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# Onshore wind energy potential for small island developing states: Findings and recommendations from Barbados

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**Abstract** Small Island Developing States (SIDS) are often burdened with high electricity prices whilst being bestowed with excellent wind resources. Wind energy is the most proven of the modern renewable energy technologies and, in areas with a good resource, is often the cheapest form of electricity generation. Many small island states have yet to tap into their wind energy potential. Using the Caribbean island of Barbados as a case study, this paper applies basic engineering processes and a spatial planning methodology to determine an island's maximum potential installed wind capacity. In order to encourage repeated studies for other islands, publicly available global historical hourly weather data is identified and forms part of a technical assessment to estimate the expected annual energy yield. The paper highlights the complexities of wind energy development on small islands when compared with mainland countries and explores the key factors that are to be addressed if SIDS are to make use of their wind resource. Economic analysis of the expected annual energy yield for Barbados predicts a levelized cost of energy (LCOE) for wind of 0.13 US$/kWh (±0.01 US$/kWh), which compares favourably with other forms of generation that are an option for the island.

**Keywords:**
Small Island Developing States
Wind Energy
Sustainable development

## 1 Introduction

Small Island Developing States encompass a group of 57 countries and overseas territories from across the African, Caribbean and Pacific regions [1]. Their shared development challenges lead to commonalities in the structure of their energy systems, with their remoteness leading to high transport costs for imported fuels, and a limited demand for fuel domestically resulting in dis-economies-of-scale [2]. Historically, these shared development challenges have burdened these islands with some of the highest energy prices in the world [3]. For many of these SIDS, solar photovoltaic (PV) generation has become the front-runner in a move away from imported fossil fuels, mainly due to solar PV's suitability at all scales of deployment, from domestic rooftop systems to utility-scale multi-megawatt systems. Conversely, wind energy remains a largely underappreciated resource, requiring higher scales of investment before its economic rewards can be fulfilled. The aim of this study was therefore to highlight the crucial part that wind energy can play in helping SIDS transition from expensive, fossil-fuel derived energy sources towards 100% renewable energy generation. Understanding the wind energy potential of a country allows energy sector stakeholders to plan their energy systems accordingly. In particular, knowing the maximum possible installed wind capacity and expected annual energy production provides vital information that can be incorporated into future planning scenarios and used to determine the extent to which a national wind energy strategy can be pursued.

There is limited academic literature discussing wind energy deployment on SIDS in detail. Existing analyses either explore methods for determining wind resource or outline wind energy market status, and these are discussed in Section 1.2. Given advances in wind resource assessment and wind turbine technology over the last decade, along with improved access to publicly available wind speed data, there is an opportunity to revisit and supplement previous studies. Therefore, this work was based on the following objectives: (1) to devise a methodology that employs open-source wind speed data to produce a desktop study into an island's wind energy resource potential; (2) to compare the cost of utility-scale wind with other electricity generation options for SIDS; and (3) to define the key constraints to wind deployment on SIDS.

The remainder of this section discusses how the wind energy markets of SIDS differ to those of more established and larger mainland countries. It also summarises the existing wind energy deployment across SIDS before outlining the current energy system of Barbados. Sections 2 presents an outline of a methodology that applies basic engineering processes to provide an initial assessment of an island's maximum installed wind power capacity. In Section 3, this methodology is then applied to the island of Barbados as a worked example, with the expectation that it can be adopted as a framework for other SIDS interested in determining their wind energy potential. Section 4 focuses more on the island context, collating and presenting knowledge gained from stakeholder interaction with utility operators, wind energy experts and planning authorities whilst conducting this research. This culminates in a sequence of SIDS-specific considerations that can help guide policymakers interested in understanding and harnessing their wind energy resources.

### 1.1 Uniqueness of SIDS

Small island developing states are mostly located in the tropics and have good renewable energy resources, including solar, bioenergy, marine, geothermal and wind [4]. In addition to their exposure to favourable trade winds (see Figure 1), many of these islands share a host of circumstances that differ to wind energy markets found elsewhere in the world, described below:

1. SIDS usually have isolated electricity systems that introduce difficulties in realising high penetration levels of wind when compared to continental countries, which can often rely on large, interconnected electricity grids [5].
2. They often have high population densities, which can limit the amount of space that is available for a technology like wind energy that can pose unique environmental and social impacts.
3. Tropical flora and fauna can result in different background noise profiles than those of wind markets in temperate regions (Section 4.2).
4. Tropical cyclones and hurricanes provide different risks that must be assessed and mitigated for safe and reliable operation of any wind capacity (Section 4.5).
5. Island states are often surrounded by quickly steepening bathymetry, whereas coastal countries elsewhere might exhibit shallow continental shelves that providing good opportunities for offshore wind. This limits the scope of most SIDS for offshore wind using fixed foundations, although hopes exist for floating offshore wind as the technology becomes more commercially viable [6].

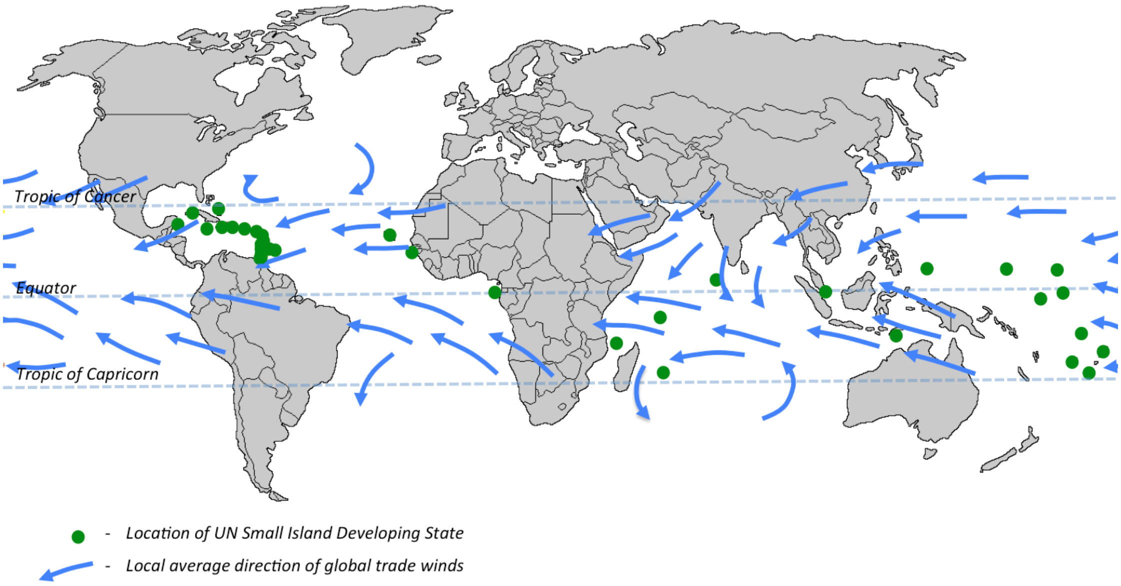


**Figure 1. Location of members of the Small Island Developing States, along with prevailing trade wind direction.**[1]

## 1.2 Existing wind energy market status of SIDS

Surroop *et al.* (2018) examine the share of electricity generation sources for SIDS and note that wind energy contributes approximately 1.5% of total supply, compared with 3.8% for the rest of the world [7]. This varies between regions with SIDS around Africa sourcing 4.2% of their electricity generation from wind energy, 1% for Pacific SIDS, and just 0.8% for Caribbean SIDS. In the Caribbean, the Dominican Republic and Jamaica dominate the wind energy market with installed capacities of 135MW and 99MW, equating to 8% and 2% of total electricity generation capacity in their countries, respectively and market expansion taking place [8].

