U.S. Virgin Islands Wind Resources Update 2014

Joseph Owen Roberts and Adam Warren
National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy
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Technical Report
NREL/TP-7A40-63094
December 2014

Contract No. DE-AC36-08GO28308

NATIONAL RENEWABLE ENERGY LABORATORY

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Prepared under Task No. ID14.1005

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Acknowledgments

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List of Acronyms

EDIN	Energy Development in Island Nations
kW	kilowatt
m	meter
m/s	meters per second
MERRA	Modern-Era Retrospective Analysis for Research and Applications
MIDC	Measurement and Instrumentation Data Center
MW	megawatt
NREL	National Renewable Energy Laboratory
SODAR	sonic detection and ranging
USVI	U.S. Virgin Islands

Executive Summary

This report summarized the data collected from two 60-meter (m) meteorological towers (met masts or met towers) and three sonic detection and ranging (SODAR) units on St. Thomas and St. Croix in 2012 and 2013. These results are an update to the previous feasibility study; the collected data are critical to the successful development of a wind project at either site (Lantz et al. 2012). The wind maps for the territory were updated based on these improved data.

The National Renewable Energy Laboratory (NREL) conducted measurements from met towers and SODAR units for several locations in the U.S. Virgin Islands (USVI). Both met masts were deployed for more than a year and produced high-quality data (standard industry practice in the wind industry). The Longford (St. Croix) and Bovoni (St. Thomas) sites are estimated to have long-term corrected wind speeds that exceed 7 meters per second (m/s), which may produce financially viable wind projects for both sites. The levelized cost of energy for both sites was estimated at $0.08–$0.14 per kilowatt-hour for typical utility-scale wind turbine with the uncertainty in the estimate driven by uncertainty in the installed capital costs of the proposed wind farms (see Figure 1). These estimates assume that the wind production tax credit is not reinstated, but that accelerated depreciation is in place.

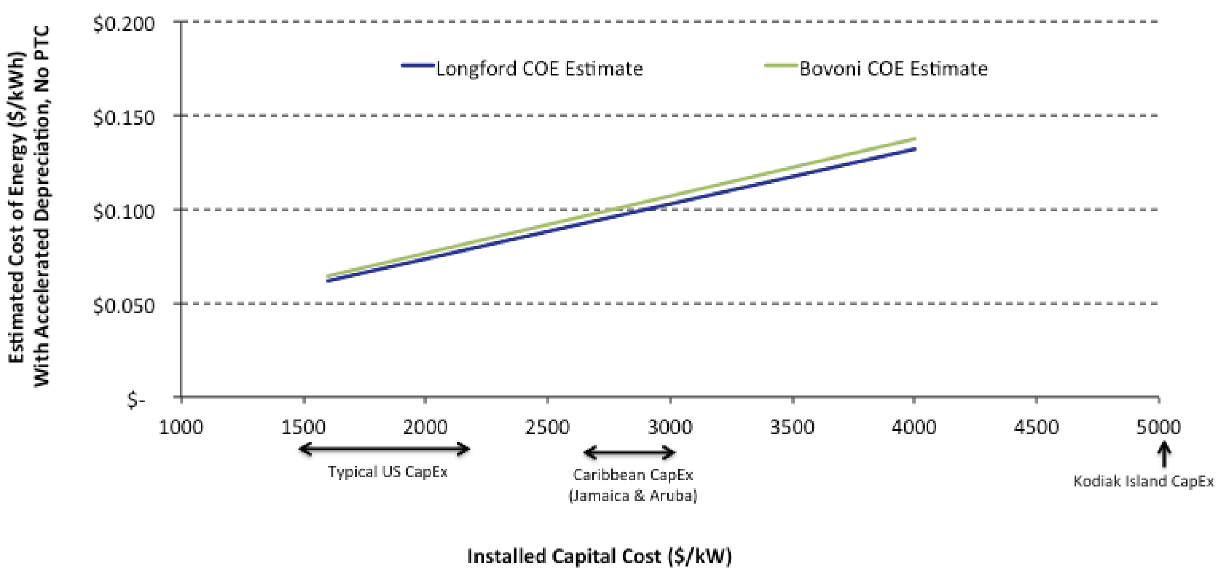

Figure 1. Estimated cost of energy for utility-scale wind in USVI

An updated wind map for the territory is shown in Figure 2. Strong wind resources are accessible from ridges and along shorelines that have access to the prevailing trade winds. This map notes the locations of the deployed instrumentation in the USVI.

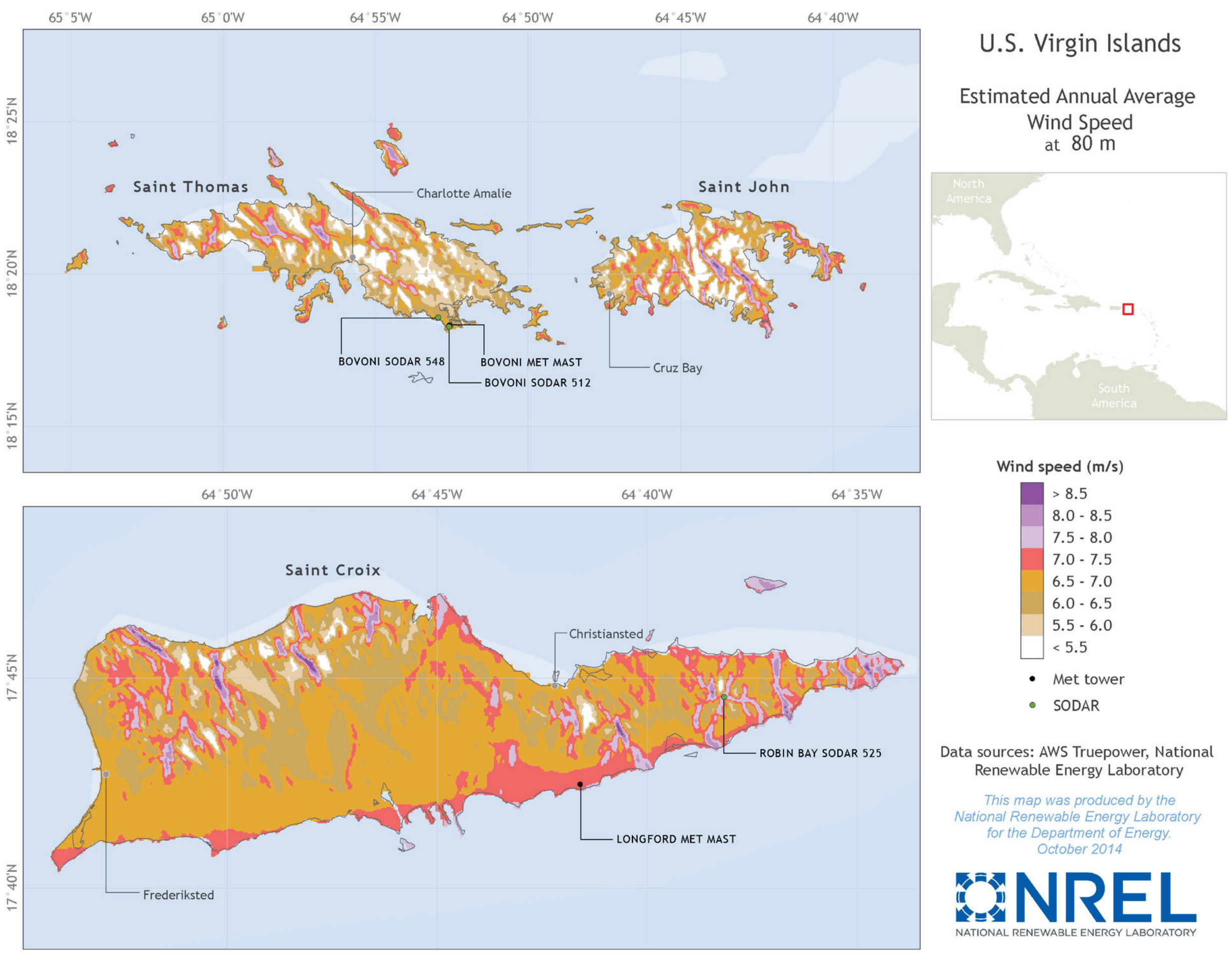

Figure 2. Estimated annual average wind speed at 80 meters

St. Thomas. Previous meteorological modeling by NREL suggested wind speeds of 5.5–6.5 m/s at 70 m above ground level at the Bovoni site. This updated study shows that the observed and long-term corrected annual average wind speed at the Bovoni site is approximately 10% higher than originally estimated—7.2 m/s at 58 m with the resource weakening to roughly 6 m/s at the northernmost end of the developable area. A 10% increase in wind speed can result in a 30% or greater increase in power output because of the nonlinear relationship between speed and power. The Bovoni peninsula has a high likelihood for developing a wind farm because the wind resource is adequate, and the site is of sufficient size for a 5- to 18-megawatt (MW) wind farm, depending on the size of turbines selected. The Bovoni site composes fairly complex terrain, which increases the difficulty of developing a project and increases the uncertainty of wind estimates on the peninsula, particularly for the SODAR measurements.

St. Croix. If developed for wind, the Longford site or a similarly sized site on the souther shore have the potential for up to seven turbines for a total nameplate capacity of 11–21 MW, depending on the turbine model. The long-term adjusted annual average wind speed is estimated at 7.2 m/s at 58 m as measured at the meteorological tower (met mast or met tower) location. The Longford site would require greater distances between the turbines because of the east-west orientation of the developable area and the prevailing trade winds. If other sites could be found where turbines could be aligned on the north-south axis, the spacing between the turbines could be greatly reduced.

NREL worked with AWS Truepower to develop the updated wind speed estimates and wind maps included in this report. The geospacial data can be found and downloaded from NREL's Wind Prospector website (NREL 2014a). Wind Prospector is a central location where spatial data for wind analysis can be accessed and where users can explore, visualize, query, and download data. The application is also intended to provide a high-level, preliminary summary of data for a region or area. Estimates of wind plant performance at specific sites are associated with higher uncertainty. Users interested in developing a wind project can reduce uncertainty by means of on-site data measurements.

Full details on the approach, assumptions, and results for the USVI wind analysis can be found in Appendix A. All of the updated wind maps are presented in Appendix B. All of the data, including the raw data, used for this report can be found at NREL's Measurement and Instrumentation Data Center website (NREL 2014b).

This report leverages the previous feasibility studies conducted by NREL, including *Wind Power Opportunities in St. Thomas, USVI: A Site-Specific Evaluation and Analysis* (Lantz et al. 2012). It is recommended that readers consult the previous feasibility study for a more comprehensive background of potential wind projects in the USVI.

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1 Project Background

The U.S. Virgin Islands (USVI) is heavily dependent on imported oil for electricity production, but has recently emerged as a leader among Caribbean islands seeking to reduce their reliance on imported fossil energy. Through its work with the Energy Development in Island Nations (EDIN) team—a consortium of the territorial government, the Virgin Islands Water and Power Authority (WAPA), the U.S. Department of Energy, the U.S. Department of the Interior, and the National Renewable Energy Laboratory (NREL)—the USVI has developed a strategy to achieve a 60% reduction in its fossil energy consumption by 2025 goal (60 by 25) (see Figure 3). Achieving this goal will require the deployment of a mix of renewable energy resources as outlined in the USVI Energy Road Map (Lantz et al. 2011; NASA 2013).

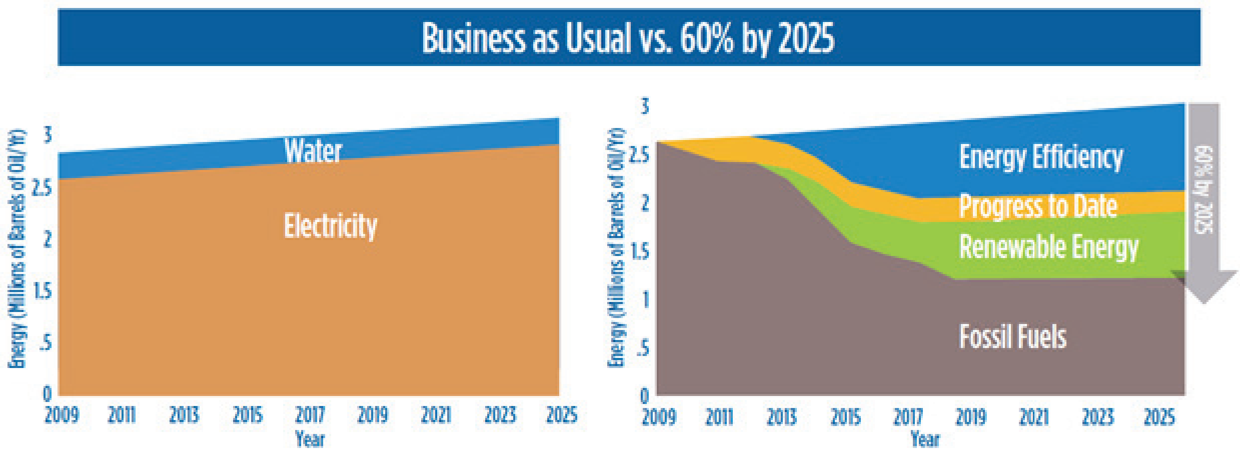

Figure 3. Business as usual versus 60%-by-2025

The original 60 by 25 energy plan calls for 16.5–33 megwatts (MWs) of wind (NREL 2011). These wind goals could be economically met by developing wind at the two sites evaluated in this report—Bovoni point in St. Thomas and the south shore in St. Croix (see Figure 4). A first step in developing wind in the territory is to reduce the uncertainty associated with the wind resource by collecting a year or more of bankable data at sites likely to be developed for wind. Meteorological towers (met masts or met towers) and sonic detection and ranging (SODAR) units were deployed to measure the wind resource characteristics on the Bovoni peninsula in St. Thomas, and at Robin Bay and Longford Estate on St. Croix. These sites were indicated to have good wind resources based on preliminary wind mapping by NREL.

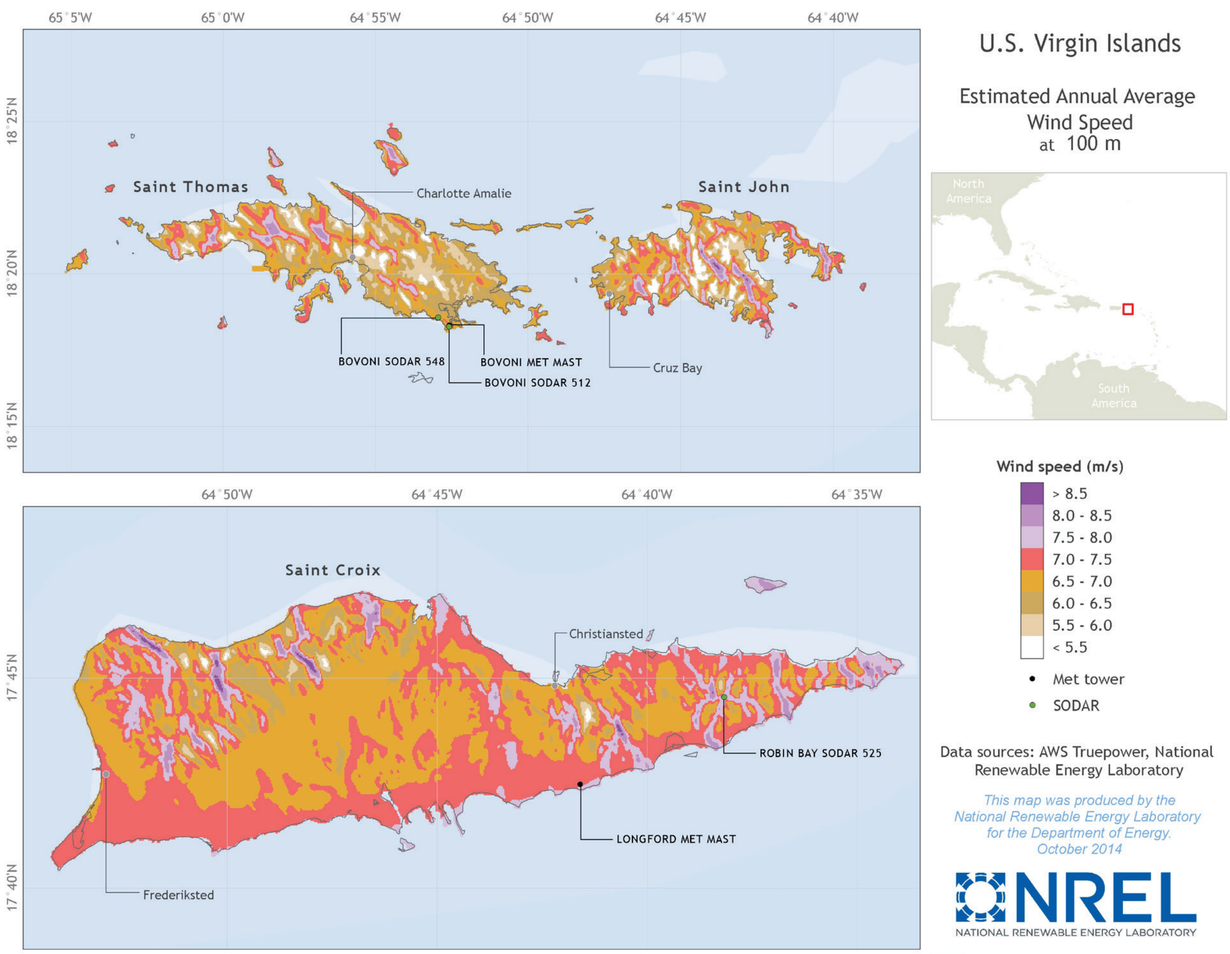

Figure 4. Estimated wind resource for St. Croix and St. Thomas

A high-level preliminary screening based on wind resource maps, local stakeholder input, and existing land use suggested the potential for wind power projects on the islands of St. Croix and on St. Thomas. Figure 4 indicates best wind resource areas on St. Croix are on the various ridges and the southern shore of the island. South and east of Christiansted, the topography is a series of elevated landscape features that are estimated to have average annual wind speeds of 7–7.5 meters per second (m/s) at 100 meters (m) above the ground. Such wind speeds are generally sufficient for successful deployment of utility-scale wind power, and with current technology, even lower average annual wind speeds can be viable (Lantz et al. 2012). These elevated areas are relatively free of residential populations; however, their development will be more logistically challenging than the flatter agricultural lands on the south shore of the island. Sites east of the former Hovensa refinery are promising, as they avoid the airport and are located in an industrialized area of the territory. Initial discussions with local residents and government officials indicate that locating wind turbines in relative proximity to the refinery site and the Renaissance industrial park will facilitate the development of public support for the first utility-scale wind development on St. Croix. Some initial discussions have suggested that historic or culturally sensitive sites may affect wind turbine installation on parts of the south shore of St. Croix. Should they exist, such sites would need to be properly identified, avoided, or mitigated.

