the recommendations of energy sector stakeholders (Ince & Haynes , 2017). For the scenarios, a range between these recommended installed capacities was utilised for optimisation.

* Wind Resource

The trade-wind belt occupies the latitudes between 30 degrees in the winter hemisphere and 35 degrees in the summer hemisphere (American Meterology Society , 2010). This wind resource is steady, constant and reliable in their direction. These winds blow out of the subtropical highs towards the equatorial low in both the northern and southern hemisphere between the latitudes of 5 degrees and 25 degrees (Petersen , Sack , & Gabler , 2012). Barbados is located within the trade-wind belt that acts as the main driver for hurricanes that regularly devastate the region. However, as the island is located on the most southern edge of the belt, most storms pass to the north of the island (Aronson, 2007). Nonetheless, the local wind resource is excellent and reliable such that Barbados was second only to the Netherlands having the highest number of wind turbines per square mile in the world (Buchinger, Ince, Perch, & Hatvan, 2018). The wind speeds are shown to range between 4.8 m/s and 8.0 m/s at 10m hub height, with the lowest wind speeds occurring between August and September (Alleyne , 2014). The average hourly wind output follows the hourly demand curve for the island, indicating that the peak output occurs midday when cooling demand is at its highest and in the evening when most people have returned home. Based on independent research a total of 472MW of wind energy was recommended for installation in Barbados (Rogers, 2017). However, the Barbados National Energy Policy explored an installed capacity of 127 MW was recommended.

* Dispatch

For electricity generation, the Barbadian energy system was designed over the years to provide reliable, universally available energy resourced at reasonable prices. Barbados continues to have a liable power supply with few instances of blackouts, in comparison to other regional island territories. There is 100% access to electricity, that is powered mainly by imported fossil fuel resources, which is highly unsustainable. Fuel consumption by sector can be summarised as follows: transportation (51%), other (24%), industrial (13%) and residential (12%) (Caricom Energy , 2018 ). The current fossil fuel mix on the island was summarised as follows: heavy fuel oil (37%), diesel (18%), gasoline (17%), kerosene/jet fuel (7%), sugarcane and other products (3%) and natural gas (2%) (Research Department, 2018).

There is a total installed capacity of 239.1 megawatts (MW), with plans in the development for the installation a 33MW flexible power plant to replace the retire the oldest gensets and to provide back-up capacity for the future 100% RES (Wärtsilä , 2020). Presently, as shown in Fig. 1 there is a total of three-generation sites referred to as the following: spring garden (155MW), Garrison (13MW) and Seawall (73MW) (BL&P, 2019) . The utility operates 113.1MW of low-speed diesel generators, 103.5MW of gas turbines and 40MW of steam capacity. A summary of the conventional dispatch can be seen in Table 1.12 below. Heavy fuel oil is the cheapest fuel source used by most of the low-speed diesel plants. Between the period of 1993 to 2013, the peak demand grew from 92MW to 152MW reach a maximum of 167.5MW in 2012. However, as shown in Table 1.12 from 2014 to 2019 the peak demand oscillated between 150MW to 155MW. This drop in the peak demand within more recent years can be attributed to limited economic growth and the expansion of distributed solar PV generation (Espinasa , Gischler , Humpert , González , & Sucre, 2016 ).

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| Information | Data |
| System peak demand (MW) | 155.2 (2015) |
| Total generation (MWh) | 967,800 (2015) |
| Total Sales (MWh) | 915,200 (2015) |
| Total number of customers | 129,000 (2017) |
| Transmission and distribution losses | 6.2% (2019) |

* Bioenergy: Biogas and Bagasse

The sugar crop is typically harvested from January to May with a total of 258,600.63 tonnes of sugar cane grown from 12,203.00 acres of land (Simpson, 2017). The industry benefited from a favorable remuneration price for the purchase of sugar from the United Kingdom (UK). This rate was secured under the Commonwealth Sugar Agreement that provided an agreed price based on actual production costs for an agreed quota of sugar with an obligation to supply, which continued after Britain joined the EU (Business Barbados, 2010). Following the rule of the WTO, that rate was nullified and in having to compete with the international market sugar was sold for less than half the production costs on the international market. There are plans for the installation of 20MW bagasse plant apart of plans to restructure the sugar industry for energy production; however, more research is required to confirm that yield of biogases could be produced from land available. Also, the utilisation of bioenergy resources is limited to the harvest or crop season; therefore, there is significant seasonal variation in the resource potential that is heavily influenced by drought conditions over the past decade (Shingirirai, De Vries, & De Vries, 2018). Despite, these limitations an estimated installed capacity of 79MW of bagasse of considered in the investigation (Ince & Haynes , 2017). In implementing anaerobic digestion (AD), independent studies have confirmed that 1.5 million m3 of biogas could be produced from guinea grass (Holder, 2019). Considering the island has an extensive natural gas network other stakeholder consultation supported that about 49MW or approximately 21, 974 523m3 of natural gas inclusive of biogas was explored for use in the BNEP (Ince & Haynes , 2017). Furthermore, the island has aa significant problem regarding the management waste approximately 300 - 400 tonnes of sorted waste that goes to the landfill, which could be used for waste-to-energy (The Central Bank of Barbados , 2019 ). To-date, these estimates have not been supported by large-scale feasibility studies, however, these were considered in the modelling.

* Transport Industry: Cruise ship and electric vehicles Sectors

In 2016, tourism accounted for nearly 13% of the islands gross domestic product, 62.1% of exports, both directly and indirectly employs 40% of the national workforce (Ship Technology 2019). The tourism industry is an important economic sector for the island that may bring new energy demands for the future energy system. In 2018, approximately 681,197 visitor arrivals to the island were recorded, which was an 18,000 increase to the previous year. The cruise ship industry provides a significant portion of these tourism arrivals as the island earned $57 million US/BBDs from the industry. However, the cruise ship industry is a substantial source of noise pollution, nitrogen-oxides, sulphur-dioxide and other particulate emissions to near-shore environments. when the ships are berthed in the harbour (Lind, et al., 2018). A more sustainable solution is the use of ship-to-shore plugin or alternating marine power (AMP), which is the use of the onshore power grid to meet the berthing power demand of cruise ships or other large ships docked in the harbour. The concept is advantageous by reducing greenhouse gas effects (Zis, Angeloudis, Ochieng , Geoffery , & Bell , 2014). Furthermore, large-scale electricity generation is usually cheaper than the operational costs of running diesel generators on the ship.

Considering, government’s plans to pursue a 100% RES, how the energy system will satisfy this demand must be considered. According to Hoyte (2016 ) the demand was estimated as an hourly load curve for type of cruise liners categorised as Type-1 ships that dock for 10 hours and, Type-2 ships that dock for 24 hours. A combination of these vessel where used to simulate the demand from the cruise industry. For the year 2030, peak demand for a combination of both cruise- ships was estimated to be\_\_\_\_\_\_

* Vehicular transportation

Fuel consumption by sector can be summarised as follows: transportation (51%), other (24%), industrial (13%) and residential (12%) (Caricom Energy , 2018 ). As recent as 2015, there was one vehicle for every two persons, which also serves to highlight the importance of electrifying the transport sector (Haynes , 2019). Based on the best available information there are approximately \_\_\_\_\_\_ vehicles in Barbados, of which \_\_\_\_\_\_\_\_\_\_are passenger transport vehicles, which can be replaced by similarly classed electric vehicles. For the model, an estimated total of \_\_\_\_\_\_vehicles were replaced with electric vehicles and the peak demand from these vehicles was estimated to be \_\_\_\_\_\_\_.