To date, there has been minimal wind energy market growth in the smaller SIDS of the Caribbean. This is in spite of a favourable wind resource throughout the region. Chadee and Clarke (2014) applies near-surface reanalysis of various wind data sets and finds wind power densities of between 300 and 400 W/m$^2$ across the eastern Caribbean [9]. Scheutzlich (2011) reviews historical technical, economic, and political issues around 15 existing and planned wind energy projects of varying sizes (3MW to 18MW) [10]. Of the nine wind projects listed as 'planned' in the 2011 report, only two are now operational. Whilst highlighting the significantly attractive resource availability, Scheutzlich's report also highlights several factors of differing weighting that have led to low wind energy deployment across the region. The most critical barrier to development *"seems to be the combination of (a lack of) energy policy and existing electricity supply acts which [can essentially] guarantee the utilities a rate of return on investment"* [10]. To clarify, whilst a rate of return is never *guaranteed* by a regulator, the opportunity is provided for a stated return on investment. This barrier continues today, with many Caribbean utilities permitted to apply a fuel surcharge that, whilst insulating them from the turbulence of the international oil market, does not provide any incentive for a utility to focus on fuel efficiency. Jamaica is an exception; an efficiency factor is built into its fuel cost pass-through (fuel surcharge) formula thus mitigating the unfettered full pass through of fuel costs to customers [11].

Overall, this has resulted in little incentive for many of the Caribbean SIDS to explore alternative energy sources and is an issue that is investigated by Hohmeyer (2015) for the island of Barbados

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1 - Produced based on data provided at https://earth.nullschool.net/ (accessed: 30th May 2019)

[12]. Hohmeyer (2017) goes further and provides an economic analysis of several solutions, advising a differentiated and dynamic feed-in tariff (FIT) system to create a fair investment climate and help solve the problem of unsupportive policy frameworks [13]. The work presented here builds on Hohmeyer's 2015 study and helped inform his 2017 study.

### 1.3 Barbados overview

At the start of 2019, the total installed electrical power capacity for Barbados was 249 MW, with an annual peak demand of 152 MW. At present around 20.8 MW of installed solar photovoltaic systems dominate the island's renewable energy generation, with 10 MW sourced from a single utility-owned project and 10.8 MW sourced from distributed systems. The island's annual net electricity generation is 996GWh, of which 3.5% is provided by the aforementioned renewable technologies. With the island also pursuing the electrification of its transport sector there are expectations that this demand will rise [14]. Gay *et al.* (2018) estimates a doubling of the island's electricity demand if the transportation sector is electrified [15].

Following a change in Government in May 2018, the island has indicated a target of 100% renewable electricity supply by 2030 [16]. Hohmeyer (2017) presents an extensive analysis of multiple energy mix scenarios in order to arrive at four scenarios for a 100% renewable energy-sourced power system. Onshore wind energy forms a vital aspect of each of these four scenarios, varying from 200MW to 265MW of installed capacity. The work reported here helped inform this study, allowing modellers to appreciate the maximum installed potential wind capacity available on the island.

Although Barbados has no utility-scale wind operating at present, in the 1980s the island did experiment with large-scale wind, installing a 200kW Howden wind turbine in the north of the island. However, the project was short-lived with limited operation and safety concerns leading to it being abandoned 4 years after commission. Its noisy operation and low performance left a lasting impression of wind energy in Barbados and the wider Caribbean. This lasting impression has, to some extent, outlived the advancements in wind turbine technology with modern wind turbines being significantly quieter and more reliable [10]. Since then, the local utility, Barbados Light and Power (BL&P), has battled with a laborious, undefined and uncertain permitting process to actively pursue a 10MW wind farm project since 2006, with pre-construction activities only now being finalised [17].

## 2 Methodology

A spatial planning approach to estimate wind energy potential can be considered an established process [18], with some studies even focussing specifically on islands. Shallenberg-Rodíguez and del Pino (2011) evaluates the wind energy potential of the Canary Islands by applying a geographical information system approach [19], whilst the IRENA guidelines for islands explains in detail how to conduct high-quality wind resource measurement campaigns [20].

The technical wind energy potential for any given location is determined by two main factors: the wind regime, and the geographical considerations of the site. These tend to be specific to any given location, with a site's geography yielding multiple constraints, including: proximity to electrical integration; environmental impact; transport routes to the site; local planning constraints; wind farm layout; wind turbine selection; and proximity to habitation (including the impact of noise, shadow flicker, visual influence, and electromagnetic interference on telecommunications and RADAR systems). All of these factors were investigated for the island of Barbados with an underlying goal of determining both the maximum installed capacity and the corresponding annual energy yield. Figure 2 summarises the steps of the research approach, with Section 3 providing a worked example for Barbados, explaining each step in detail along with the results of each of these steps and a discussion of each output.

Confirmation and triangulation of this approach is achieved by comparing the outputs with expected capacity factors presented in previous studies. The first wind energy studies for Barbados took place in 1984 and 1988 and are reported in Schuetzlich (2011) [10]. Measured at heights of 20m, 25m and 100m, capacity factor of 36.6% is expected for the north of the island (using Vestas V52-850 wind turbines). The second study is reported in Hohmeyer (2017) and uses airport wind speed data and EMD's WindPRO software package (with WAsP) to produce a wind resource map for the whole island. This study reports capacity factors ranging from 31.5% and 51.8% [13].

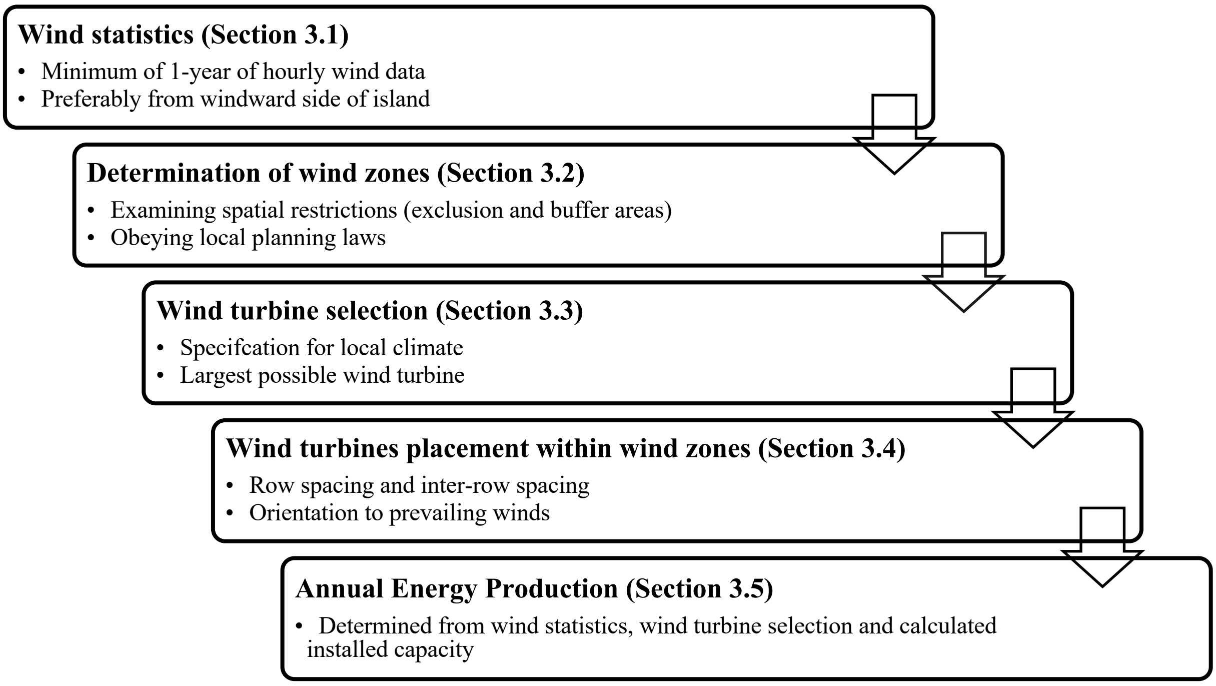


**Figure 2. An overview of the methodology for a desktop investigation into a SIDS potential wind energy resource.**

# 3 Results and discussion – a worked example for Barbados

## 3.1 Estimating the island-wide wind regime

The quality of local wind speed data is key to providing an accurate estimate of the expected annual wind energy yield. Ideally, at least a year's worth of 10-minute interval averaged wind data is required from the intended site of a wind farm, measured at multiple heights up to the expected tip height of a chosen wind turbine (hub height plus blade length). However, high-quality measurements of this kind are seldom readily available for SIDS.