Residents at the Lorraine Village Apartments in St. Croix did not object to the installation of a 100-kilowatt (kW) Northern Wind turbine (St. Croix Source 2013).

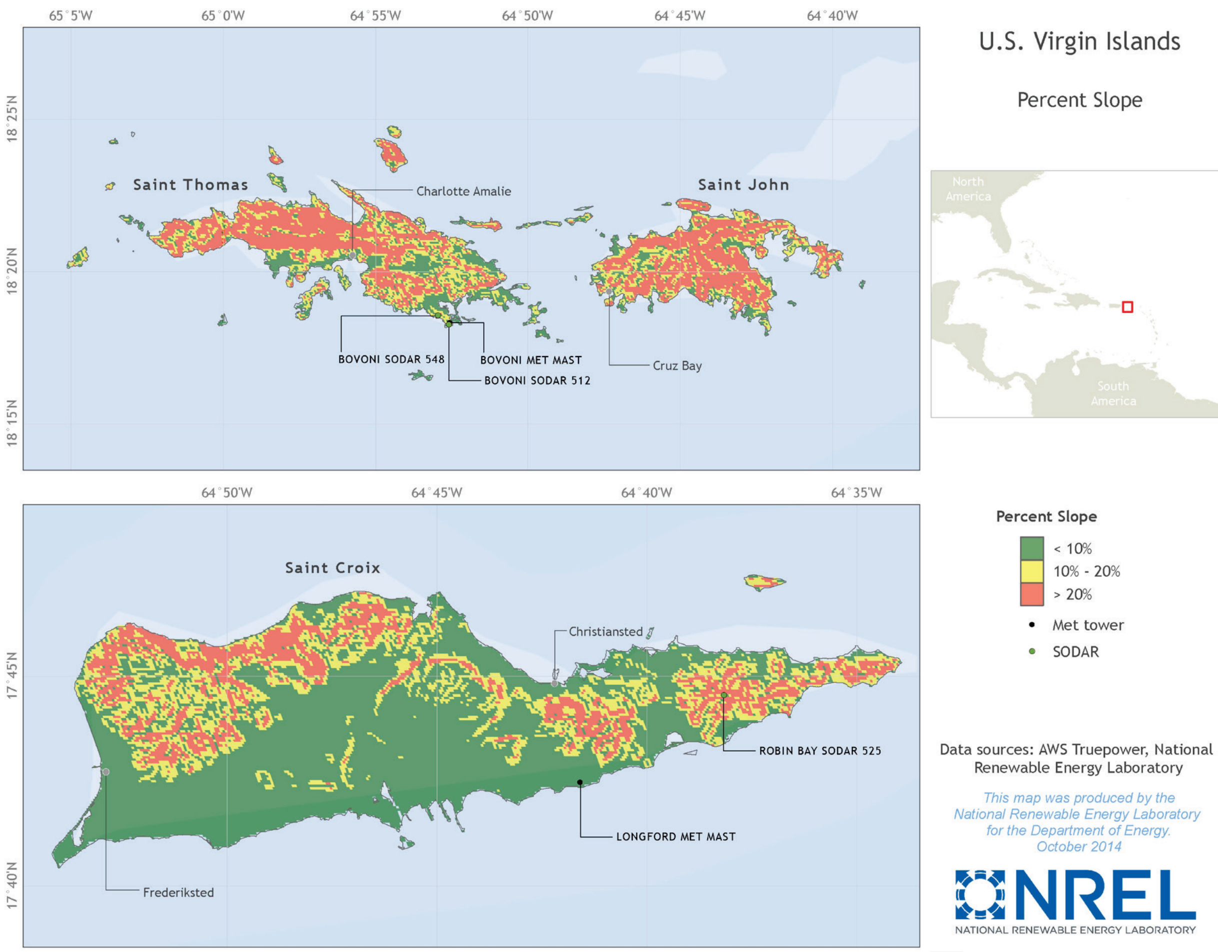

Figure 5. Areas of variable slope in USVI

On St. Thomas, meteorological measurements indicated the best wind resource areas are located on the elevated areas that make up the west-central portions of the island. These localities are a part of Crown Mountain and lie directly north of the Cyril E. King Airport. However, these sites have significant residential populations and terrain that is too steep for wind turbine installations (i.e., slopes in excess of 20%). Potentially viable wind resource areas were also identified in the central portion of the island east of Charlotte Amalie and west of Anna's Retreat. Again, however, these sites were unable to pass a preliminary screening because of slope restrictions and the presence of residential populations in the vicinity.

St. John was rejected as a site for industrial wind turbines because of its small power demand and the presence of the Virgin Islands National Park on the island. It is very unlikely that utility-scale development would be seen as acceptable in this environment.

Having eliminated some of the best wind resource sites from consideration, NREL analyzed sites that had viable wind resources and more compatible land use and geographic features. Bovoni, located on a peninsula on the southeast coast of St. Thomas, was observed to have estimated average annual wind speeds of 6.0–7.0 m/s (Figure 4) and was determined to have the best mix of wind resource and compatible land use. This site is an industrialized area and includes the St. Thomas landfill. Also, the peninsula proper has no residential presence south of the Route 30 corridor, and no environmental or wildlife issues were raised in initial discussions with local officials and stakeholders.

In addition to a favorable wind resource and land-use compatibility, the Bovoni site on St. Thomas has a handful of other attributes that make it a favorable location for utility-scale wind power. The higher overall demand for energy and higher peak capacity of the combined St. Thomas/St. John power system should make the integration of variable wind power more manageable than on the smaller St. Croix power system. The potential for future interconnection with Puerto Rico and the British Virgin Islands (VI WAPA 2011) could significantly reduce the challenge of balancing variable-output wind power in the St. Thomas/St. John system and may ultimately offer a second off-taker for a wind facility located on Bovoni point.

The south shore of St. Croix has several positive attributes for wind development. Although the wind resource is marginally poorer than Bovoni, the region should be much easier to develop. The topology of the southern shore of St. Croix is relatively flat, and an industrial port is located at the recently closed Hovensa refinery. The presence of the refinery and surrounding industrial sites also suggests that residents may be more open to the addition of utility-scale wind in the area. Note that the most of St. Croix’s southern shore has access to excellent trade winds that could support utility-scale wind development.

1.1 Technology

Choosing the appropriate turbine technology for a site is critical. In an island environment, additional factors limit the number and type of turbine models that are applicable. In the context of the Caribbean, hurricanes and tropical storms are factors that must be considered. On St. Thomas specifically, additional critical variables include a more challenging logistics environment, topography, and limited land availability. With these factors in mind, a limited number of utility-scale turbines employ anti-cyclonic technology and smaller technologies designed for simplified assembly, installation, and maintenance.

The increased probability of hurricanes occurring in the USVI can be reasonably anticipated to have an incremental cost impact, resulting from the need for more robust equipment and the increased risks borne by insurers and financiers. However, these hurdles should not preclude wind development in the USVI, as wind parks have been successfully developed throughout the Caribbean, including the recently completed 95-MW Finca de Viento Santa Isabel wind project that is just 100 miles away in southern Puerto Rico (Dallas 2012). As the wind industry continues to grow and mature globally, it is highly likely that more original equipment manufacturers will provide technical and financing solutions for hurricane risk. The continued development of the offshore wind industry is anticipated to result in new innovations that will further increase the resiliency of wind turbines in hurricane-prone regions around the world. These factors have been successfully addressed by other developers of utility-scale wind in the Dominican Republic, Puerto Rico, Jamaica, and other islands in the region.

Other considerations are the impact of the technology on the grid system and its operations. Some integration aspects are specific to a given turbine's technology and design characteristics. Modern variable-speed machines with full power conversion are capable of providing a great deal more grid support and grid services relative to constant-speed turbines with induction generators or even variable-speed machines with partial power conversion. Even with the most advanced turbine power electronics, however, high levels of variable renewable generation may also require significant changes in a utility's operational practices. These impacts should be modeled and analyzed before a wind farm is developed in the USVI.

1.2 Siting and Permitting

Ideal sites for wind power projects represent an optimization of multiple variables. At the highest level, a site must have a viable wind resource; an ability to interconnect and move power on the existing grid system; a credit-worthy consumer or off-taker; and the ability to satisfy all requisite local ordinances, permitting criteria, and environmental considerations. In addition, a given site must be logistically feasible in terms of moving the wind turbine equipment to the site and assembling and installing wind turbines. A given site must also be publicly acceptable and politically feasible.

In order to remain politically and publicly viable, wind power projects must maintain certain setbacks from occupied buildings, roads, airports, and other features. Often such setbacks are regulated by explicit requirements for the issues of concern (e.g., sound). Distances that generally meet the minimum requirements for potential nuisance issues, including sound and shadow flicker for turbines in other parts of the world, are often on the order of 500 m from occupied residences. To comply with typical safety standards, turbines are usually located 1 to 1.5 times the maximum turbine height from all structures, nonparticipating property lines, roads, high-voltage transmission lines, and other potential fall hazards.

Slope of the terrain is typically limited to less than a 20% grade. Projects typically cannot be sited in wetlands and must be set back from gas or power lines as well as certain communications towers and pathways.

Environmental regulations often emphasize wildlife such as birds and bats and habitat for protected species. When endangered species, migratory birds, or other protected wildlife are encountered on a particular site, impacts must be demonstrated to be below the requisite thresholds such that the relevant take permit(s) can be acquired to account for any incidental wildlife mortality. If protected habitat is affected, impacts below the requisite thresholds must also be demonstrated. Sites must be able to avoid or mitigate any impacts to significant cultural or historic resources.

The Bovoni peninsula represents a reasonable compromise in terms of wind resource, distance from residences, and developable terrain. Hurricane risk and variable terrain on the peninsula and on potential equipment transport routes add technical and logistical challenges but do not appear to represent insurmountable challenges. In addition, grid integration of wind power into the St. Thomas power system will present certain operational challenges, but based on experience in other islanded power systems, integration is generally expected to be manageable.

Access to Bovoni is also expected to be challenging and may impact turbine selection. Three potential options have been identified for moving wind turbine equipment, cranes, and other heavy equipment to the site:

- **A beach-side drop point on Bovoni Peninsula.** This drop point would involve bringing a barge or freight ship as close to shore as possible and then lifting the equipment with a vessel-mounted crane to shore, or in the case of a barge, potentially driving it off onto a temporary pier. This option was researched by a planned waste-to-energy developer and found to be technically feasible.
- **A drop point in Red Hook Bay.** Red Hook is a relatively small port but does have the capability of roll-on, roll-off cargo (VIPA 2012). Overland, the approach from Red Hook entails relatively few steep grades compared with the alternatives, but localized slopes in excess of 20% are present and there might also be two problematic corners.
- **A drop point just east of the peninsula and associated mangroves.** From research to date, this is the most viable solution for moving turbine components to the Bovoni point site.

Anecdotal evidence suggests that migratory birds may be an issue in certain areas of the southern shore of St. Croix. A detailed environmental impact assessment was beyond the scope of this report. Obviously, this is an issue that must be further assessed before wind projects can be developed at specific sites in St. Croix or St. Thomas.

2 Wind Resource Assessment Results

NREL, in conjunction with the USVI Energy Office, installed two met masts and three SODAR remote sensing devices to characterize the wind resources on St. Thomas and St. Croix. The Bovoni site was selected for its exposure to the predominant easterly winds as well as its high development potential (lack of residential areas). The south shore of St. Croix was selected for its exposure to the predominant winds as well as its distance from residences. These factors suggest that both regions have a higher likelihood of developing wind projects. Other considerations include electrical integration, transportation and logistics of turbine components and large cranes, and environmental impacts.

Observed wind speeds for both met masts were correlated with both Modern-Era Retrospective Analysis for Research and Applications (MERRA) (NASA 2013) and ERA-Interim reanalysis datasets (ECMWF 2006). The correlation method used was the matrix method, which produced the lowest mean absolute and bias errors. The correlation period for all datasets was from 1997 to 2014, which should represent the long-term average wind speeds at both sites. Once the correlation of the observed and long-term data was completed, a synthesized dataset from 1997 to 2014 was created. These synthetic data reflect the long-term trends in the reference datasets but adjusts the reference data to approximate the observed data.

Table 1, Figure 6, and Figure 7 show the observed annual average wind speeds for the Longford and Bovoni sites as well as the corrected long-term annual average wind speeds at each site. The data from both met masts was correlated to both MERRA and ERA-Interim long-term re-analysis datasets. The resulting annual average wind speeds suggest that the observed annual wind speed for 2013 for the Bovoni site was roughly 3% higher than both long-term datasets suggest. The Longford site annual average wind speed for 2013 was nearly equal to the long-term annual average wind speed, as predicted by the ERA-Interim dataset, and is roughly 1% higher than the MERRA dataset suggests.

Table 1. USVI Corrected Annual Average Wind Speeds by Location

Observation Location	2013 Observed Annual Wind Speed @ 58 m	Long-Term Corrected Annual Wind Speed @ 58 m	
		MERRA	ERA-Interim
Bovoni Met Mast	7.41 m/s	7.17 m/s	7.20 m/s
Longford Met Mast	7.17 m/s	7.12 m/s	7.18 m/s

Figure 6 and Figure 8 represent the monthly P10, P50, and P90 wind speeds for both locations. The P value is the probability of the wind speed exceeding this value in a given month or year. For example, a P90 wind speed of 6.5 m/s means that wind speeds will meet or exceed 6.5 m/s with a 90% probability (see Figure 7 and Figure 9). Developers use these values to protect themselves against potential shortfalls when a given year has lower than expected wind speeds.