To address the lack of wind speed data across the island, alternative sources of data were sought. Routine aviation weather data is ordinarily hourly or 3-hourly data and is measured at 10m. It is available for most airports around the world and was the source of wind velocity data for this study. For the purposes of studying wind resources for small island states, it is preferable to acquire data from airports that are located on the windward side of an island, with as few obstacles as possible in the prevailing wind direction. Wind speed data from airports on the sheltered side of an island are not suitable for performing wind energy analysis and in this case alternative sources should be sought. For example, Chadee and Clarke (2014) provide the spatial variation of wind resource for the Caribbean, and simulated, rather than measured, datasets are commercially available online from companies like Meteoblue[2]. Routine aviation data is publicly available online from the United States' National Oceanic and Atmospheric Administration (NOAA) through its National Centers for Environmental Information (NCEI)[3].

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2 - Meteoblue Ltd. - https://www.meteoblue.com/en/historyplus (accessed: 30th May 2019)
3 - US National Centers for Environmental Information: https://www7.ncdc.noaa.gov/CDO/cdoselect.cmd (Accessed: 30th May 2019)

Barbados's Grantley Adams International Airport (GAIA) is located on the windward side of the island (see Figure 9) and hourly wind speed data is available from the NCEI from 2003 onwards. To account for wind shear, the log law equation (1) with a roughness length ($z_0$) of 0.0024m, appropriate for airports, was used to convert each wind speed value ($U_{ref}$) from 10m ($z_{ref}$) to 80m ($z$), the hub height of the wind turbine selected for this investigation (see Section 3.3), to give $U_i$, the wind speed at hub height.

$$U_i = U_{ref} \frac{\ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{z_{ref}}{z_0}\right)} \tag{1}$$

This modified dataset was then analysed to determine the wind speed distribution, prevailing wind direction (through wind rose analysis), together with diurnal, monthly and annual temporal variations. These analyses were performed using MATLAB[4] and MS Excel[5], although the work would also be possible with other analysis packages, such as Python[6], and more dedicated packages like AWS Truepower's Windographer software[7].

Figure 3 shows the wind speed distribution for the weather station data recorded at GAIA. It shows that the variation of wind speed conforms to a Weibull distribution:

$$P(U_i) = \left(\frac{k}{C}\right)\left(\frac{U_i}{C}\right)^{k-1} e^{-\left({U_i}/{C}\right)^k} \tag{2}$$

with a scale parameter, $C$ = 9.81 m/s and a shape parameter, $k$ = 3.3. As expected, the wind speed distribution indicates that the island receives a broadly constant and predictable wind speed that is synonymous with the Atlantic trade wind belt. The wind energy rose in Figure 3 supports this assertion, indicating that any wind turbine installed on the island will point eastwards most of the time. The wind power density (*WPD*) for the site can be found by calculating the average of the wind power density for each wind speed value at 10m ($U_{ref}$):

$$WPD = \frac{1}{2} \cdot \rho \cdot {U_{ref}}^3 \tag{3}$$

where $\rho$ is the air density, 1.225 kg/m$^3$. At a height of 10m the wind power density for this site was calculated to be 350 W/m$^2$, which is in the middle of the 300 W/m$^2$ to 400 W/m$^2$ range estimated by Chadee and Clarke (2014) for the Eastern Caribbean [9].

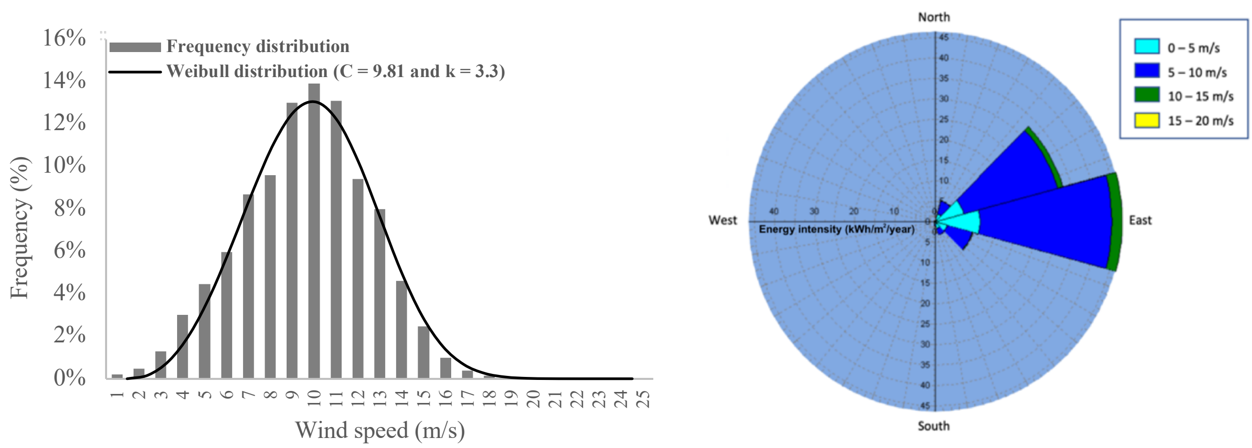



**Figure 3. Weibull distribution and wind energy rose (kWh/m$^2$/year) for GAIA weather station.**

4 - MATLAB wind analysis tutorial: https://www.youtube.com/watch?v=7ViMVNY5kG4 (accessed: 30th May 2019)
5 - MS Excel wind analysis tutorial: https://www.youtube.com/watch?v=Fib3aVRLpQU (accessed 30th May 2019)
6 - Python wind analysis tutorial: https://www.youtube.com/watch?v=4TfIbsaVj58 (accessed: 30th May 2019)
7 - AWS Truepower - https://aws-dewi.ul.com/software/ (accessed: 30th May 2019)

Figure 4 shows how the inter-annual average wind speed varies between 2003 and 2015. There is notable variance in the inter-annual value, with a clear difference between strong and weak wind years, which has a big impact on the inter-annual energy yield.

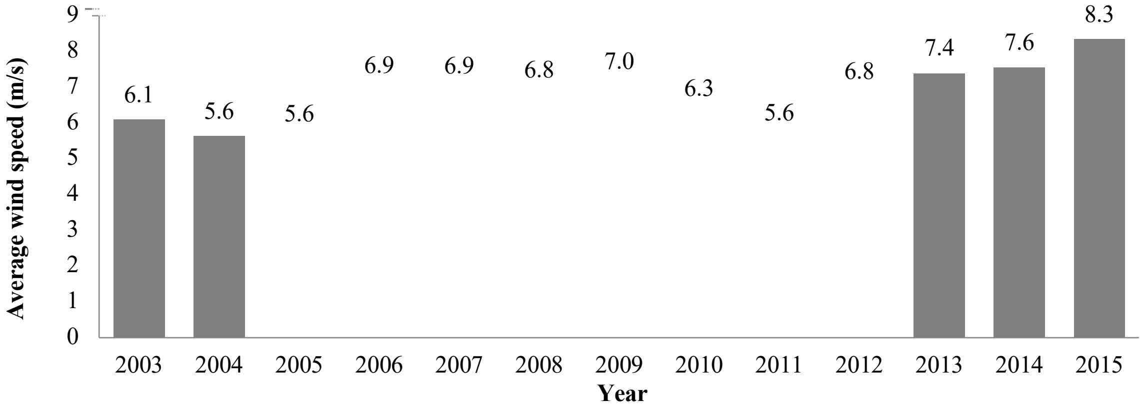



**Figure 4. Annual average wind speeds for Grantley Adams International Airport (GAIA) (at 10m above ground level).**

To determine the energy yield for the wind speed profile, a normalised power curve was mapped onto each hourly wind speed value in order to determine a time series for the average hourly energy yield. This normalised power curve, shown in Figure 5, was generated from the manufacturer's power curve for the wind turbine selected for this investigation, the Enercon E-82 2MW with an 80m tower (discussed in Section 3.3). The wind turbine power output ($P_{turbine}$) at hour, $i$, was determined by using MS Excel's LOOKUP function for the wind speed, $U_i$. Conroy *et al.* (2011) discusses wind farm availability and indicates that wind turbines will typically be available for 90% of the time. Therefore, a 10% reduction is applied to the hourly output, resulting in an hourly energy yield, $E_i$ [21]:

$$E_i = P_{turbine}(U_i) \cdot 0.9 \tag{4}$$

These values were then summed for the whole time series and divided by the total number of hours in the time series to calculate the site's capacity factor, which was found to be 38% (further discussed in Section 3.5).