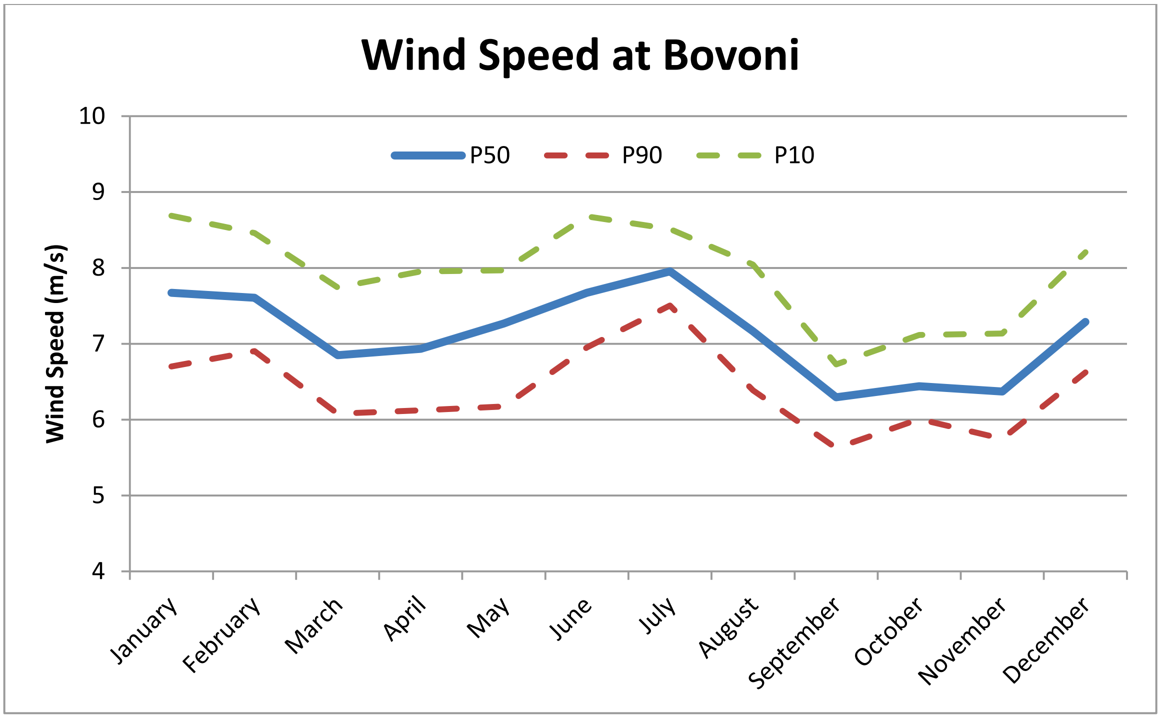

Figure 6. Monthly P10, P50, and P90 wind speeds for Bovoni

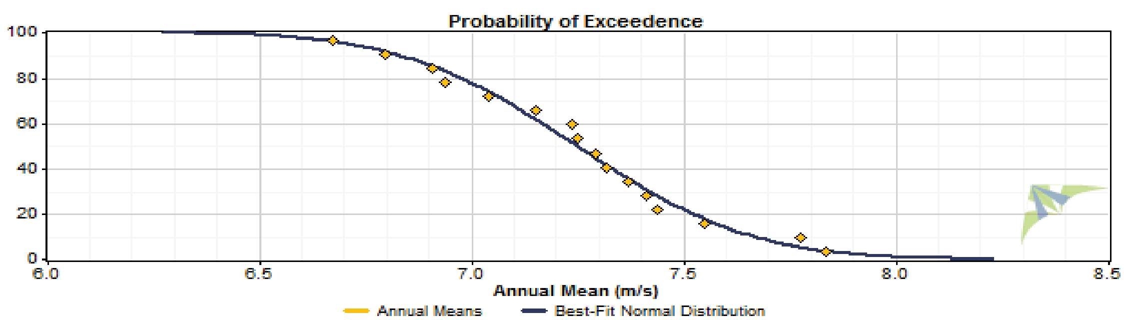

Figure 7. Bovoni annual average wind speed @ 80 meters—probability of exceedence

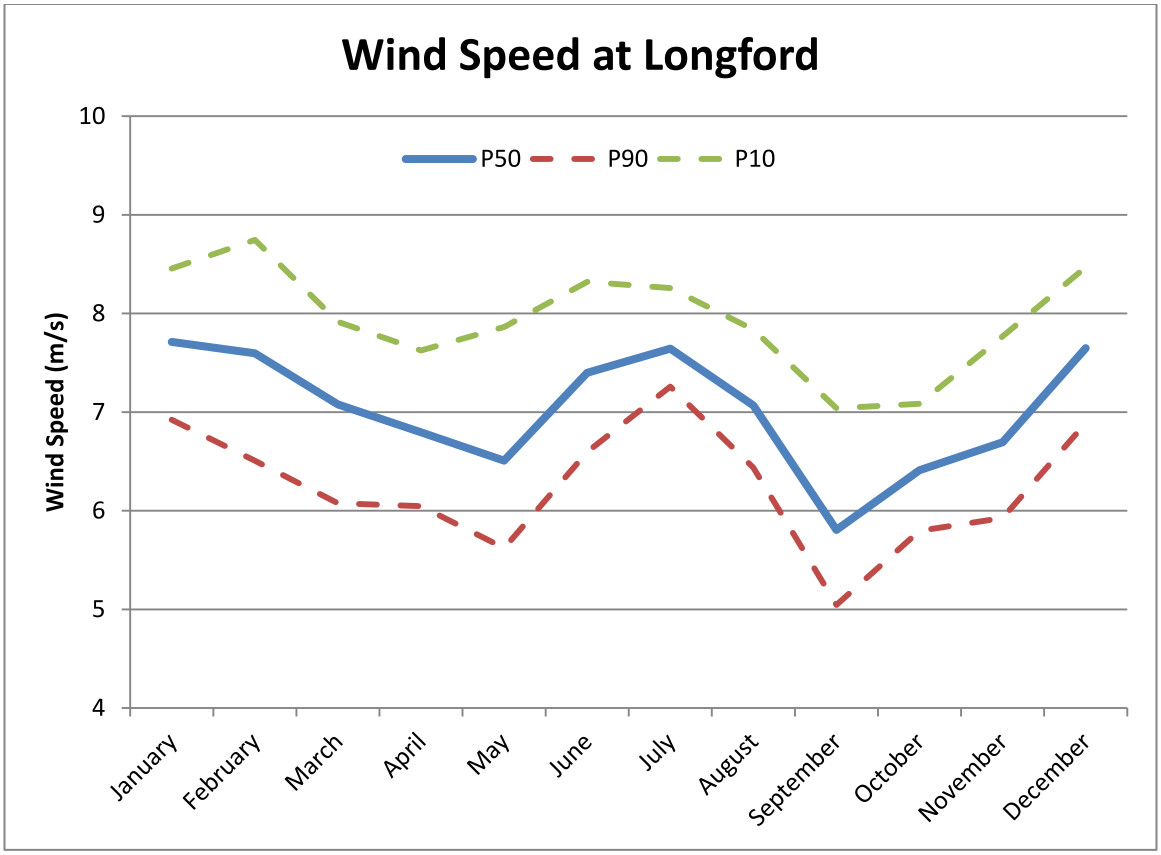

Figure 8. Monthly P10, P50, and P90 wind speeds for Longford

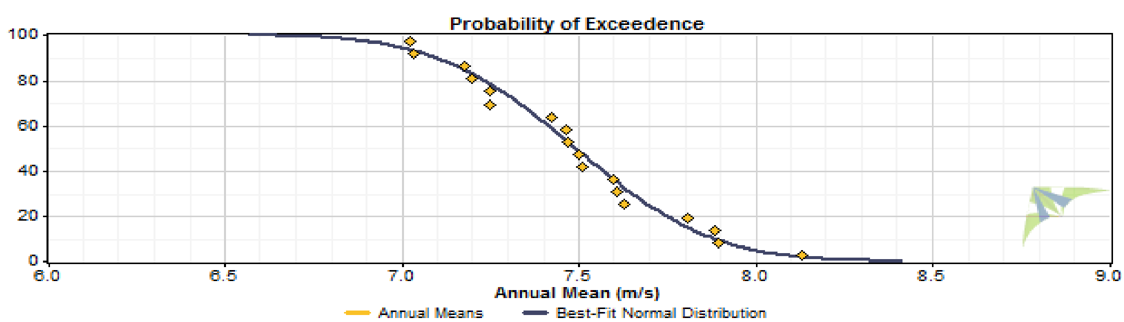

Figure 9. Longford annual average wind speed @ 80 meters—probability of exceedence

Of course, investment decisions are not made based on the speed of the wind at a given location; rather, they are based on how much energy will be produced from the available wind. The expected output of a given wind farm depends primarily on wind speeds and the characteristics of the wind farm (layout, technology, etc.). The different turbine technologies react differently to fluctuations in wind speed. The magnitude of this fluctuation is mainly dependent on the size of the generators and the size of the turbine blades. Specific power is defined as the electrical nameplate capacity of a turbine in watts divided by the swept area of the rotor in square meters. The lower the specific power, the higher the amount of energy produced for a given site or wind speed (DOE 2013, p. 45).

2.1 Bovoni, St. Thomas

Figure 10 shows the measurement locations of SODAR remote sensing units and the 60-m met mast. The entire Bovoni peninsula has steep slopes, which classifies the terrain as complex.

Figure 10. Bovoni Peninsula wind measurement locations

Source: 2014 Google, Map Data

2.1.1 Background on Bovoni

Bovoni, or Long Point, is bordered to the east by Jersey Bay and to the west by Bovoni, Bolongo, and Stalley bays. The land that makes up Bovoni is currently used for a variety of public and private purposes, including a landfill, firing range, wastewater treatment facility, asphalt plant, and communications tower. Private landowners control a significant portion of the land. However, there are no residential structures on the peninsula proper. There are some residences on the south side of Route 30, which passes directly north of the peninsula and immediately west where the peninsula joins the mainland of the island.

At present, the Bovoni Landfill is noncompliant with U.S. Environmental Protection Agency regulations and is under orders to close (EPA 2014). In March 2012, Virgin Islands Waste Management Authority contracted Island Roads Corporation of St. Thomas to begin constructing a landfill methane collection and power generation facility on the peninsula. This 850-kW landfill gas facility is currently the largest single renewable energy resource in the territory. (The combined distributed solar generation is estimated to be 15 MW; 10 MW of utility-scale solar should be in place by 2015.)

Input from local sources indicates that no other near-term or long-term changes in use are anticipated for the peninsula. This suggests, at least preliminarily, that the future development of wind power is not likely to conflict with other potential uses. At least one landowner has expressed interest in seeing wind development occur at the site and has provided access for the placement of wind resource assessment equipment on the site.

Access to Bovoni is expected to be challenging. However, at least two potential options have been identified for moving wind turbine equipment, cranes, and other heavy equipment to the site. These routes are discussed in detail in previous NREL studies (Lantz et al. 2012, Section 6.3.1).

2.1.2 Bovoni Met Tower

A 60-m NRG HD tubular guyed tower was installed on Dec. 13, 2012, near the southern point of the Bovoni peninsula. Full details of the instrument types, calibration coefficients, installed heights, and commissioning report can be found at the NREL Measurement and Instrumentation Data Center (MIDC) website (NREL 2014b). The tower was decommissioned Aug. 25, 2014, and produced roughly 20 months of data. All channels were recorded at 1-minute intervals; the logger also shows solar insolation data.

Figure 11 shows the frequency of winds by direction. The wind rose shows a unidirectional flow from the predominant easterly trade winds. This unidirectional wind combined with the north-south orientation of the Bovoni peninsula produces a great opportunity for a wind farm, as turbines can be positioned much closer together than if the predominant winds were parallel with the peninsula.

Figure 12 shows the frequency of wind speeds as observed by the Bovoni met mast. The Weibull k factor describes the shape of the wind speed distribution. The measured k value for all observations at 58 m is 3.5, which is expected for a coastal location such as the Bovoni site.

Figure 13 shows the measured wind shear profile of the Bovoni met mast for the entire 20-month observation period. The wind shear is very low, which means that the difference in wind speed near the surface of the ground is very similar to the wind speed at taller heights such as 58 m as measured by the met mast. Because of the low shear when estimating turbine output, we recommend that developers contact turbine suppliers to obtain turbine specific power curves.

Figure 14 shows the monthly wind speed averages as observed by the Bovoni met mast in blue and the long-term MERRA monthly wind speed estimates in black. The MERRA-estimated long-term monthly averages are much lower than the observed monthly average wind speeds by the Bovoni met mast. However, the trend in the seasonal fluctuation of wind speed is very similar. In general the strongest winds occur most consistently in the summer; significantly strong winds occur in the late winter.

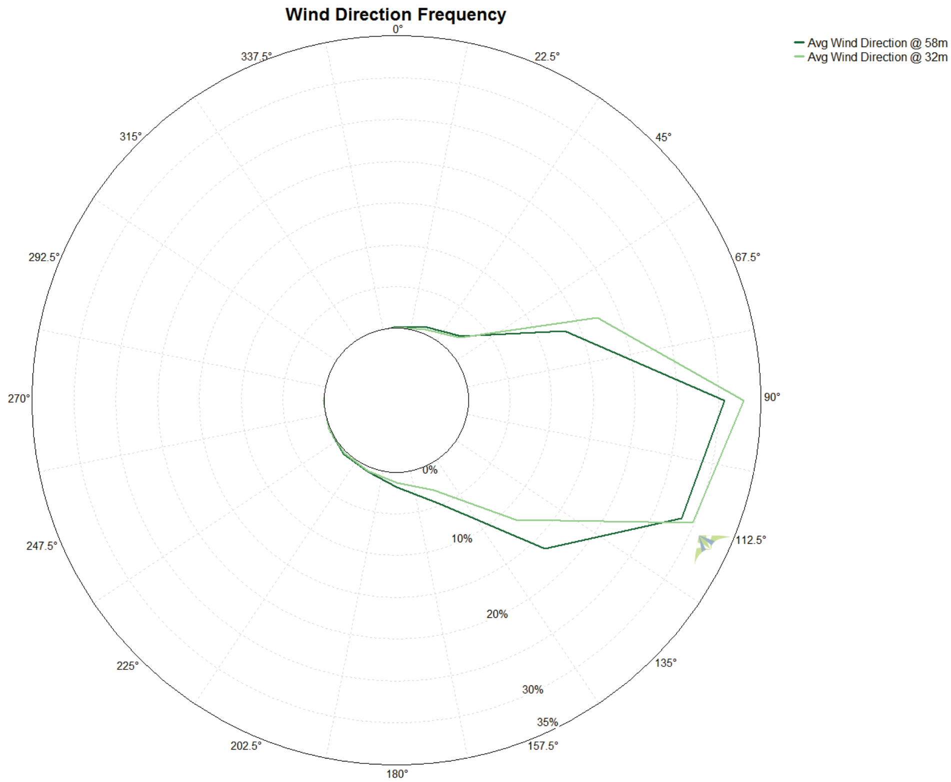

Figure 11. Bovoni met mast wind frequency rose

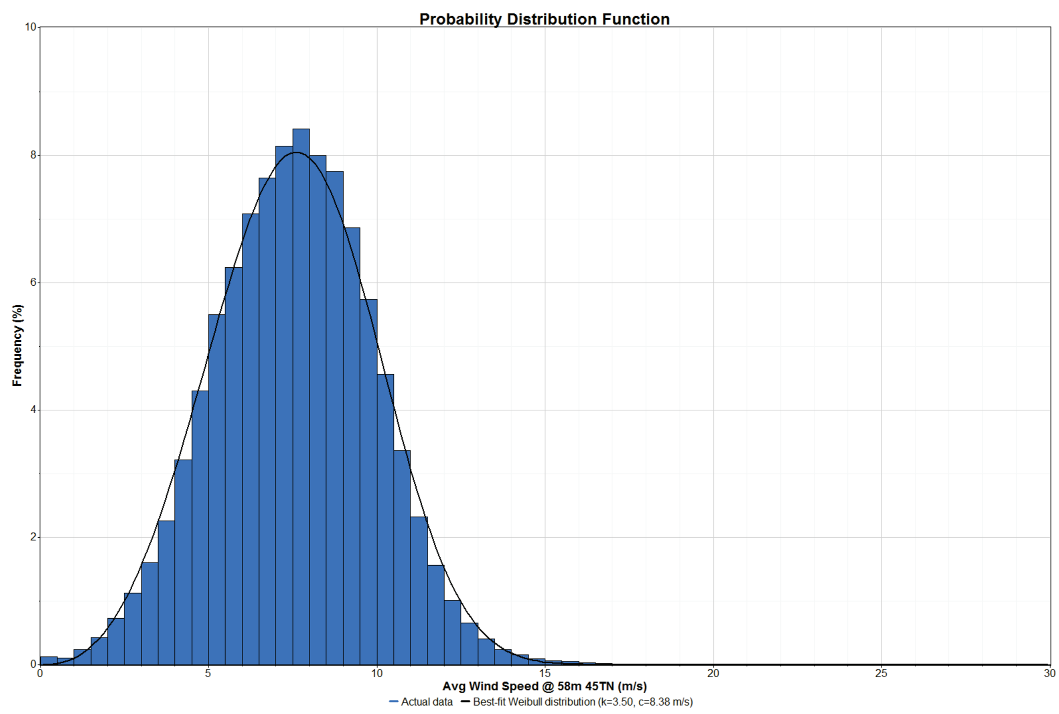

Figure 12. Probability distribution function of wind speeds at the Bovoni met mast

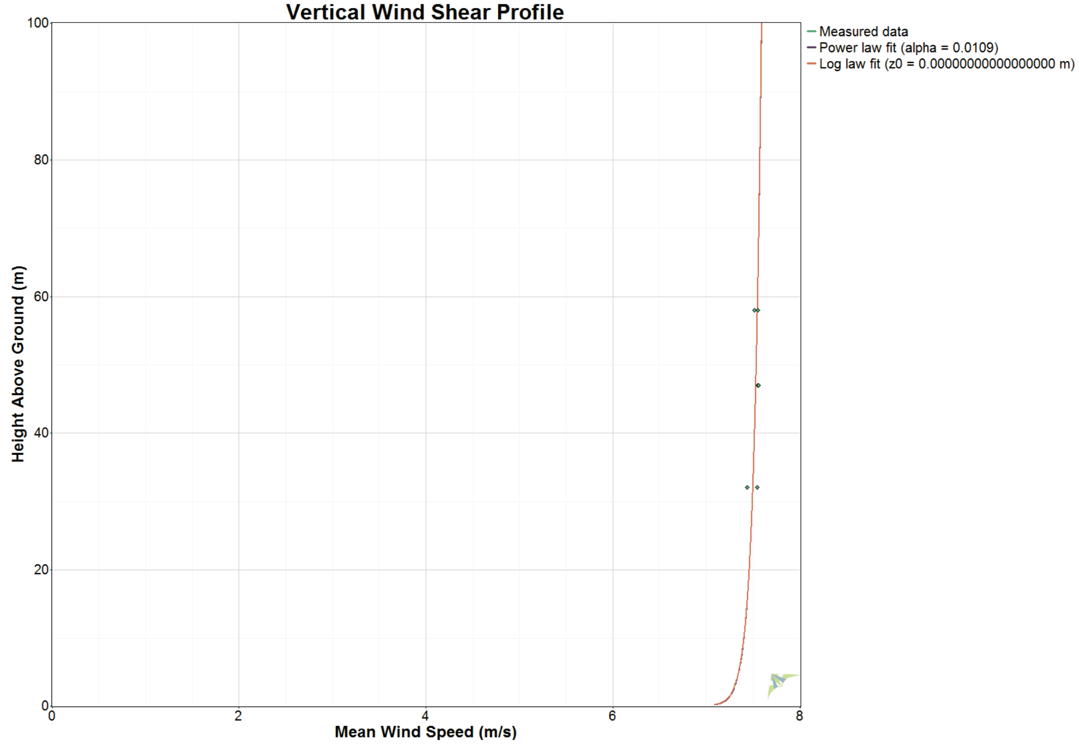

Figure 13. Bovoni met mast measured wind shear

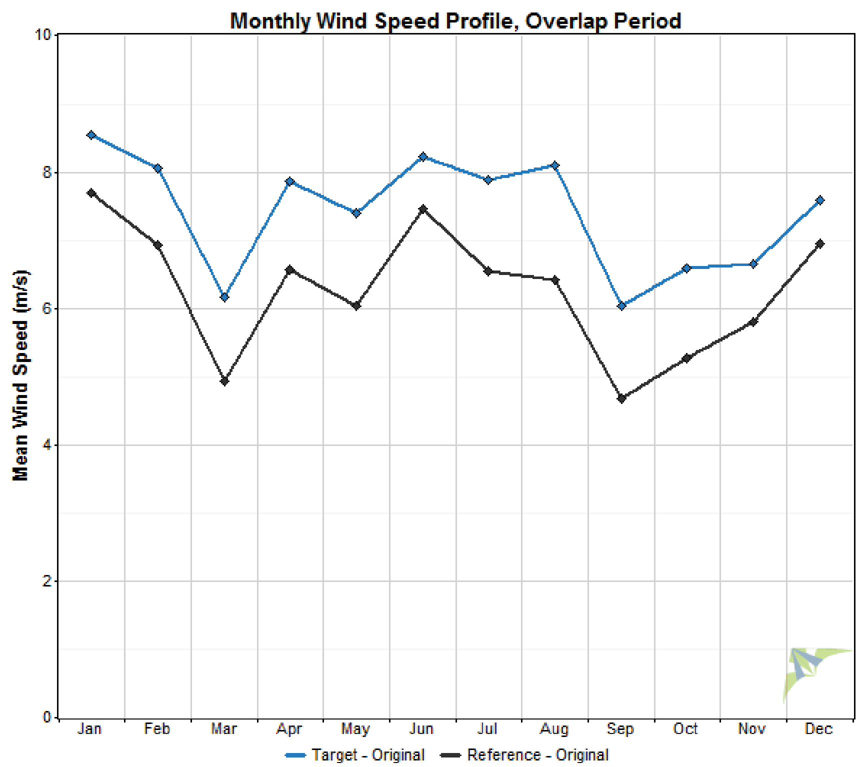

Figure 14. Observed (blue) and MERRA (black) monthly wind speed profiles at Bovoni met mast location

Figure 15 shows the measured turbulence intensity at the Bovoni met mast was significantly below the lowest turbulence intensity threshold designated by the International Electrochemical Commission 61400-1 3rd edition standard (IEC 2005). Low turbulence intensity has varying effects on wind turbine output depending on wind speed. Developers should consult with turbine manufacturers, as various turbines react differently to these low turbulence intensity conditions (Clifton et al. 2013). It should also be noted that various turbine manufacturers have different approaches to mitigating the risk of hurricanes and extreme wind speeds. Typically, turbines with smaller rotors have been employed, as these are usually rated for higher extreme wind speeds. Smaller rotors typically decrease the annual energy production for a given wind resource which will negatively impact the financial feasibility of a project. Some manufacturers, such as Vestas, offer hurricane mitigation solutions that allow the installation of a larger rotor for a given site, which increases the energy production of a site (Lantz et al. 2012). Turbine selection and the financial risk associated with various turbine options should be considered early in the development of a project in the USVI.