Any uncertainty in the capacity factor arises from the selection of the surface roughness length, $z_0$. Sensitivity analysis was performed to determine the change in the capacity factor based on a range of surface roughness lengths, from 0.001m (flat desert) to 0.01m (flat grassy plains), which are the typical values for terrain with a roughness value above and below that of an airport (0.0024m) [18]. This resulted in a capacity factor that ranged between 36% and 41%, respectively. Additional uncertainty may be expected from the impact that turbulence intensity could have on the wind turbine's performance. Along with wind shear, turbulence intensity is not measured at the site. It is assumed that as the site faces open sea in the prevailing wind direction the turbulence intensity is low and would have a minimal impact on wind turbine operation. However, turbulence intensity will differ across the island and this is discussed in Section 3.5.

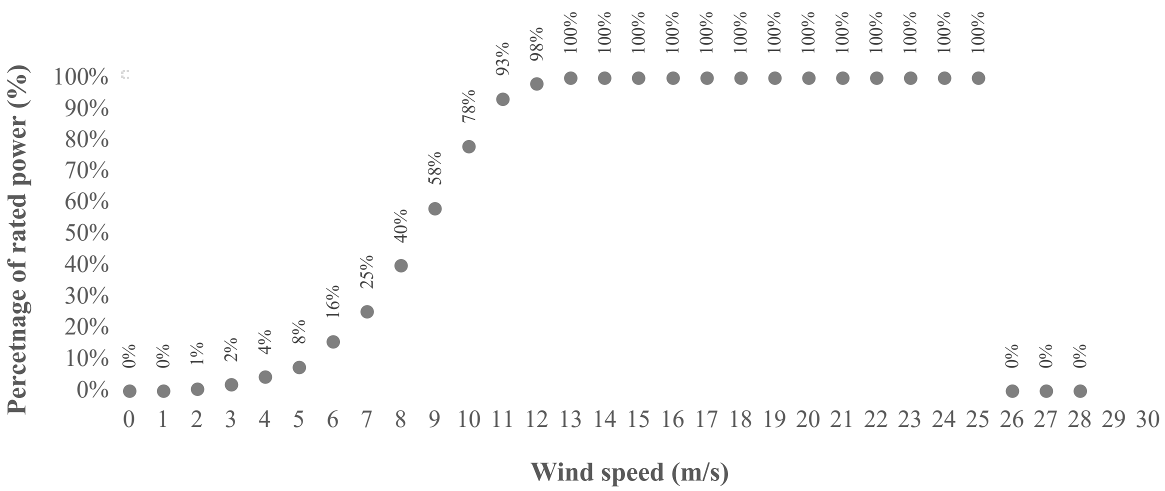



**Figure 5. Power curve for the Enercon E-82 2MW wind turbine as a percentage of the rated power.**[8]

Figure 6 shows how the annual average energy yield for a wind turbine installed in Barbados might vary each year from the thirteen-year average. Together, Figure 4 and Figure 6 show that for a weak wind year (2011), equating to a 2m/s reduction in the inter-annual average wind speed, there will be an almost 25% reduction in the average annual energy yield. As compared with a strong wind year (2015), for which there was a 30% increase in wind energy yield.

Figure 7 shows the expected average hourly power output of a wind turbine over 24 hours, indicating a distinct diurnal pattern. This figure also includes the electricity demand curve for the island, highlighting the broadly similar pattern of wind energy resource to national electricity demand. Figure 8 compares the island's monthly system load factors with expected monthly wind energy capacity factors, highlighting the calmer autumn months which would likely pose issues for utility operators.

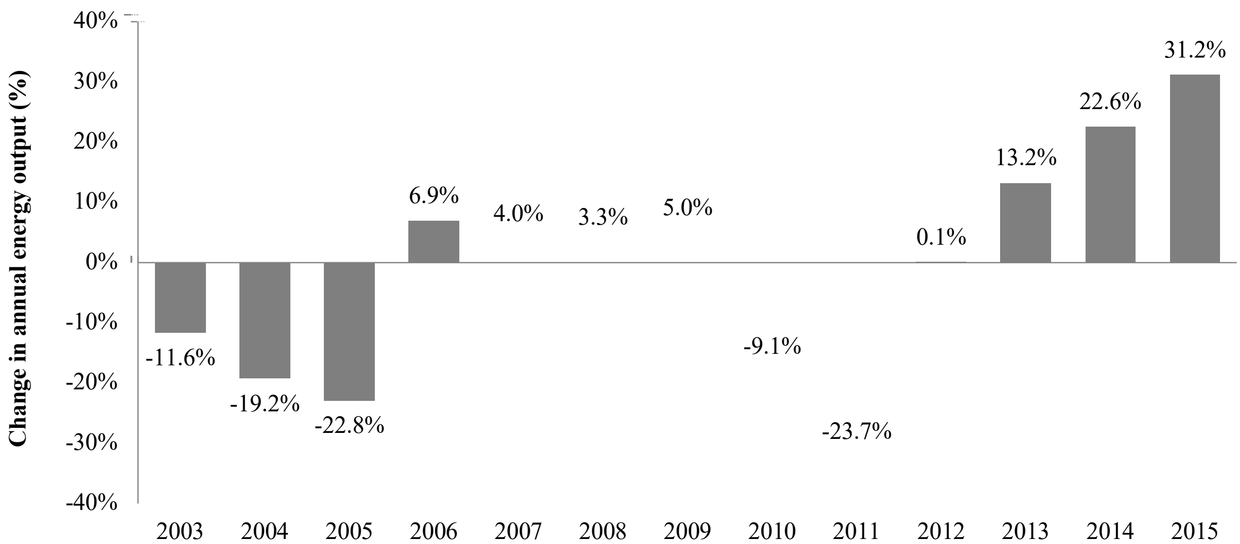



**Figure 6. Predicted yearly change in energy output from 13-year average for a wind turbine installed in Barbados.**

[8] - Enercon E-82 product specification: https://www.enercon.de/en/products/ep-2/e-82/ (accessed: 30th May 2019)