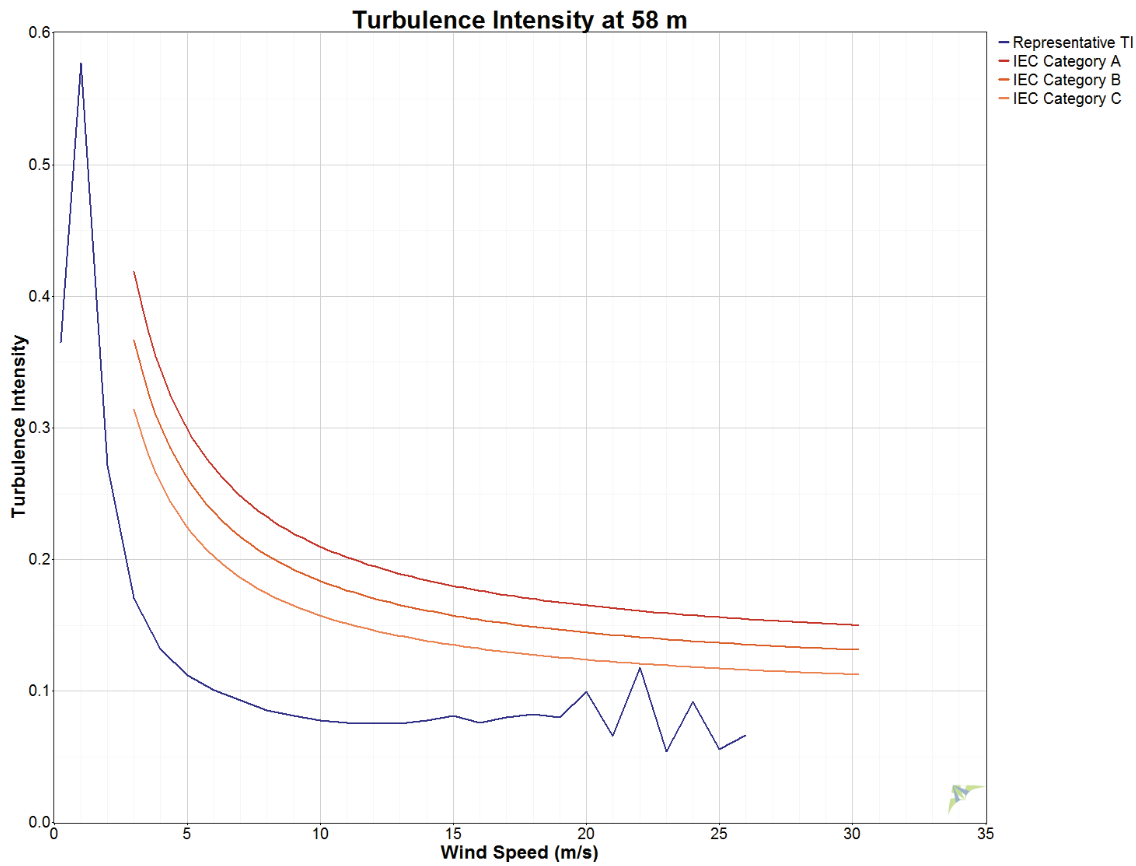

Figure 15. Bovoni measured turbulence intensity

Figure 16 below shows the diurnal profile of the wind speed at the Bovoni met mast. Times are local time. This plot shows that the strongest winds occur during the middle of the day with lower winds at night. Careful consideration should be given to the electrical integration study, as the plot below suggests that the average wind contribution to the electricity grid decreases from noon until after sunset. This down ramp combined with an expected increase in demand from electricity consumers may require the dispatchable generation to increase power production at a faster rate than the generation units can increase their output.

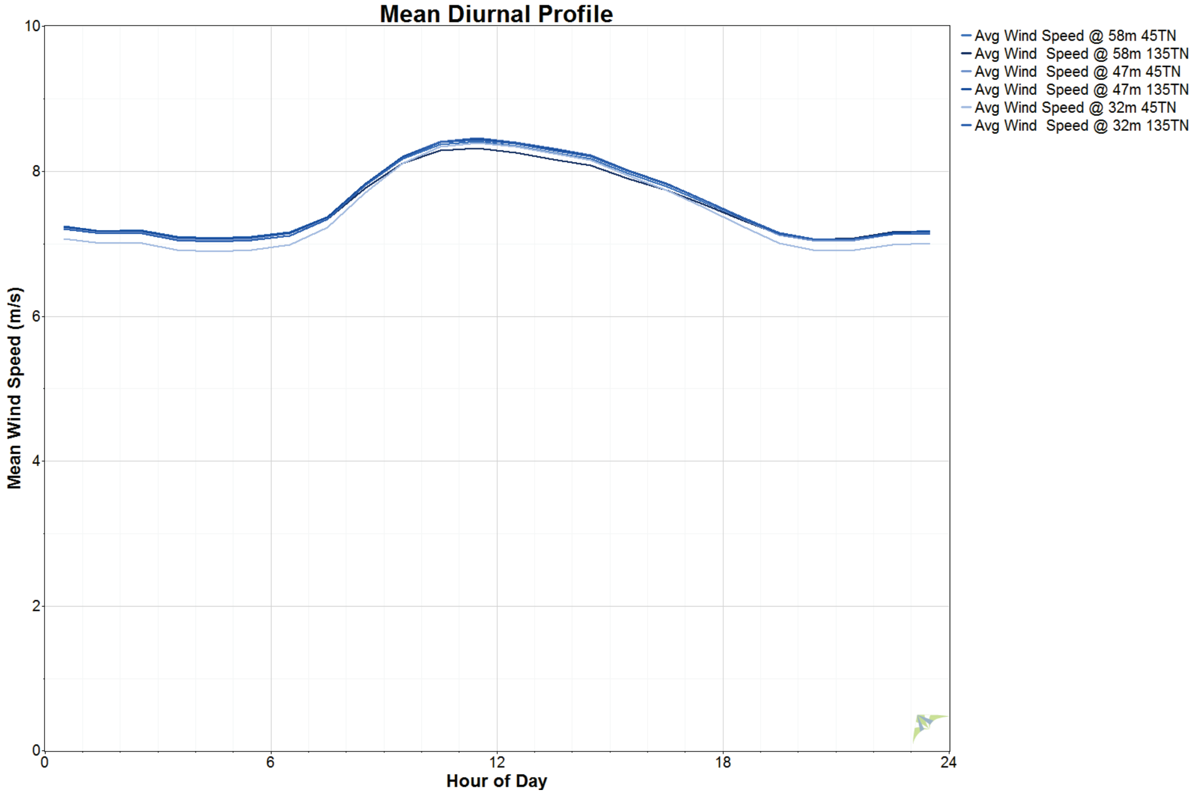

Figure 16. Observed diurnal wind speed profile at the Bovoni met mast

Table 2 shows the 2013 observed annual wind speed and corrected annual average wind speeds as predicted using the matrix method (RES 2004) for correlation. The resulting synthesized annual average wind speeds suggest that the observed annual wind speed for 2013 for the Bovoni site was roughly 3% higher than both long-term datasets suggest.

Table 2. Bovoni Met Mast Long-Term Corrected Wind Speed

Observation Location	2013 Observed Annual Wind Speed @ 58 m	Long-Term Corrected Annual Wind Speed @ 58 m	
		MERRA	ERA-Interim
Bovoni Met Mast	7.40 m/s	7.17 m/s	7.20 m/s

Figure 17 shows the monthly average wind speed and the estimated variability for the predicted wind speeds for each month.

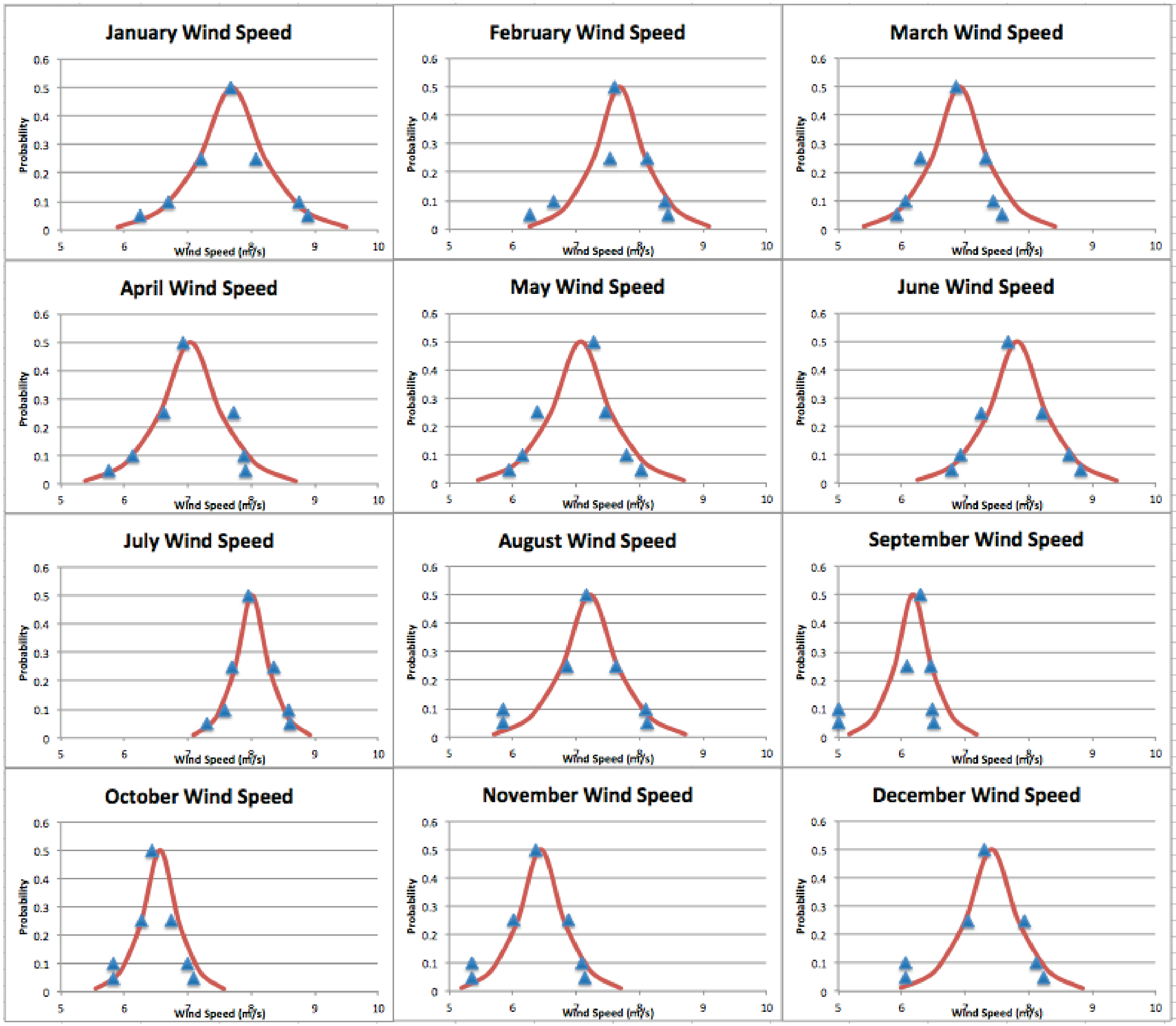

Figure 17. Monthly average wind speed and the estimated variability for the predicted wind speeds for each month

2.1.3 SODAR Installations at Bovoni

Two remote sensing SODAR units were deployed on Bovoni peninsula along with the met mast. SODAR 512 was deployed roughly 100 m south of the met mast to assist in estimating wind shear. The complexity of the terrain at the Bovoni peninsula causes the SODAR unit to record lower than actual wind speeds (Rovers 2012). Table 3 shows the 2013 measured average wind speeds at 60 m above ground level as well as the measured power law exponents. As previously stated, the wind shear at the Bovoni met mast was very low but the measured wind shear exponent at SODAR 548 is much higher than the measured wind shear at SODAR 512 or the met mast. This is expected as the predominant easterly winds will be affected significantly by the upwind terrain for sites on the northern part of the Bovoni peninsula.

Table 3. Bovoni Observed Wind Speed and Shear

Observation Location	2013 Observed Annual Wind Speed @ 58 m	2013 Observed Power Law Exponent @ 58 m
Bovoni Met Mast	7.40 m/s	0.0157
SODAR 512[a]	6.68 m/s	0.0495
SODAR 548[b]	6.37 m/s	0.133

[a] Complex terrain biases measured wind speeds lower than actual

[b] Observation period July 2012–July 2013

2.1.4 Bovoni Wind Farm Production Estimates

Four key elements are necessary to estimate power production from a wind facility:

1. Wind resource potential
2. Project size or capacity (in megawatts)
3. The respective wind turbine power curve, a function that demonstrates the energy produced at a given wind speed
4. Estimated losses likely associated with a given project.

Suitable turbines for the Bovoni site range from 275-kW units to multi-megawatt units. The two Vergnet turbines and two Vestas turbines were selected based on the fact that these manufacturers are currently operating equipment in the Caribbean (Vergnet 2014; Vestas 2011). Moreover, they are convenient examples of the midsize to large turbines available on the market. Similar turbines, such as the Vestas V112 3.0 MW, GE 1.6-100, Siemens 2.3-113 or 2.3-101, or Nordex N117-2.4 MW, among others, could be expected to produce comparable results to one another with the exception that larger rotor machines capture much more energy per turbine. Other suitable turbine options include offerings from Vergnet with 275-kW and 1-MW models that are designed specifically for hurricane-prone areas as well as being much more easily constructible than larger utility-scale units.

Based on turbine type the installed capacity ranges from 5.5 MW to 13 MW. Figure 18 and Table 4 illustrate the wide range of potential turbine types and associated annual energy production estimates.

Figure 18. Potential turbine locations on Bovoni point, assuming a turbine with an approximately 100-m rotor

Source: 2012 Google, Map Data

Table 4 shows estimated wind speeds and capacity factors as extrapolated from the met mast location. As previously discussed, the met mast placement resulted in one of the highest wind resource locations on Bovoni point and the average wind speed and turbine production across the peninsula will be lower than those in the table below. This table is meant to serve as a comparison between turbine models and their performance.

Table 4. Representative Estimated Annual Productivity for Various Turbines on Bovoni Point at the Met Mast Location

Turbine	Hub Height Wind Speed (m/s)	Net AEP* (MWh/yr)	NCF* (%)
GE 1.6-100 (80m)	7.34	6,308	45
Vestas V100 - 1.8 MW 60Hz (80m)	7.34	6,575	41.4
Vestas V100 - 2.0 MW (80m)	7.34	6,821	38.9
Nordex N117/2400 (91m)	7.35	9,400	44.7
Siemens SWT-2.3-113 (99.5m)	7.35	9,493	47.1
Vergnet GEV HP LWS (70m)	7.33	3,036	34.7
Vergnet MP C/R (55m)	7.31	662	27.5

Figure 19 shows a wind map of the Bovoni Peninsula with six Vestas V100-1.8 turbines. This wind map illustrates the significant decline in the strength of the wind resource from south to north. This preliminary layout was created to illustrate the decrease in wind resource for the northern end of the Bovoni site. Developers should take note of this and be ready to install a met mast closer to the northern end of the site to further understand this gradient of wind speed if necessary.

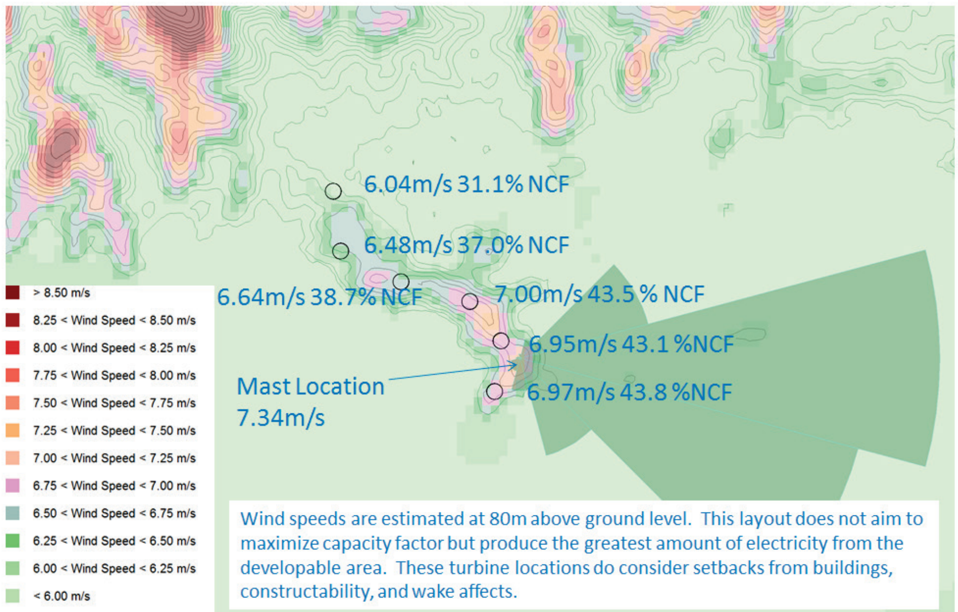

Figure 19. Wind map of the Bovoni peninsula with potential turbine locations

Note: Estimates shown here do not account for terrain, roughness, wake losses, or localized differences in wind resource. The number of turbines in each case was determined by local topography and turbine spacing of roughly three rotor diameters between turbines. Capacity factor is a means of illustrating the average energy production of a turbine or plant as a share of its theoretical potential over the course of a year. Capacity factors shown here are a function of the wind resource and the expected performance of the turbine models listed here.

Table 5 illustrates the variation in annual energy production of turbines over the Bovoni site as shown in Figure 19.