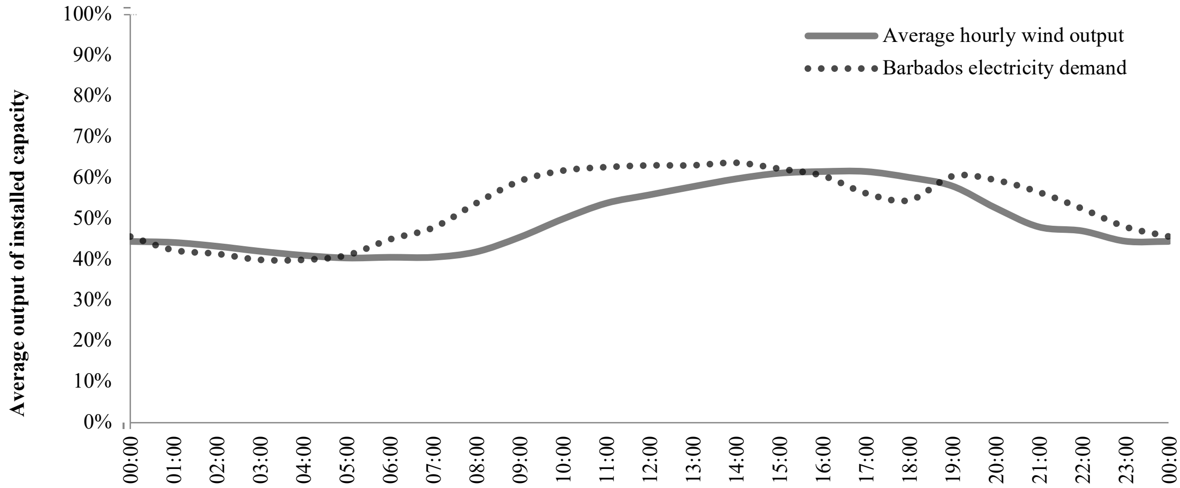



**Figure 7. Average hourly wind speeds for Barbados along with the country's typical daily demand curve [20].**

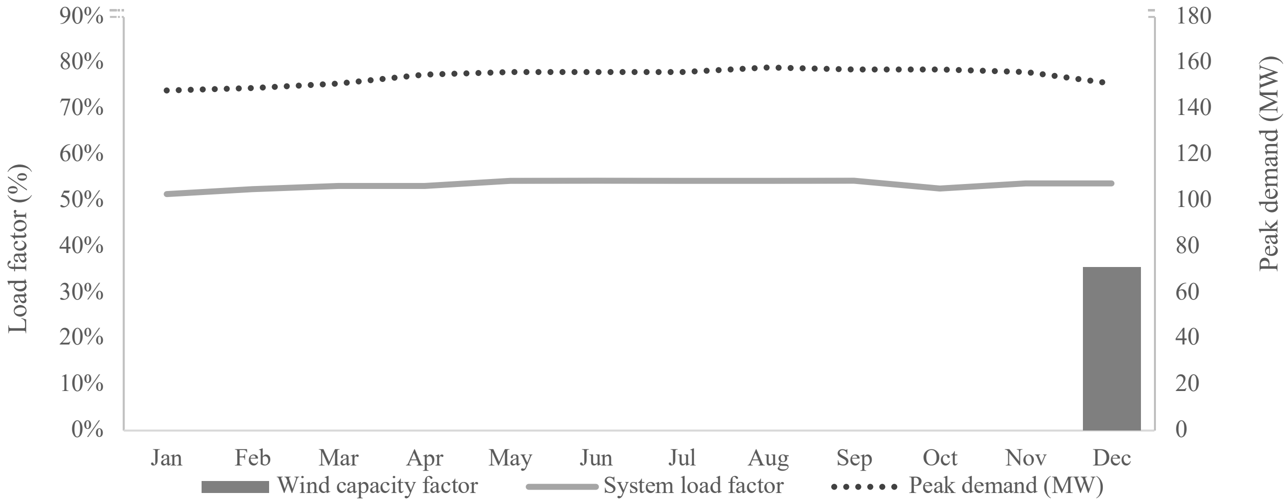



**Figure 8. Monthly system load factor and peak demand, with expected average monthly wind capacity factors [20].**

The above outputs provide vital information for various energy sector stakeholders. As well as the expected annual energy yield (see Section 5.2), the wind speed distribution curve allows wind farm developers to select wind turbines whose power curves match the wind speed profile of the site. The wind rose helps wind farm planners site wind turbines to reduce wake effects, and the hourly, diurnal, seasonal and inter-annual average wind speeds allow utility companies to begin basic modelling simulations of the expected impact of wind energy deployment on their electricity grids [20].

## 3.2 Spatial restrictions

The process of identifying appropriate sites for wind turbines involved the collation and analysis of technical and environmental considerations for the whole island, as per industry spatial planning guidelines covered extensively in the literature – for example, Burton *et al.* (2011) [18]. As there is little publicly available digital geospatial information for Barbados, of the kind used in Geographical Information Systems (GIS), there was a reliance on Google Earth[9] satellite imagery along with local knowledge and site visits. From this, initial technical and environmental assessments were made that outlined areas with suitable terrain slope, avoided complex terrain, with good transport access, and observed local planning regulations for proximity to buildings. Spatial

9 - Google Earth - https://earth.google.com (accessed: 30th May 2019)

restrictions for Barbados were identified according to the local Government's regulations.[10] The Barbados Town and Country Development Planning Office stipulates that wind turbines should be:

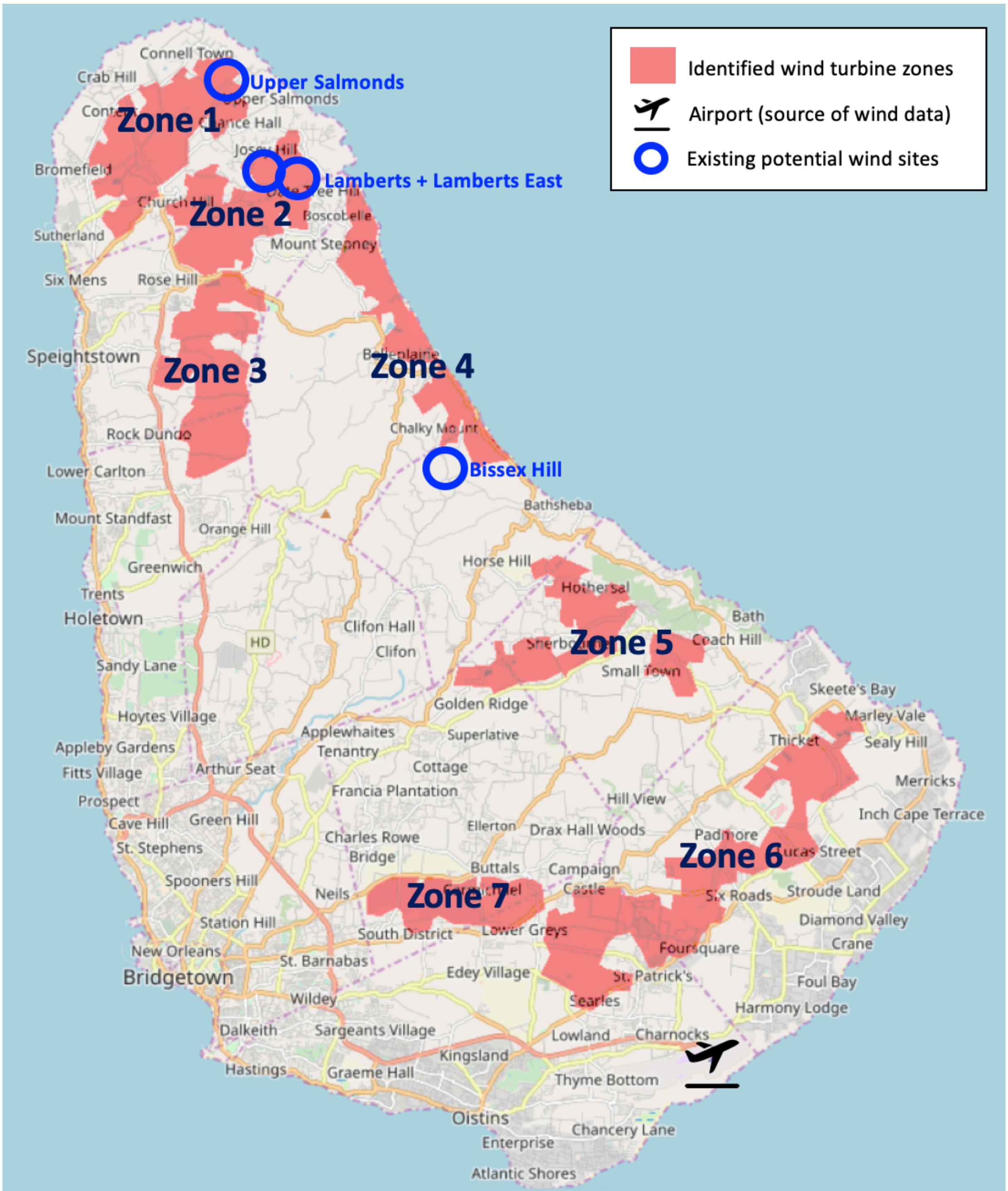
1. 1.5 times their height away from any roads and buildings,
2. A minimum of 350m away from the landowners' boundary, and,
3. The wind turbine sound pressure level should be below 45dB(A) at the nearest dwelling.