Table 5. Vestas V100-1.8 AEP Estimates for Bovoni

Turbine Type	Mean Free (m/s)	Net Yield (MWh/yr)
V100 1.8 80m (northernmost turbine)	6.04	4,903
V100 1.8 80m	6.48	5,834
V100 1.8 80m	6.64	6,112
V100 1.8 80m	7.00	6,861
V100 1.8 80m	6.95	6,800
V100 1.8 80m (southernmost turbine)	6.97	6,911

2.2 Estate Longford, St. Croix

One 60-m NRG HD tower was deployed at the Estate Longford site and one SODAR remote sensing unit was deployed atop a high peak near Robin Bay (see Figure 20). The met mast collected data from Dec. 13, 2012, to Dec. 20, 2013, while the SODAR collected data from Dec. 13, 2012, to Dec. 18, 2013. The raw data, commissioning reports, and calibration certificates are available on the NREL MIDC website (NREL 2014b).

Figure 20. St. Croix measurement locations

Source: 2012 Google, Map Data

2.2.1 Longford Met Mast

One 60-m NRG HD tubular guyed tower was installed on December 13, 2012 on the southern edge of St. Croix. Full details of the instrument types, calibration coefficients, installed heights, and commissioning report can be found at the NREL MIDC site (NREL 2014b). The tower was decommissioned Dec. 20, 2013, which produced roughly 12 months of data. All channels were recorded at 1-minute intervals because the logger also recorded solar insolation, which required the higher resolution data. Data recovery for the 58-m anemometer oriented at 45 degrees relative to true north was only 90.4% for the observation period; the majority of the bad data were recorded in November and December 2013. Care should be taken when performing quality control measures, as these erroneous data skew wind speed and energy production estimates if not properly controlled.

Figure 21 shows the frequency of wind direction as observed by the Longford met mast. The wind rose shows a unidirectional flow from the predominant easterly trade winds. This unidirectional wind from the east causes a potential wind farm at the Longford site or a similar site along the southern shore to have wider spacing of turbines because the coast is oriented roughly east to west. Turbines will need to be spaced farther apart than if the turbines were oriented north to south, as the wakes generated by the turbines not only affect the energy production of the turbines, but cause turbulence that can damage the downwind turbines. Developers must coordinate with turbine manufacturers to determine the appropriate spacing of turbines, as the spacing will determine the total number of turbines and the amount of land to be leased.

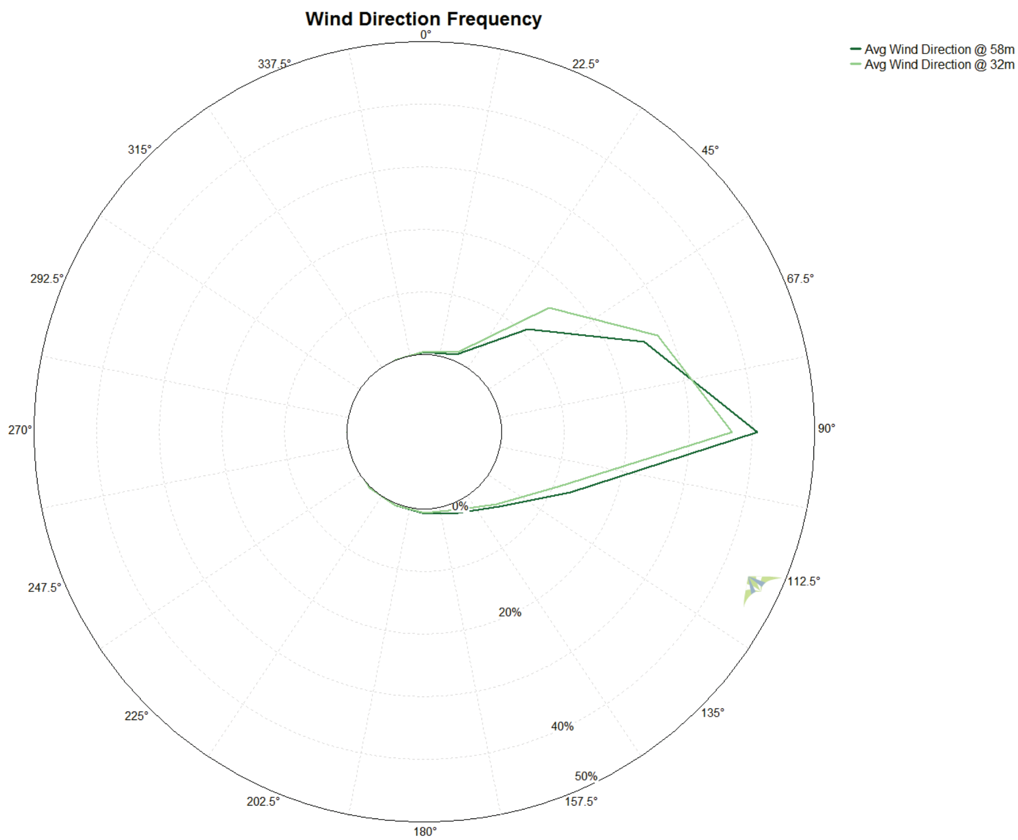

Figure 21. Longford met mast wind frequency rose

Figure 22 shows the distribution of wind speeds as observed by the Longford met mast. The Weibull k factor describes the shape of the wind speed distribution. The measured k value for all observations at 58 m is 3.16, which is expected for a coastal location such as the Longford site.

Figure 23 shows the wind shear profile as observed by the Longford met mast. The observed power law exponent is 0.154, which reflects the fact that a large portion of the winds at the Longford site are affected by the upwind terrain. Wind shear values are typically lower in coastal areas because of the lack of upwind terrain and roughness. This higher shear value may cause taller turbines to be more cost effective, because the energy production of a turbine increases as the hub height increases. Again, specific turbines should be considered carefully when estimating the financial feasibility of a project.

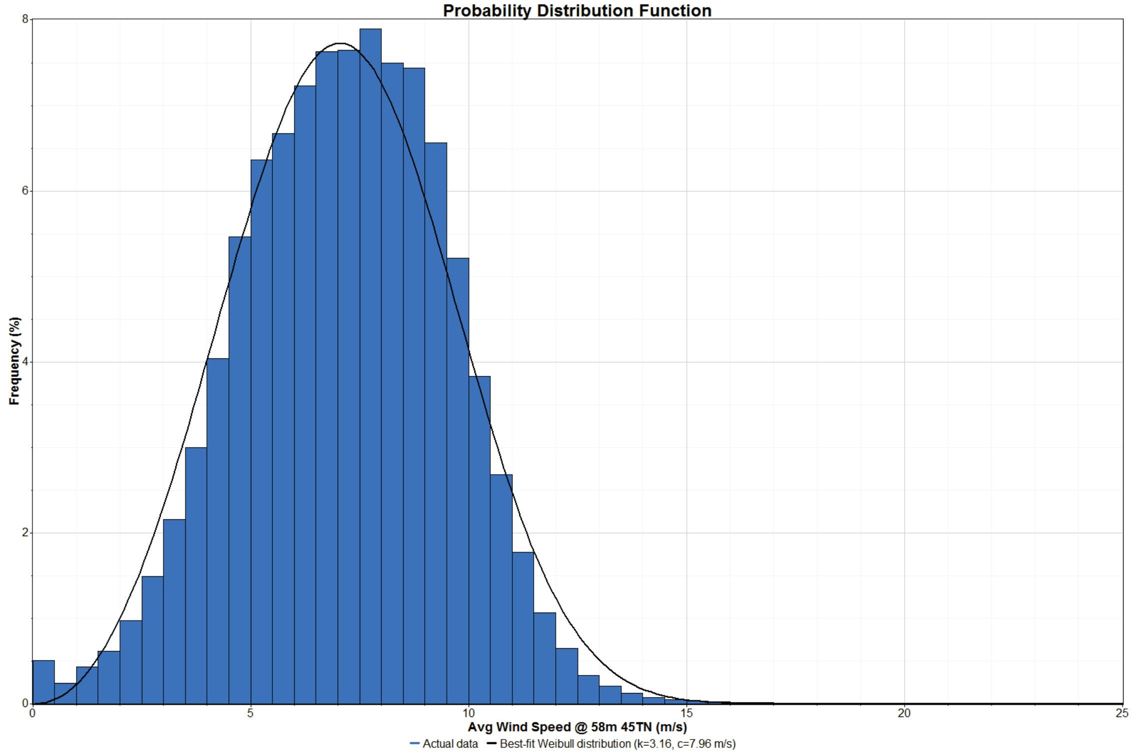

Figure 22. Observed probability distribution of wind speeds at the Longford met mast

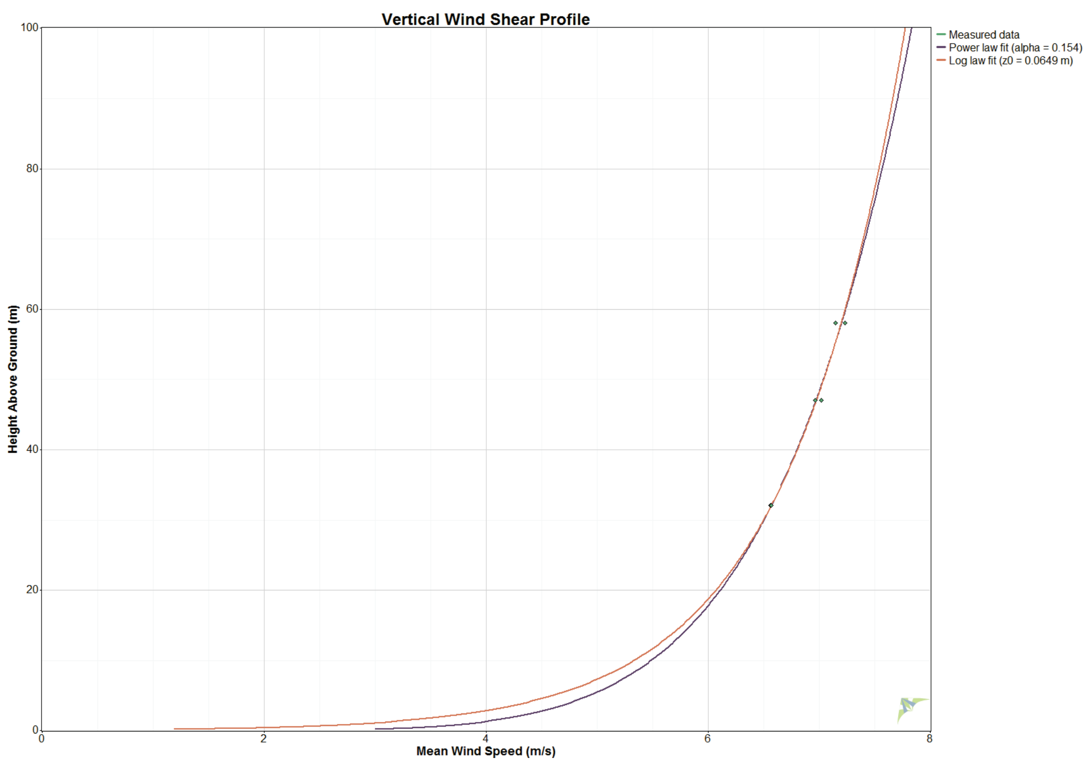

Figure 23. Observed average wind shear at the Longford met mast

Figure 24 shows the monthly wind speed averages as observed by the Longford met mast in blue and the long-term MERRA monthly wind speed estimates in black. The MERRA estimated long-term monthly averages are very similar to the observed monthly average wind speeds by the Longford met mast and the trend in the seasonal fluctuation of wind speed is very similar. In general the strongest winds occur most consistently in the summer and significantly strong winds occur in the late winter.

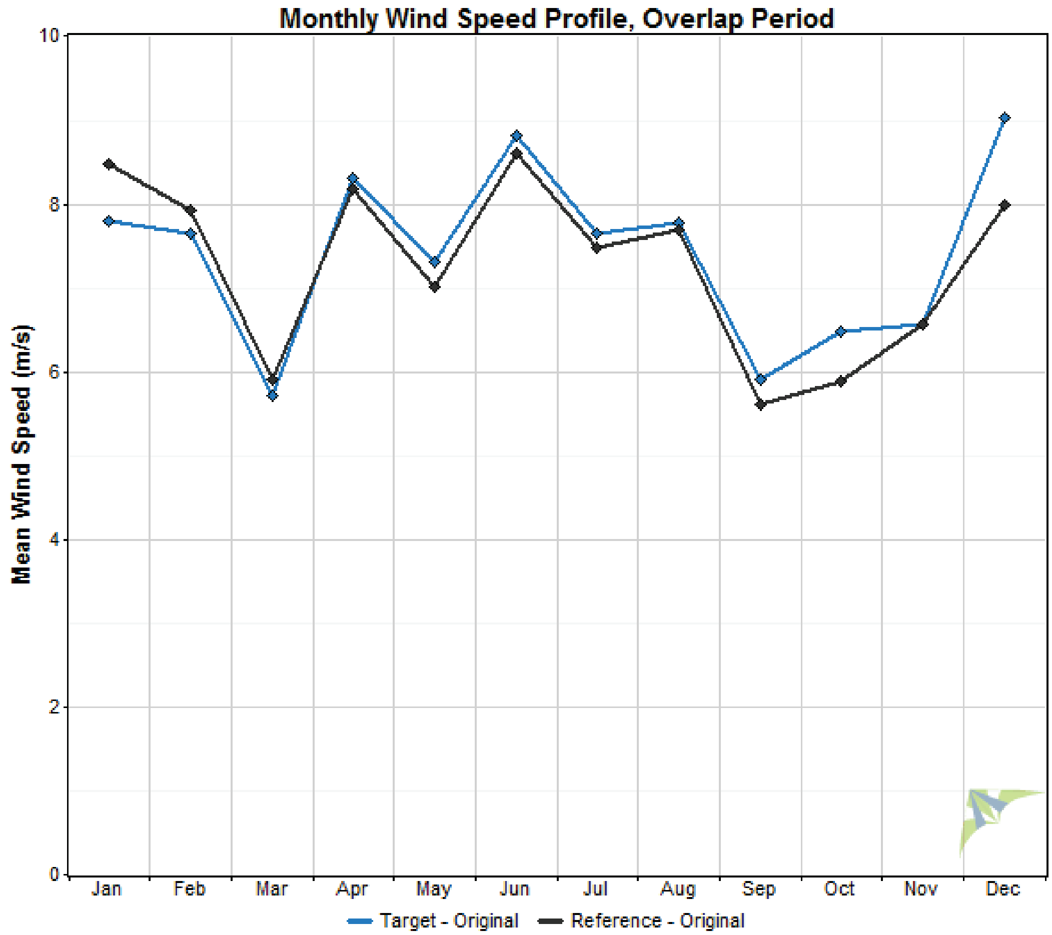

Figure 24. Observed (blue) and long-term corrected (black) monthly wind speed averages at the Longford met mast location

Figure 25 shows the average turbulence intensity binned by wind speed. The recorded turbulence above 10 m/s is extremely high and unexpected for the topography of the Longford site. Further investigation revealed that fraction of events equal to or above 13 m/s represented less than 2% of all records from the 12 months of observed data, and less than 1% of records were equal to or above 15 m/s. This is a unique instance, as the statistical significance of the wind speed occurrences at industry standard wind speeds (15 m/s and 20 m/s) may misrepresent the turbulence at the Longford site. Again, collaboration with turbine manufacturers is critical to selecting the appropriate turbine.

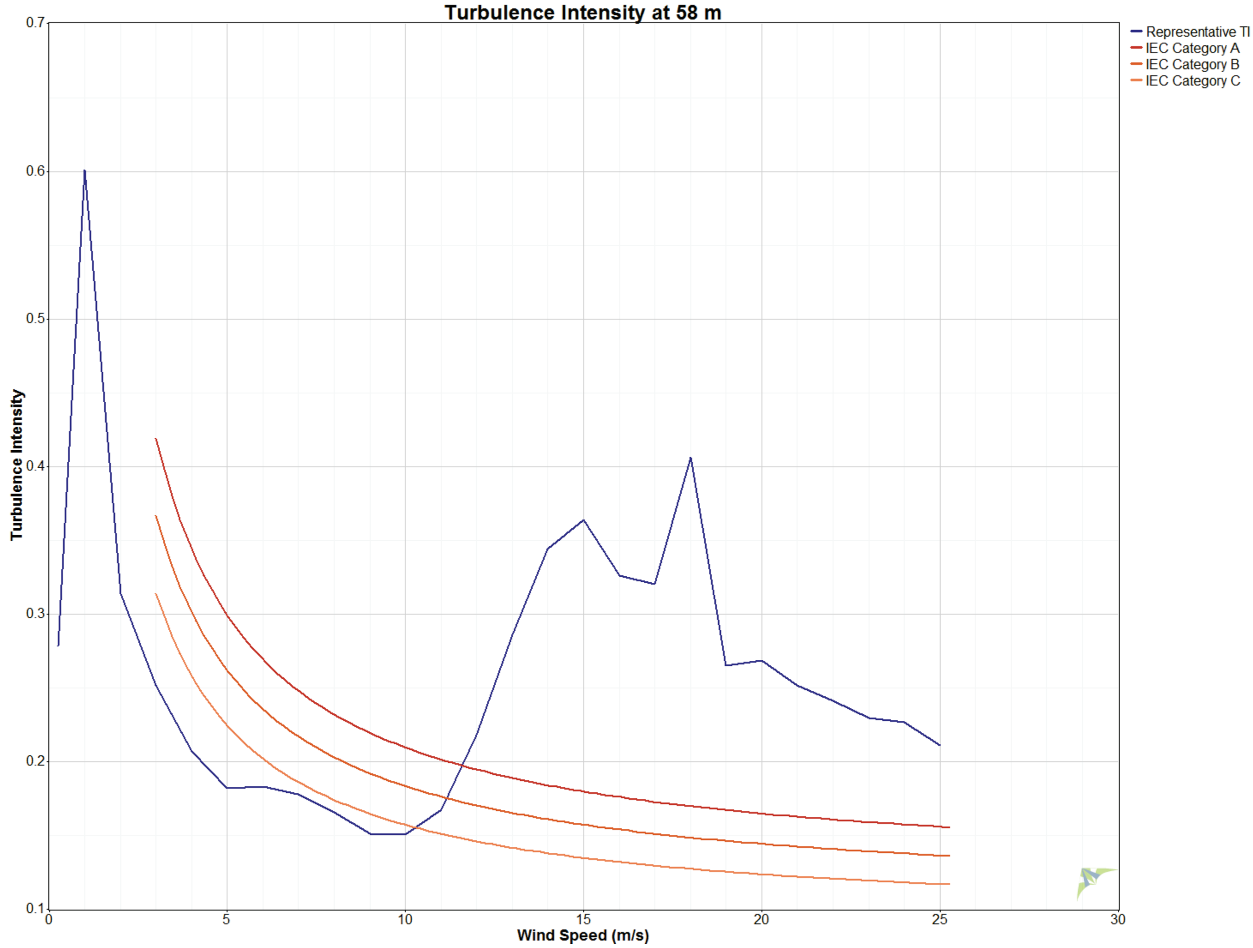

Figure 25. Observed turbulence intensity at the Longford met mast

Figure 26 shows the observed fluctuations of the average wind speed versus time of day at the Longford met mast location. The time on the x-axis is local time . This plot shows that the strongest winds occur during the middle of the day with lower winds at night. Careful consideration should be given to the electrical integration study, as the plot suggests that the average wind contribution to the electricity grid decreases from noon until after sunset. This down ramp combined with an expected increase in demand from electricity consumers may require the dispatchable generation to increase power production at a faster rate than the generation units can increase their output.

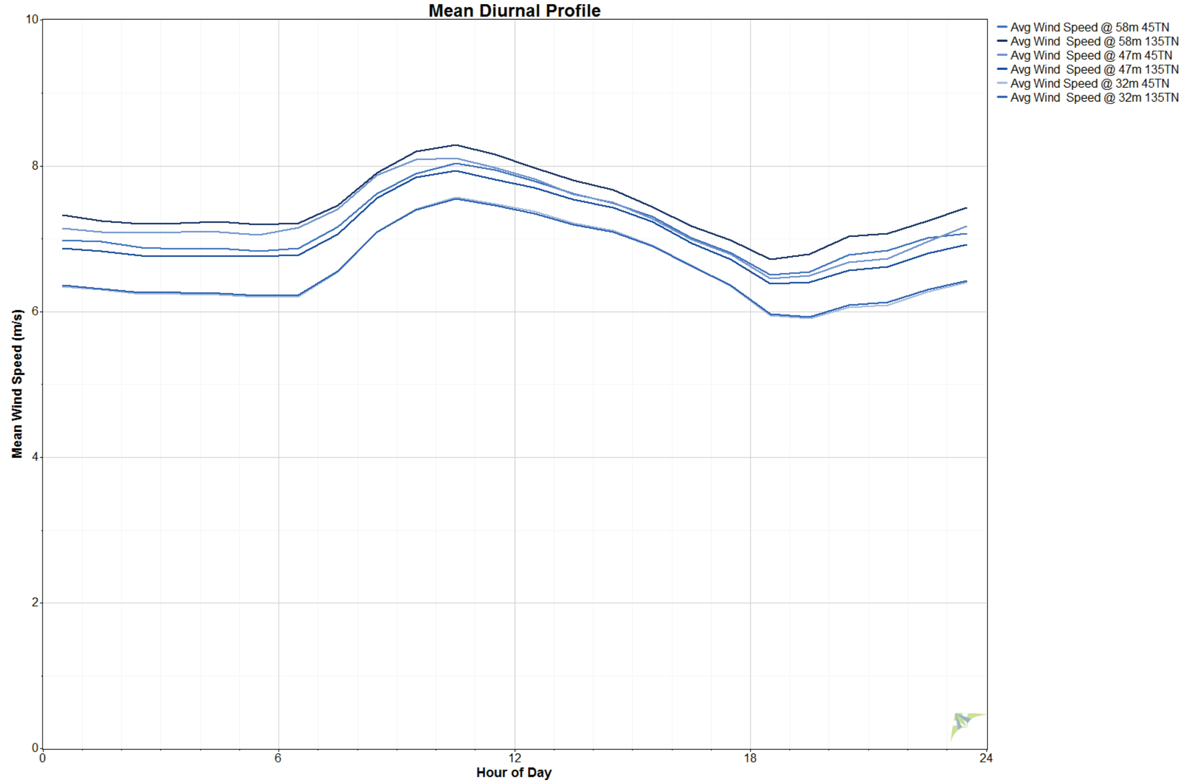

Figure 26. Diurnal wind speed profiles at the Longford met mast location

Table 6 shows the Longford site annual average wind speed for 2013 was nearly equal to the long-term annual average wind speed as predicted by the ERA-Interim dataset and roughly 1% higher than the MERRA dataset suggests. Thus, developers should take these biases into account though they seem small.

Table 6. Longford Observed and Long-Term Corrected Annual Average Wind Speeds

Observation Location	2013 Observed Annual Wind Speed @ 58 m	Long-Term Corrected Annual Wind Speed @ 58 m	
		MERRA	ERA-Interim
Longford Met Mast	7.17 m/s	7.12 m/s	7.18 m/s

Figure 27 shows the monthly average wind speed and the estimated variability for the predicted wind speeds for each month.

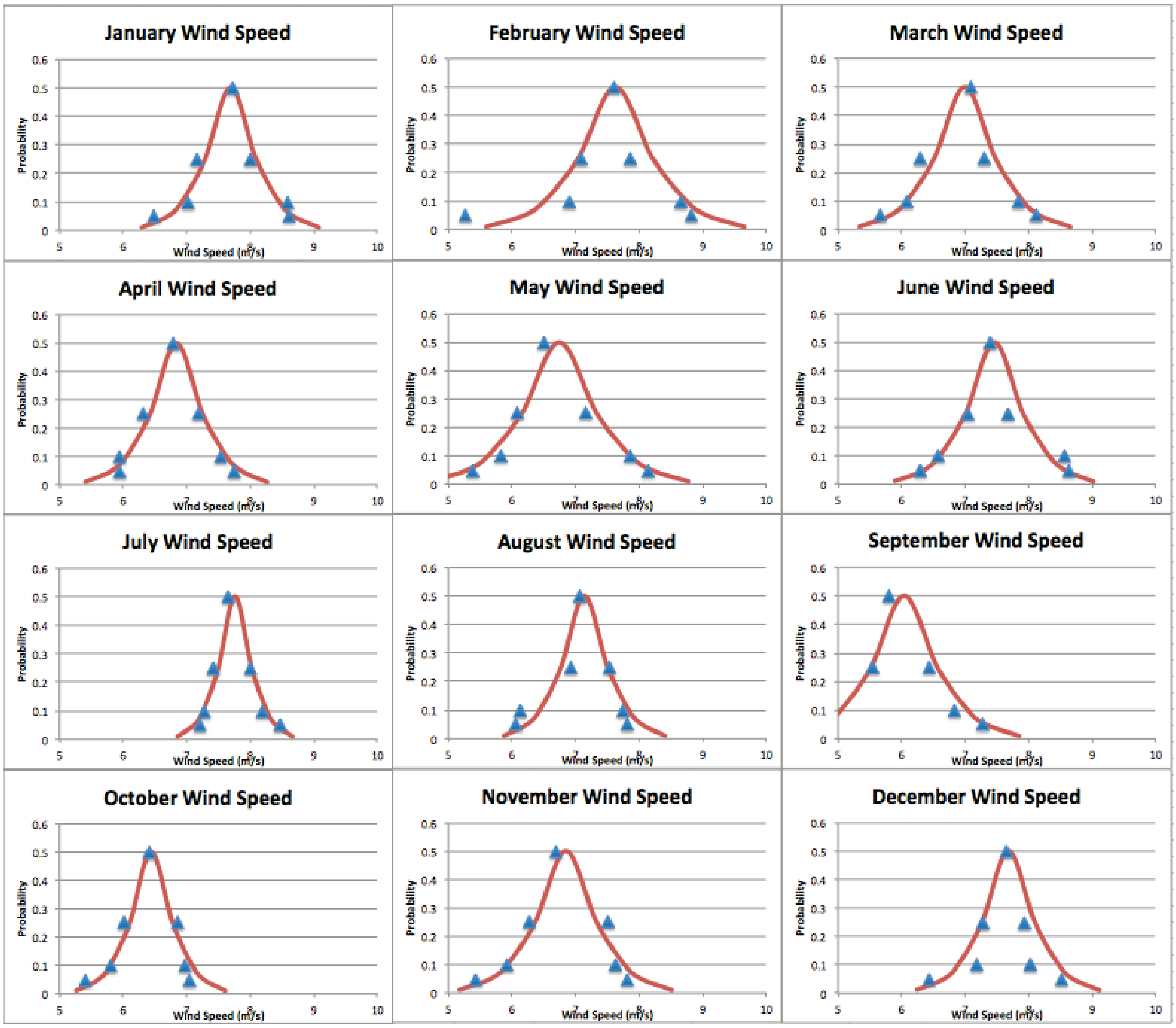

Figure 27. Monthly average wind speed and the estimated variability for the predicted wind speeds for each month

2.2.2 SODAR Near Robin Bay

Table 7 shows the Longford met mast and Robn Bay SODAR 525 observed annual average wind speeds as well as the observed power law exponents. SODAR 525 was sited atop a steep hill north of Robin Bay, which causes the SODAR to record lower than actual wind speeds. SODAR 525 was installed primarily to glean an understanding of the characterization of the predominant winds on St. Croix, not to produce estimates of potential wind projects at the installed location.

Table 7. Longford Met Mast and SODAR 525 Observed Annual Wind Speeds and Shear Exponents

Observation Location	2013 Observed Annual Wind Speed @ 58 m	2013 Observed Power Law Exponent @ 58 m
Longford Met Mast	7.17 m/s	0.154
SODAR 525*	6.84 m/s	0.177

* Complex terrain biases measured wind speeds lower than actual

3 Results

3.1 Wind Measurement Campaign Results

Both met masts were deployed for more than a year and produced high-quality, vetted data. All three SODAR devices were installed in locations that cause underestimates of the strength of the wind resource, so SODAR data should not be used to estimate potential turbine performance. Both the St. Croix south shore and Bovoni site are estimated to have long-term corrected wind speeds above 7 m/s, which may produce financially viable wind projects at both locations. Other potential barriers such as electrical integration and turbine transport must still be thoroughly addressed.

Table 8 shows the 2013 observed annual wind speeds at both sites as well as the long-term corrected annual average wind speeds.

Table 8. USVI Corrected Annual Average Wind Speeds by Location

Observation Location	2013 Observed Annual Wind Speed @ 58 m	Long-Term Corrected Annual Wind Speed @ 58 m	
		MERRA	ERA-Interim
Bovoni Met Mast	7.41 m/s	7.17 m/s	7.20 m/s
Longford Met Mast	7.17 m/s	7.12 m/s	7.18 m/s

3.2 Wind Mapping Exercise

NREL contracted AWS Truepower to generate estimates of wind speed for all three U.S. Virgin Islands. The data can be found and downloaded from NREL's Wind Prospector website (NREL 2014a). Full details on the approach, assumptions, and results can be found in Appendix A.

The results of the wind mapping exercise show that there are significant discrepancies between the actual measurement locations and the wind map estimates. Table 9 shows annual average wind speeds for 2013 from the measurement locations and from the AWS Truepower modeled data. It should be noted that the SODAR units were all deployed at locations with complex terrain and these results have a higher level of uncertainty than if the units were installed in flat terrain (Rovers 2012). This result illustrates that the wind maps should be used to identify potential measurement locations and not to estimate energy production for a given site.

Table 9. Observed Versus Modeled Wind Speed Results

ID	Name	Island	Lat	Lon	Elev (m)	Obs Mean Speed (m/s)	Map Mean Speed (m/s)	Bias (m/s)
1	Longford	St. Croix	17.708	-64.693	28	7.21	7.00	–20
525	Triton 525	St. Croix	17.743	-64.636	239	6.82	7.61	0.79
2	Bovoni	St. Thomas	18.306	-64.876	49	7.41	6.66	–0.74
512	Triton 512	St. Thomas	18.305	-64.877	36	6.68	6.43	–0.25
Avg						**7.03**	**6.93**	**–0.10**
SD								**0.64**

At the Bovoni site the measured wind speed for 2013 was 7.41 m/s and the AWS Truepower model predicted an annual average wind speed of 6.66 m/s. The complexity of the terrain is most likely causing the discrepancy between the model results and the measurements. The Longford met mast recorded an annual average wind speed for 2013 of 7.21 m/s; the model predicted an annual average wind speed of 7.0 m/s. Because the Longford site and the upwind terrain are fairly flat, the discrepancy between the model and the measurements is smaller than at the Bovoni site where the terrain is complex. This result illustrates that the wind maps should be used to identify potential measurement locations and not to estimate energy production for a given site.

4 Conclusions

Overall, the strength of the wind resource at Bovoni and St. Croix southern shore should produce economically feasible wind projects despite the fact that the cost of installing utility-scale turbines at both sites will likely be higher than the average installed costs in the continental United States. Consideration of electrical interconnection and integration on both islands is critical to understanding the financial feasibility of potential wind projects. Smaller turbines that reduce the transportation and logistical costs were considered (Lantz et al. 2012), but capacity factors are estimated to be much lower than those of utility-scale wind turbines. This suggests that wind project developers should consider a wide range of turbines when considering the development of a potential wind farm.

The previous wind estimates were biased low and underestimated the true value of wind in the territory. This demonstrates the importance of deploying met masts and SODAR units to reduce uncertainty before attempting to develop wind projects in new areas. This reduction in uncertainty should help attract quality developers to the territory, as initial development costs can be minimized.

Wind power offers opportunities for cost-effective renewable power generation in the USVI. Successfully developing a project will not be simple, but with the right mix of local leadership and expertise, cost-effective wind power projects developed in St. Thomas and St. Croix can play a meaningful part of meeting USVI’s 60%-by-2025 goal.

References

Clifton, A.; Kilcher, L.; Lundquist, J.K.; Fleming, P. (2013). "Using Machine Learning To Predict Wind Turbine Power Output." *Environmental Research Letters* 8:024009. Accessed October 31, 2014: http://iopscience.iop.org/1748-9326/8/2/024009/pdf/1748-9326_8_2_024009.pdf.

Dallas, M. (2012). "Pattern Energy Begins Operations at First Commercial Wind Project in Puerto Rico." PR Newswire. Accessed October 31, 2014: www.prnewswire.com/news-releases/pattern-energy-begins-operations-at-first-commercial-wind-project-in-puerto-rico-176242771.html.

DOE (2013). *2012 Wind Technologies Market Report*. Washington, D.C.: U.S. Department of Energy. Accessed October 31, 2014: www1.eere.energy.gov/wind/pdfs/2012_wind_technologies_market_report.pdf.

ECMWF (2006). ERA-Interim. Reading, UK: European Centre for Medium-Range Weather Forecasts. Accessed October 31, 2014: www.ecmwf.int/en/research/climate-reanalysis/era-interim.

EPA (2014). 2010 Region 2 Compliance and Enforcement Annual Results. Washington, D.C.: U.S. Environmental Protection Agency. Accessed October 31, 2014: www.epa.gov/region02/capp/10results.html.

IEC (2005). *International Standard 61400-1 Wind turbines – Part 1: Design Requirements*. Geneva, Switzerland: International Electrochemical Commission. Accessed October 31, 2014: http://webstore.iec.ch/preview/info_iec61400-1%7Bed3.0%7Den.pdf.

Lantz, E.; Olis, D.; Warren, A. (2011). *U.S. Virgin Islands Energy Road Map: Analysis*. Golden, CO: National Renewable Energy Laboratory. Accessed October 31, 2014: www.edinenergy.org/pdfs/52360.pdf.

Lantz, E.; Warren, A.; Roberts, J.O.; Gevorgian, V. (2012). *Wind Power Opportunities in St. Thomas, USVI: A Site-Specific Evaluation and Analysis*. Golden, CO: National Renewable Energy Laboratory. Accessed October 31, 2014: www.nrel.gov/docs/fy12osti/55415.pdf .

NASA (2013). MERRA: Modern-Era Retrospective Analysis for Research and Applications. Greenbelt, MD: National Aeronautics and Space Administration. Accessed October 31, 2014: http://gmao.gsfc.nasa.gov/contact.php.

NREL (2011). *USVI Energy Road Map Charting the Course to a Clean Energy Future*. Golden, CO: National Renewable Energy Laboratory. Accessed October 31, 2014: www.nrel.gov/docs/fy11osti/51541.pdf.

NREL (2014a). Wind Prospector. Golden, CO: National Renewable Energy Laboratory. Accessed October 31, 2014: http://maps.nrel.gov/wind_prospector.

NREL (2014b). Measurement and Instrumentation Data Center. Golden, CO: National Renewable Energy Laboratory. Accessed October 31, 2014: www.nrel.gov/midc/usvi/.

RES (2004). *A Review of MCP Techniques*. Hertfordshire, UK: Renewable Energy Systems Ltd. Accessed October 31, 2014: www.res-group.com/media/234585/a%20review%20of%20mcp%20techniques.pdf.

Rovers (2012). "Correction of Sodar Wind Speed Bias in Complex Terrain Situations." Presented at EWEA 2012. Accessed October 31, 2014: http://proceedings.ewea.org/annual2012/allfiles2/1247_EWEA2012presentation.pdf.

St. Croix Source (2013). "V.I. Energy Office Blast." Accessed October 31, 2014: http://stcroixsource.com/content/community/environment/2013/12/24/vi-energy-office-blast.

Vergnet (2014). Vergnet Wind Turbines Caribbean. Ormes, France: Vergnet Wind Turbines. Accessed October 31, 2014: www.vergnet.com/en/vergnet-caribbean.php.

Vestas (2011). "Vestas in the Caribbean." Presented at the 2011 CARILEC Renewable Energy Forum, St. Thomas, VI, September 2011. Accessed October 31, 2014: www.carilec.com/members2/uploads/RE2011_Presentations/OrchidRoomSessions/3_JCNavarrete_VestasintheCaribbean.pdf.

VI WAPA (2011). USVI-BVI-Puerto Rico Interconnection. Christiansted, St. Croix: Virgin Islands Water and Power Authority. Accessed October 31, 2014: www.viwapa.vi/AboutUs/Projects/ProjectDetails/11-08-02/USVI-BVI-Puerto_Rico_Interconnection.aspx.

Bibliography

Baring-Gould, I. (2012). “USVI Wind Energy Update.” Presented at the EDIN-USVI Energy Workshop, June 11, 2012, St. Croix, Virgin Islands. Accessed October 31, 2014: http://www.edinenergy.org/pdfs/usvi_201206_5_usvi_wind_nrel.pdf.

Burman, K.; Olis, D.; Gevorgian, G.; Warren, A.; Butt, R.; Lilienthal, P.; Glassmire, J. (2011). *Integrating Renewable Energy into the Transmission and Distribution System of the U.S. Virgin Islands*. Golden, CO: National Renewable Energy Laboratory. Accessed October 31, 2014: www.edinenergy.org/pdfs/51294.pdf.