The second guideline is unusual in that planning policies for countries with successful wind energy sectors will often stipulate setback distances from dwellings, settlements, streets, nature conservation areas and other sites to be protected from wind turbines, rather than from the property perimeter [21]. The Barbados approach to setback distances would have a significant impact on the potential maximum installed capacity and, as no property boundary information is publicly available, this study disregarded the setbacks from property boundaries and focused on distance to residential dwellings, buildings and roads; the assumption being that the resulting wind zones could be incorporated in the island's physical development plan and help guide future energy policy to support wind energy development (see Section 4.2).

The existing Physical Development Plan for the island identifies four possible sites set aside for wind energy development; Upper Salmonds, Lamberts, Lamberts East in St. Lucy, and Bissex Hill in St. Joseph, the locations of which are given in Figure 9 [22]. All together, these sites would expect to yield an installed capacity of around 30-40MW.

Emerging from the spatial planning analysis, seven wind zones were identified. Presented in Figure 9, they are located across the north, east and south coast of the island, amongst the island's relatively flat, rural, agricultural lands – except for zone 4, which borders the island's Scotland District National Park. As a side note, the island's agricultural land is dominated by its ailing and Government-subsidised sugar cane industry [23]. There is, therefore, a potential for wind energy being able to support the island's farming community and protect its sugar cane production, which play a considerable part in its land management and tourism industry.

10 - Communicated during meeting with Barbados Town and Country Development Office's Chief Town Planner on 11th November 2016




| Zone | Area (km²) | Installed capacity (MW) | Power density (MW/km²) | Energy yield (GWh/year) | Barrels oil equivalent (boe)/year | Avoided cost* (US$ million/year) | Avoided $CO_2$ emissions** (Tonnes/year) |
|---|---|---|---|---|---|---|---|
| 1 | 9.4 | 62 | 6.6 | 208 | 122,350 | 11.8 | 141,440 |
| 2 | 9.2 | 66 | 7.2 | 223 | 131,180 | 12.6 | 151,640 |
| 3 | 9.4 | 60 | 6.4 | 203 | 119,410 | 11.5 | 138,040 |
| 4 | 7.0 | 68 | 9.7 | 230 | 135,290 | 13.0 | 156,400 |
| 5 | 7.9 | 54 | 6.8 | 182 | 107,060 | 10.3 | 123,760 |
| 6 | 16.2 | 116 | 7.2 | 392 | 230,590 | 22.1 | 266,560 |
| 7 | 5.2 | 40 | 7.7 | 135 | 79,410 | 7.6 | 91,800 |
| **Total** | **64.2 km²** | **472 MW** | (Average) **7.4 MW/km²** | **1,573 GWh** | **925,290 boe** | **US$ 88.8 million** | **1,069,640 tonnes** |

* - Assuming 96 US$/boe for 2030 [24]
** - A carbon intensity of 680 $gCO_2e/kWh$ is used [15]

**Figure 9. Seven potential wind turbine zones identified through spatial analysis of the island of Barbados.**

## 3.3 Wind turbine selection

Economies-of-scale suggest that the cost-of-electricity from wind energy generally decreases as the rated capacity of the wind turbine and the tower height increases (see Figure 10), leading to the recognition that the largest possible wind turbines should be installed. For islands like Barbados, this is even more important given the often-limited space that is available for wind turbines. The maximum size of a wind turbine largely depends upon suitable transportation routes to potential sites and the cranage available on the island.

The local utility, the BL&P, has performed a transport survey for a proposed 10MW wind farm site at Lamberts East in the Parish of St Lucy, and expect the largest sized wind turbine that they can install to be between 1.5MW and 2MW.[11] This equates to a blade length of ~40m and a hub height of ~80m, meaning a total height of 120m. This corroborates conversations with other wind energy experts that have visited the island and is the reason that this study chose a 2MW rated wind turbine. Although some stated that larger wind turbines (up to 3MW) may be possible if more widespread adoption of wind energy on the island were pursued, with the improved economies-of-scale offsetting the investment required for improved transport routes and larger installation equipment.

The German manufacturer, Enercon, was chosen for this study given that its Enercon E-82 2MW wind turbine[8], with a hub height of 78m, is well suited for sites in coastal areas with medium-high wind conditions. The indirect electrical interconnection design of its wind turbines is also more suited to small, isolated grids like Barbados'.

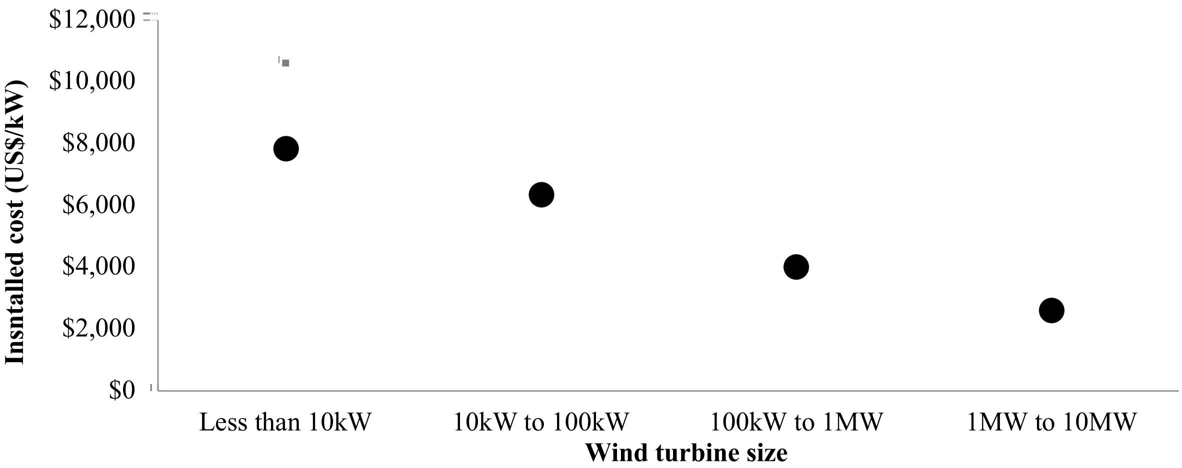



**Figure 10. Installed cost for different sized wind turbines – mean and standard deviation [25]**

## 3.4 Wind turbine placement

Once the wind zones were determined and the 2MW wind turbine selected, the next step was to calculate how many wind turbines could be installed in each zone. A simple method would be to measure the area of each zone and apply a typical power density factor of 10MW/km$^2$ [26]. However, this rule-of-thumb is more commonly used for open, flat terrain where developers are unaffected by nearby dwellings, infrastructure and natural obstacles such as vegetation and changes in topography. Given the constricted area of land available on small island states, it was necessary to individually site each turbine using the planning setbacks indicated in the previous section.

A key element of wind farm layout design is to minimise both the wind turbine spacing wake losses. For areas with predominantly unidirectional wind roses, like islands in trade wind regions, greater distances between wind turbines in the prevailing wind direction may be necessary, whilst tighter spacing perpendicular to the prevailing wind direction will prove to be more productive. The

[11] - Information provided during a presentation made by an engineer from BL&P, Mr Johann Greaves, during a Barbados Town Planning Society seminar, held on 23rd September 2016.

spacing for the wind turbines in this study was a row spacing of seven rotor diameters and an in-row spacing of four rotor diameters [27]. Tighter in-row spacing will likely be possible. However, this will require consultation and approval from turbine suppliers if warranty conditions are not to be affected.

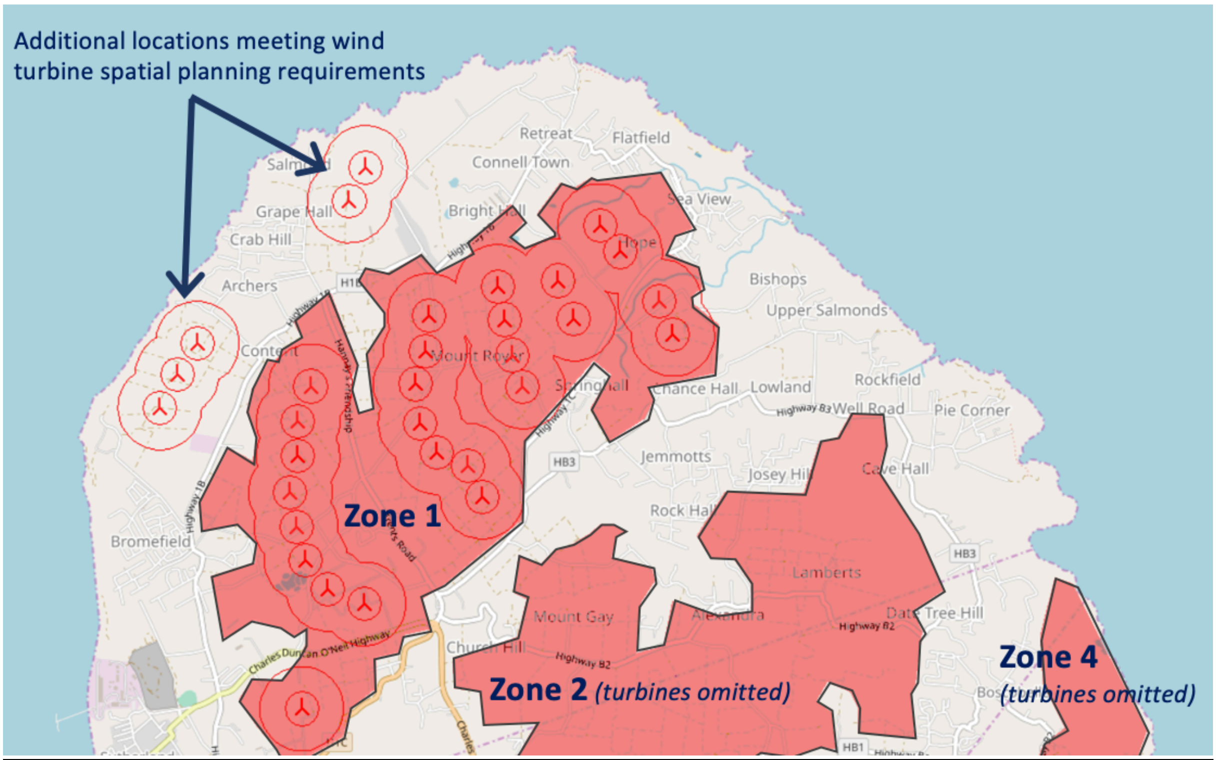



**Figure 11. Example of wind turbine placement for Zone 1, in the north of Barbados.**

## 3.5 Wind energy production

Calculation of the expected wind turbine capacity factor at the airport site is presented in Section 3.1 and returned a value of 38%, which is applied for wind turbines at each of the seven wind zones. This resulted in the main limitation of this study, in that it assumes that each wind turbine in each wind zone receives an identical wind regime to the data set taken from the local airport. Although wind speeds can be expected to be broadly similar along the exposed side of the island, moving inland the speed-up effect, flow separation and obstacles will result in positive and negative variations in wind speed [18]. Due to the cubic effect of wind speed and corresponding power in the wind, small variations in wind speed can lead to large variations in wind turbine power output and it is therefore necessary to stipulate that notable tolerances will exist in energy yields from each of the wind zones. Consequently, this study should be seen as an initial step towards a more detailed investigation of wind speed resources and this is further discussed in Section 4.1.

The table in Figure 9 provides information on each of the seven identified wind zones, including their area, expected installed wind capacity, the power density and expected annual energy yield. As outlined in Section 3.3, the expected installed capacity is based on 2MW wind turbines. The installed capacity would change for different sized wind turbines, with larger wind turbines likely resulting in a higher potential installed capacity value.

Returning to Hohmeyer's study of the requirements for a 100% renewable energy system for the island, between 200MW and 265MW of wind power would be required [13]. This could therefore be met by populating between 3 and 5 of the seven zones identified here. The total expected energy yield for 2MW wind turbines installed in all of the wind zones would be 1,594 GWh/year. This includes a 10% reduction in output due to typical wind turbine operation and maintenance schedules. This would equate to an average capacity factor of 38% across all seven zones. Previous studies discussed in Section 2 estimate capacity factors ranging from between 31.5% and 51.8%, whilst Scheutzlich (2011) reports capacity factors of between 30% and 67% across the whole Caribbean region [10].

### 3.6 Economic analysis

Hohmeyer (2017) performs a cost assessment for wind energy on Barbados [13]. His analysis first considers various international cost assessments of onshore wind energy, arriving at a capital expenditure (CAPEX) of 1,774 US$/kW and an operating expenditure of 48.30 US$/kW per year. Given higher transportation costs, a small finite market size, and additional costs for importing cranes capable of installing 2MW-sized wind turbines, these installation costs on Barbados are expected to be higher. Following discussions with Barbados-based energy sector stakeholders on the island, Hohmeyer (2017) includes a 25% increase in costs, yielding a CAPEX of 2,366 US$/kW and an OPEX of 64.55 US$/kW per year. The analysis assumes a construction period of 6-months, a useful project lifetime of 20 years, and partial equipment replacements at 10 years (413 US$/kW) and 15 years (304 US$/kW), for replacement rotor hubs and drivetrains, respectively. With an interest rate for debt financing of 7%, this results in a levelized cost of energy (LCOE) for wind on Barbados of 0.13 US$/kWh (±0.01 US$/kWh), which compares favourably with other generation sources on the island. For example, the fuel surcharge for electricity generation is 0.16 US$/kWh (May 2019). Hohmeyer (2017) includes LCOE assessments for the deployment of other technologies in Barbados [13]. Summarised in Figure 12 and including the current cost of electricity supplied by the island's utility (including the fuel surcharge of 0.16 US$/kWh), this highlights the economic benefit that utility-scale wind energy could have on the island's economy.

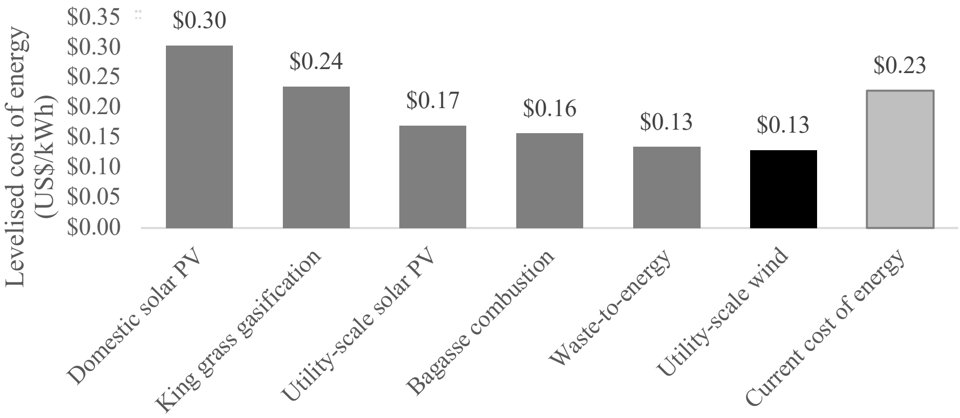



**Figure 12. Expected LCOE for energy generation technologies in Barbados [13]**

## 4 SIDS specific considerations

Discussions with energy sector stakeholders on the island (including landowners, the island's utility, regulators, planners, local communities and government) highlighted a number of wider technical, social, and environmental issues to be explored if an island like Barbados is to tap into its wind energy resource. These are considered in the following sections.