Warren, A. (2010). “USVI Project Development and Finance.” Golden, CO: National Renewable Energy Laboratory. Accessed October 31, 2014: www.edinenergy.org/pdfs/usvi_project_development_finance_061510.pdf.

Appendix A: AWS Truepower Wind Mapping Technical Memo

Memorandum

To: Owen Roberts, NREL

From: **Michael C. Brower, CTO, and Mikel Shakarjian, Project Manager**

Date: 10 September 2014

Re: U.S. Virgin Islands Wind Resource Maps and Data, Subcontract AFA-4-42036-01

We are pleased to report on the outcome of this project to map the wind resources of the U.S. Virgin Islands.

Mean annual, seasonal, monthly and diurnal wind maps of the onshore areas of the United States Virgin Islands have been completed and delivered for six heights above ground level (AGL): 30, 55, 70, 80, 100 and 120 m, on a 50 m horizontal grid. Map images (pdfs) and GIS shapefile data will be provided for the annual means at all heights. The wind resource grid data for each height include dry season (December –May) and wet season (April-Nov) (wet/dry), monthly, and diurnal gridded data sets. Hourly atmospheric datasets have been delivered for the two mast locations and include wind speed and direction for each height over a 15 year period. The datasets are for release to the public.

Method

Wind speeds over the US Virgin Islands were simulated with the Weather Research and Forecasting (WRF) model version 3.5. Initial and updated boundary conditions were provided by the ERA-Interim reanalysis dataset. The runs employed a nested grid configuration of 27-9-3-1 km with 40 vertical levels; the innermost grid covered the islands of St. Thomas, St. John, and St. Croix, with a sufficient buffer to provide valid data at all onshore points. The simulations were run for the year 2013, consistent with the period of measurements (January 1, 2013 to middle or late December 2013). The runs were re-initialized at the beginning of each calendar month, and the spectral nudging technique was used to maintain consistency between the simulations and reanalysis data. The simulations are intended to provide a reasonably accurate picture of the factors influencing wind conditions on the islands, including synoptic weather patterns, island topographic influences, and mesoscale circulations, at the 1 km resolution of the innermost WRF grid.

The WindMap software, a mass-conserving diagnostic wind flow model, was then used to downscale the 1 km simulations to a 50 m horizontal resolution. This stage is intended to capture localized terrain and surface roughness influences that cannot be seen by the WRF model. The topographic data came from the 90 m Shuttle Radar Topographic Mission (SRTM) dataset. (It should be noted that the use of 90 m topographic data resulted in some smoothing of the final maps compared to the target 50 m resolution.)

Diurnal and monthly ratios of 2013 mean wind conditions to the long term were then calculated from AWST's windTrends 20-km database (1997-2013). It was found that mean speeds in 2013 were approximately 10% higher than mean speeds over the 1997-2013 period. This would imply a downward adjustment to the 2013 maps of 10%. However, according to two leading global reanalysis data sets (ERA-Interim and MERRA), 2013 was very nearly an average year compared to 1997-2013 and 1989-2013. Therefore, after consultation with NREL, it was decided to assume the 2013 maps and data files are representative of long-term conditions, and to make no long-term adjustments to the maps

Validation and Uncertainty

The resulting maps representing 2013 conditions were compared with measurements from one Triton SODAR and one tall tower on St. Thomas[1] and one Triton SODAR and one tall tower on St. Croix, as well as to offshore wind speed estimates from satellite-based scatterometer data (QuikSCAT).

The following table summarizes the comparison of the tower and SODAR measurements with the unadjusted wind resource map at 55 m height AGL. (This height was chosen as one typical of wind projects in tropical islands prone to hurricanes.) The observed and predicted (modeled) mean wind speeds are for 2013. The observed data have been annualized, meaning the values are the average of monthly averages weighted by the number of days; in addition, the December data for Langford have been estimated by comparison with the same month at Bovoni. The data for all sites have been projected from the nearest measurement height to 55 m using the observed or estimated wind shear. The shear adjustments are small, however, and so not likely to contribute substantially to observed errors.

Table A- 1. Comparison of Observed and Predicted Mean Speeds for 2013 at 55 m Height AGL At the Four Measurement Locations With Sufficient Data

The observed speeds have been annualized to the full year.

ID	Name	Island	Lat	Lon	Elev (m)	Obs Mean Speed (m/s)	Map Mean Speed (m/s)	Bias (m/s)
1	Longford	St. Croix	17.708	-64.693	28	7.21	7.00	-0.20
525	Triton 525	St. Croix	17.743	-64.636	239	6.82	7.61	0.79
2	Bovoni	St. Thomas	18.306	-64.876	49	7.41	6.66	-0.74
512	Triton 512	St. Thomas	18.305	-64.877	36	6.68	6.43	-0.25
Avg						**7.03**	**6.93**	**-0.10**
SD								**0.64**

[1] Data from a second Triton SODAR on St. Thomas could not be used as only 4 months were available for comparison.

The average bias is quite small, only -0.10 m/s. The standard deviation (SD) of the biases, 0.64 m/s, is comparatively large, however. This is likely due in part to the complex terrain in which the measurement systems are deployed, which results in large localized speed gradients that cannot be accurately captured by the model, particularly at the 1 km resolution of the WRF simulations. In addition, it is challenging to simulate winds on tropical islands like the US Virgin Islands that experience frequent, intense convective weather systems (e.g., tropical storms) with complex features below the grid resolution of the WRF model. Errors in the placement, intensity, and structure of such systems can result in significant errors in mean wind speed.

The comparison of the offshore maps with QuikSCAT data indicate a high bias of about 10% in the mean wind speed maps at 10 m across most of the region spanned by the islands. There is considerable uncertainty in the QuikSCAT data, however, especially when extrapolated to hub heights of wind turbines. Therefore we do not believe this necessarily indicates a general high bias across the region.

Given these findings, we conclude that no adjustment should be applied to the maps. We believe there is too much uncertainty in the biases and too few observations to justify making adjustments to specific areas or islands.

Our estimate of the overall uncertainty in the mean wind speed at any location is about 10%. This is somewhat larger than usual for AWS Truepower maps for the reasons outlined above. With additional data, it is likely the uncertainty could be reduced.

Validation Plots

The plots on the following pages compare the wind resource characteristics predicted by WRF at the two towers, Longford and Bovoni. The height in each case is 50 m. The predicted values come directly from the WRF runs, with no downscaling with the microscale model. Thus the mean WRF speeds do not match the downscaled map values shown in the table above. However this does not affect the distribution patterns or scatter plots.

The scatter plots show a very good agreement (linear relationship with relatively high r^2) between the model and observations at both sites. The scatter in the daily averages is much smaller and the r^2 higher than for the hourly averages, as is to be expected given the greater noise from chaotic processes at finer time resolutions. The wind rose plots likewise show a very good agreement between the observations and WRF model. This is not surprising considering the dominant influence of easterly trade winds in this region, which are well simulated in numerical weather prediction models. A similar conclusion can be drawn from the comparison of the monthly and diurnal average speeds. The one exception to this is the larger midday peak in the observed diurnal pattern compared to the modeled data, especially at Longford. This may indicate that the model is underestimating the strength of the sea breeze. The same explanation could account for the slightly greater southerly tendency of the observed winds compared to the model at this location.

In summary, the WRF model appears to capture the essential characteristics of the wind resource these two locations. Results for the lidars are very similar.

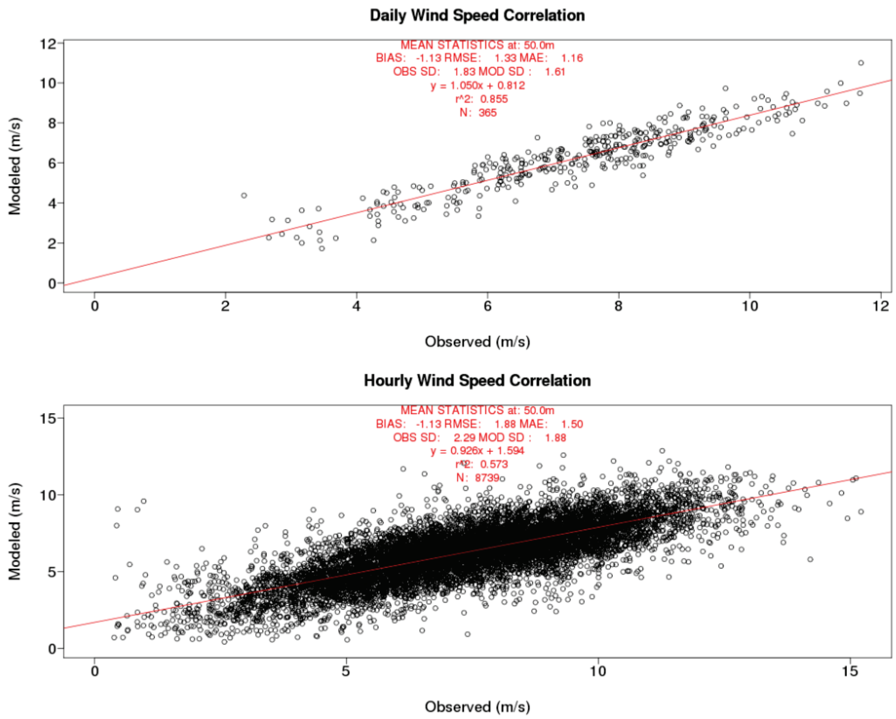

Figure A-1. Scatter plots of observed and WRF daily average (top) and hourly average (bottom) wind speeds at the Bovoni tower for 2013

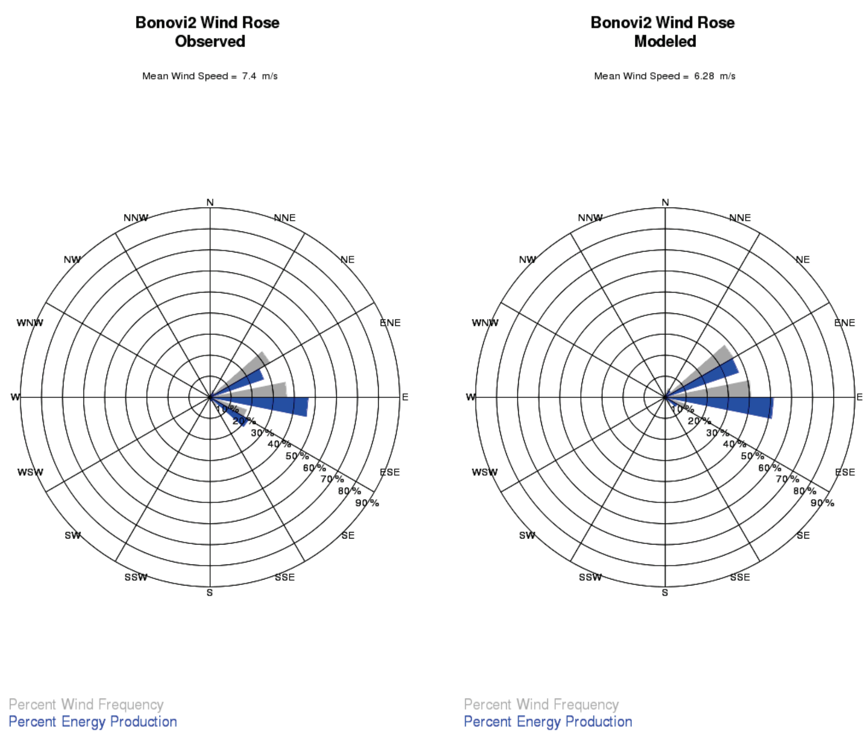

Figure A-2. Observed (left) and WRF (right) wind roses for the Bovoni tower, for 2013

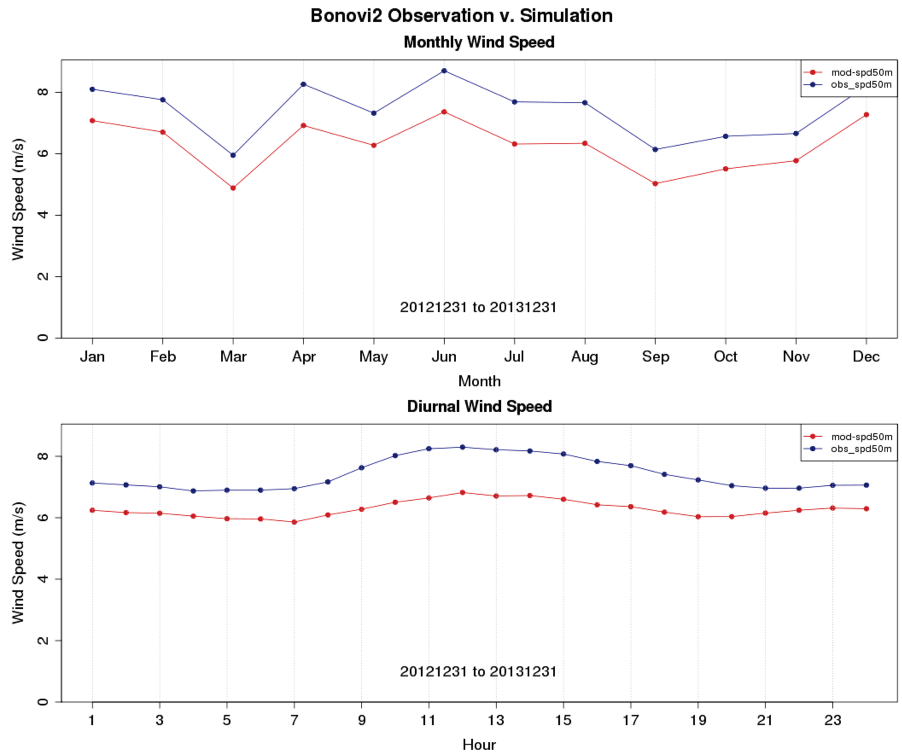

Figure A-3. Comparison of observed and WRF-generated monthly average (top) and diurnal average (bottom) wind speeds at Bovoni

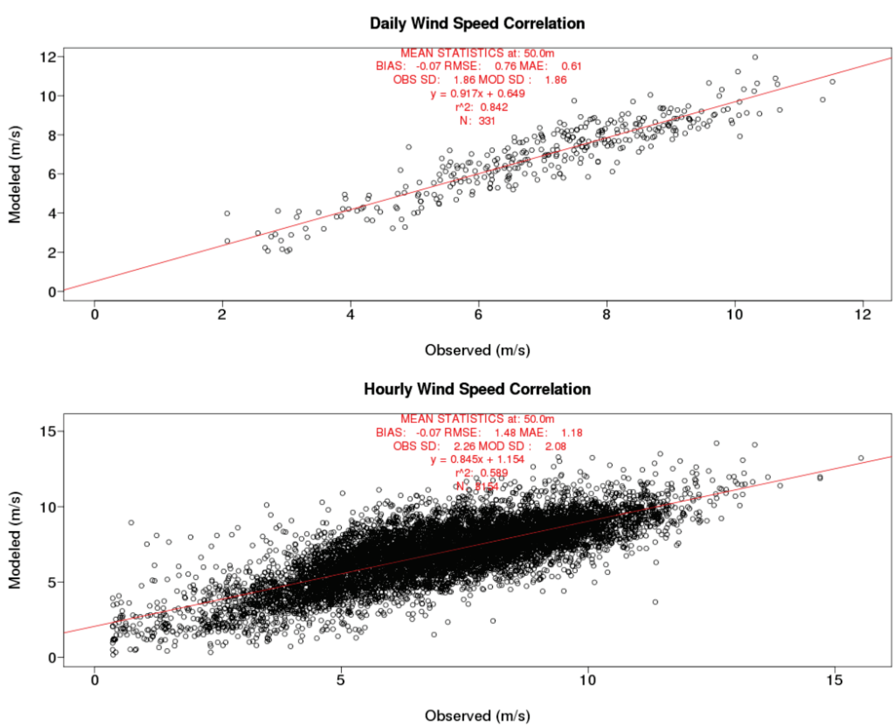

Figure A-4. Scatter plots of observed and WRF-generated daily average (top) and hourly average (bottom) wind speeds at the Longford tower for 2013

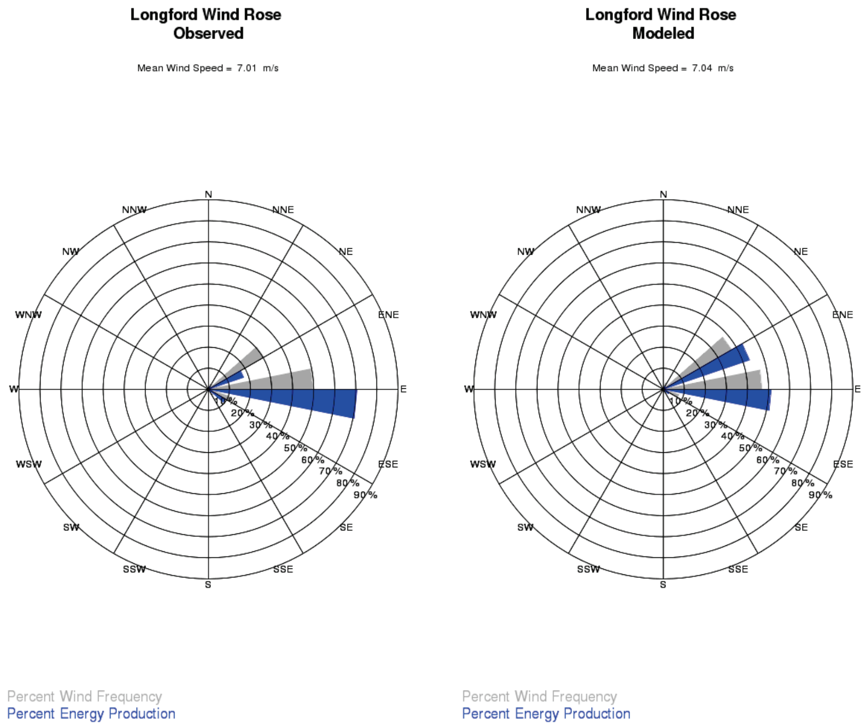

Figure A-5. Observed (left) and WRF (right) wind roses for the Longford tower for 2013