### 4.1 Wind measurement campaign

If a basic prefeasibility study finds a strong wind resource for an island, then a detailed wind measurement campaign, like the one outlined in IRENA (2015), is an important next step [20]. As well as helping to identify the best wind turbines for the local conditions, detailed measured wind data can provide proof to investors and money lending institutions that a wind farm project will have a viable financial profile. Detailed wind measurements will also allow the local regulator to set tariffs that will ensure all parties benefit from the deployment of wind turbines – including investors and consumers. Measurement campaigns in the Caribbean are often limited by high commissioning costs and wind farm developers adjust data collection timelines to suit investor needs and budget. An analysis of extreme wind data (at 10/30-second resolution) would add significant value to site planning for both near- and long-term power projections, but these data can be overlooked and substituted for short-term averaged wind regimes.

### 4.2 Planning guidelines for wind turbines

During this study, the assessment of existing planning requirements for wind turbines on the island and discussions with local planners highlighted key considerations for further investigation. Some of these considerations are specific to Barbados, whilst others are common to other SIDS. They include:

- **A review of the 350m setback rule (see Section 3.2):** the current planning guidelines will need relaxing if an appreciable amount of wind power capacity is to be installed on the island. In particular the requirement that wind turbines should be a minimum of 350m from the landowner's boundary. Instead, setback distances from dwellings, settlements, roads, nature conservation areas and other sites to be protected from wind turbines should be explored.

- **Noise limits:** Any changes in local sound levels caused by wind turbines are understandably of great concern to local residents. Local flora and fauna in Barbados produce a distinctive background noise profile compared to the traditional wind energy markets in Europe and North America. For example, cicadas and whistling frogs are nocturnally active, with the latter more so during the rainy season. It can be expected that natural background noises will mask any disturbance from nearby wind turbines. However, once a utility-scale wind turbine is installed on Barbados, a detailed noise study will help guide planners with their understanding of the noise impact of wind turbines in a local context.

- **Aviation:** Cuadra *et al.* (2019) outlines the impact that wind farms have on nearby airport facilities [28], with the moving wind turbine blades creating a radar shadow that can impede safe observation of airplane traffic. Following discussions with the Barbados Civil Aviation Department, it is understood that the existing radar system for Grantley Adams International Airport would restrict the installation of wind turbines in zones 3, 4, 5, 6, and 7, identified in this study (see Figure 9). However, they went on to state that a new, more sophisticated radar system is soon to be installed on the island. This new radar system is able to omit the impact from the installation of wind turbines.

### 4.3 Grid integration study

Scheutzlich's 2011 report on wind power in the Caribbean discusses penetration of intermittent wind energy onto isolated island electricity grids and suggests that penetrations rates of 50% of the baseload power are achievable with minimal impact on the existing operation of an electricity grid [10]. In its 2015 wind and solar integration study [29], BL&P engaged the services of General Electric Energy Consultants to examine a number of renewable energy technology integration scenarios for the island and determined that 15MW of wind energy could be connected without any noticeable impact on the grid's operation. They are now exploring scenarios with 150MW of wind energy capacity. Storage will play a crucial role in getting Barbados closer to its renewable energy targets and storage modelling will effectively allow the existing grid to meet varying demand whilst compensating for inevitable variations in renewable energy supply. The 10MW St. Lucy solar farm in the north of the island, fully commissioned in 2016, has been installed with a 5MW, 20 MWh Tesla Powerpack battery system.

### 4.4 Transport survey

A detailed survey of the island's whole road network would be required to ascertain the maximum size of wind turbine that can be installed at each particular zone (the private survey by BL&P was just from the island's main port to its Lamberts site in St Lucy). This comprises surveying the transport routes between the port and the intended wind farm sites. Depending upon the size of the wind farm, this survey may include identifying roads that need resurfacing and widening, and bridges that need strengthening; a potential benefit to the local community. For the more remote sites, it may be necessary to explore other means of transporting the wind turbine components to site, including landing the wind turbines on local beaches, or using heavy-lift helicopters.[10]

### 4.5 Hurricanes

Engineering advancements mean that modern, utility-scale wind turbines are better able to cope with the risk of hurricanes. As long as quality wind turbines are sourced, and there is close communication with the wind turbine supplier/manufacturer, a hurricane's impact should be minimal. The 38.7MW Wigton wind farm in Jamaica has survived two hurricanes with minimal damage (Category 4 and category 5) [30]. The US National Renewable Energy Laboratory reports that for US waters, several hurricanes have already exceeded wind class Ia whereby gust wind speeds have exceeded 70m/s (156mph) [31], and Musial *et al.* (2013) reports on efforts being made to improve standards [32].[12] Implementation of wind turbines in the Caribbean, particularly future proposals for offshore wind, must also consider insurance costs, which have been reported at 3.7 US$/MWh for typical European farms [32].

### 4.6 Setting up of a wind energy stakeholder group

A 2013 study by the Global Wind Energy Council examined the wind energy policies for 12 countries over the preceding 30 years [33]. One of the key lessons of this study was that all stakeholders, especially local communities, must be involved with each step of the wind farm development process. Along with the Government, key stakeholders should include community groups, the electricity utility, the government's planning office, and electrical department, utility regulator, local investment entities (credit unions, banks, etc.) and, of course, the landowners. There should also be a strong focus on raising public awareness about the benefits of wind energy and creating a simple, transparent investment climate for local investors.

## 5 Conclusions

A basic desktop wind energy analysis is a useful first step for small islands interested in understanding their renewable energy potential. This paper adopts basic engineering processes to produce a framework that can identify the maximum installed wind capacity for a SIDS along with its expected annual energy yield. Application of this framework to the island of Barbados has determined a maximum installed capacity of 472 MW, and a resulting expected annual energy yield of 1,573 GWh (±130 GWh). A fraction of this capacity, 200 MW, would actually be needed for the island to achieve its target of a 100% renewable electricity supply system. A basic economic analysis estimated a levelized cost of energy value of 0.13 $/kWh (±0.01 US$/kWh), which is the lowest of all generation options (see Figure 12). Whilst carrying out this study, interaction with local stakeholders highlighted social and environmental issues that should be considered by future policy makers if islands like Barbados are to develop their wind energy markets. Some of these are now being considered for Barbados and include:

- Once a good technical wind potential has been determined from a prefeasibility assessment, like the one described in this article, a detailed wind measurement campaign is a critical next step. This should include the collection of investment-grade wind data that will enable investors, grid operators, system planners and utility regulators to understand in detail the impact of utility-scale wind on their operations.

- Infrastructure studies, such as an electrical integration study and transportation surveys also need to be performed early on to better understand the technical wind potential. An electrical

[12] - IEC 61400 is an International Standard published by the International Electrotechnical Commission regarding wind turbines. A Class Ia wind turbine is able to withstand a turbulence intensity of 18%, average wind speeds of 10m/s at hub height, and extreme 50-year gust wind speeds of 70m/s [31].

integration study will allow grid operators to appraise their need for grid reinforcement, grid extension and the storage required for balancing the demand with supply.

- The planning departments have a critical role in developing wind energy markets. Firstly, identified wind sites should be confined to the largest possible wind turbines in order that islands can benefit from the economies of scale required to achieve the expected LCOE. In addition, given different wind profiles and environmental factors, planning guidelines should be developed in conjunction with local conditions, rather than adopted from those found in countries at higher latitudes. Finally, wind farm zoning should be incorporated into physical development plans at the earliest opportunity so that future land-use changes won't impact upon identified wind energy zones.

- Finally, the involvement of local communities with wind energy is critical to ensuring the successful deployment of large-scale wind turbines, and local/national investment is key to ensuring that local economies are best impacted by this clean, reliable and cost-effective form of electricity generation.

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