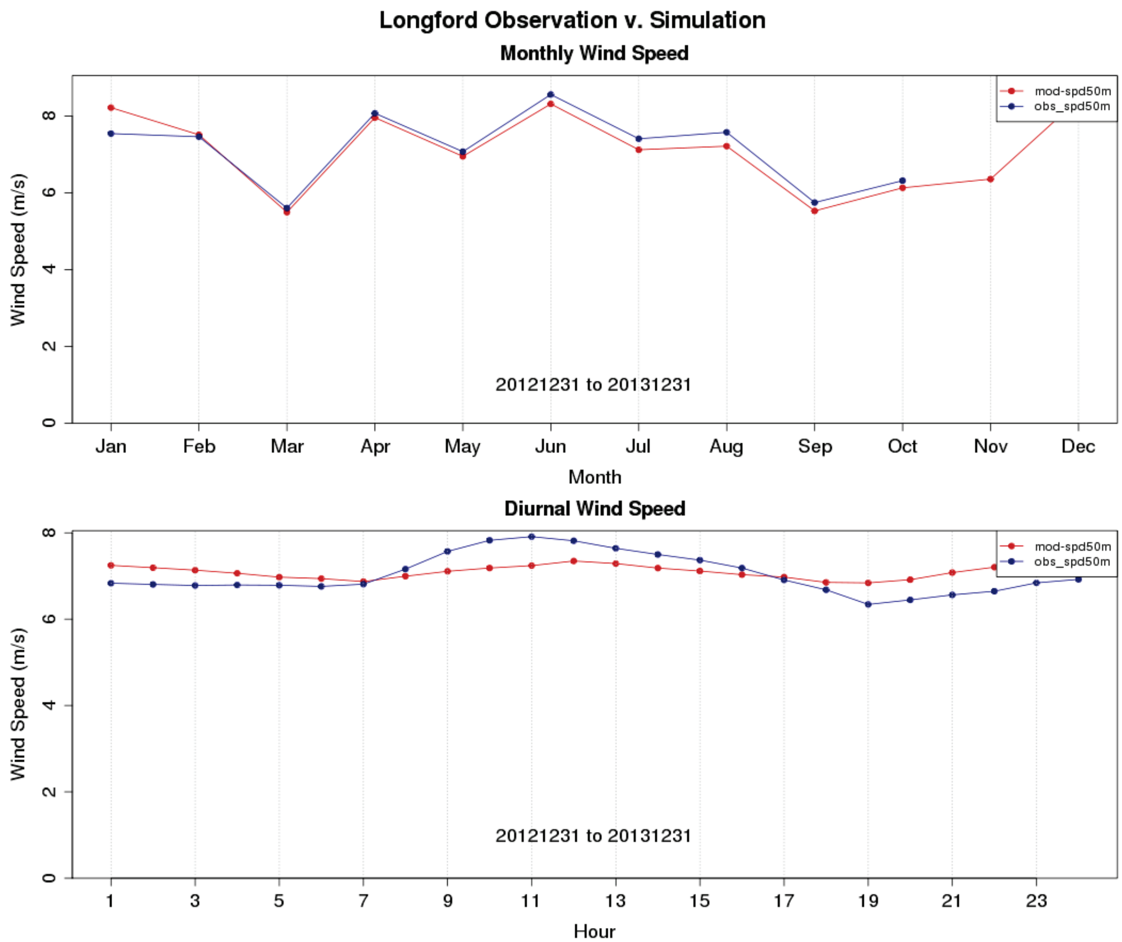

Figure A-6. Comparison of observed and WRF-generated monthly average (top) and diurnal average (bottom) wind speeds at Longford

Appendix B: U.S. Virgin Islands Wind Maps

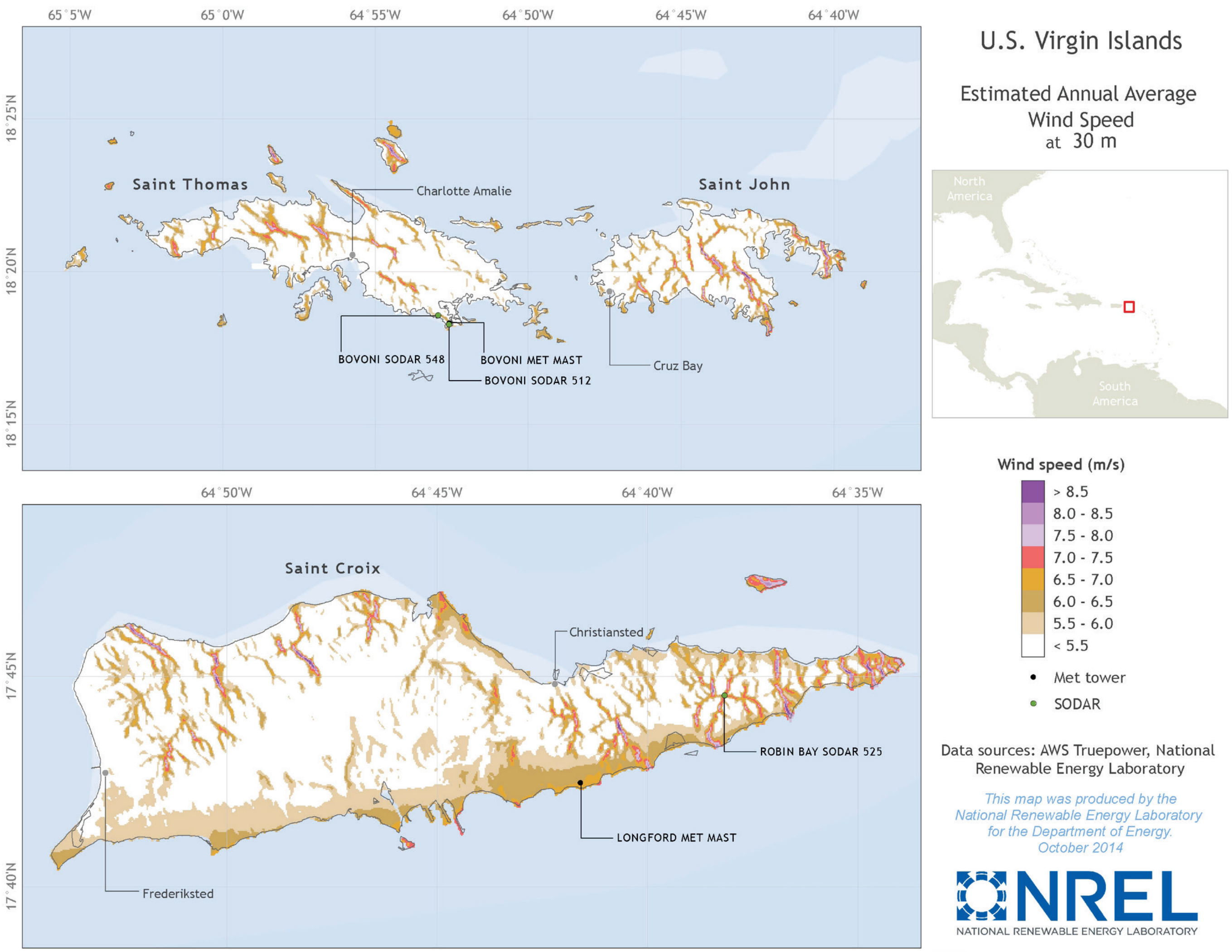

Figure B-128. Estimated annual average wind speed at 30 meters

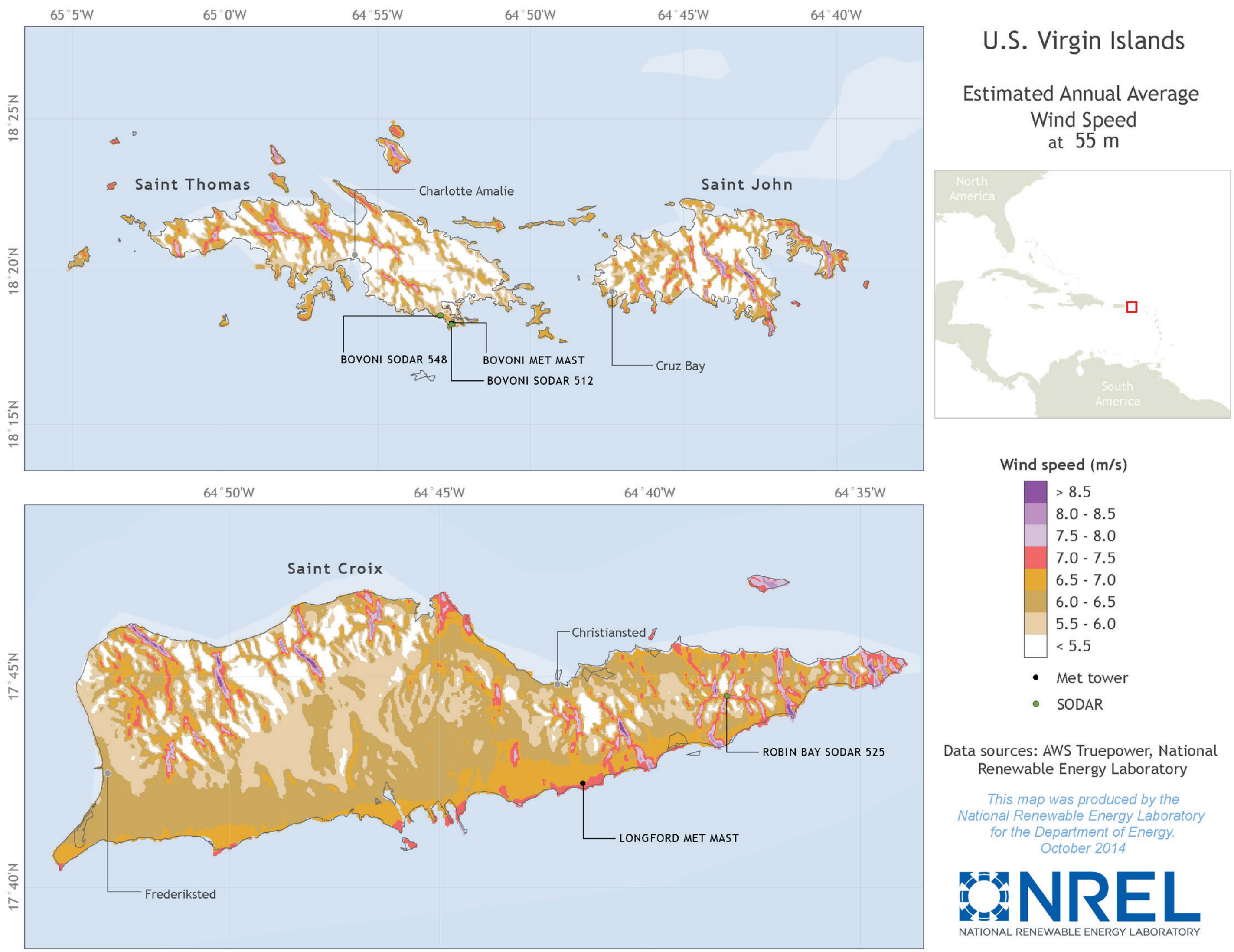

Figure B-2. Estimated annual average wind speed at 55 meters

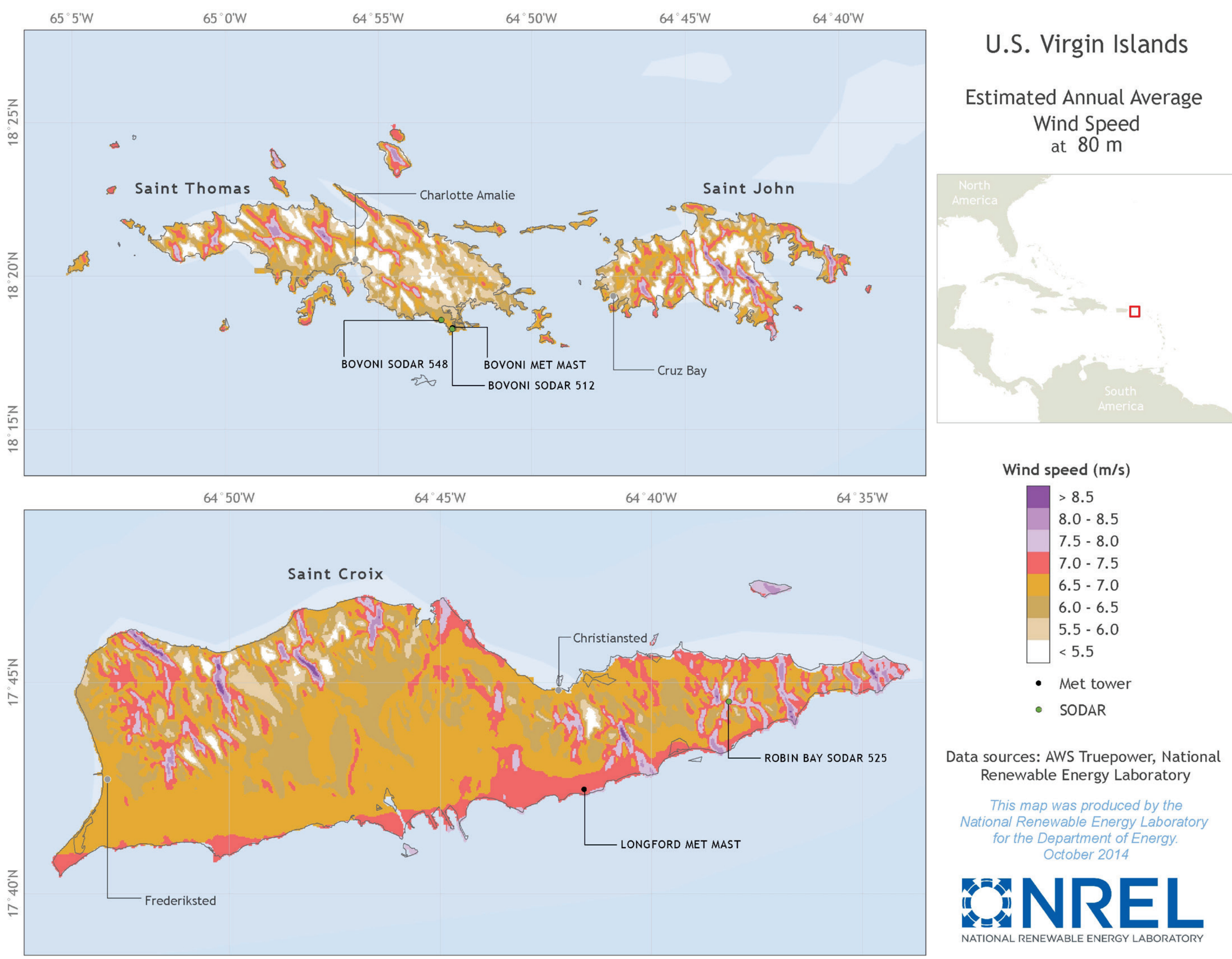

Figure B-3. Estimated annual average wind speed at 80 meters

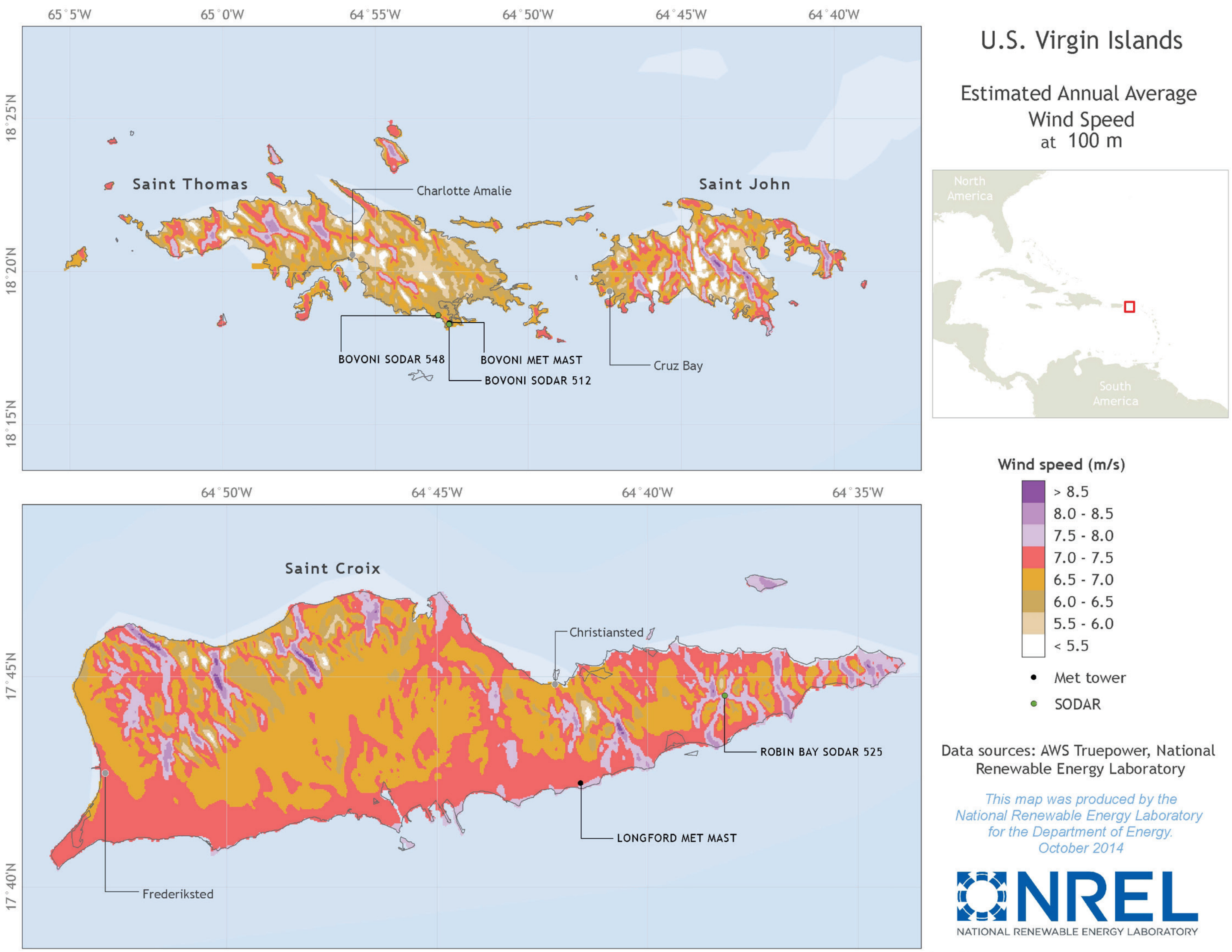

Figure B-4. Estimated annual average wind speed at 100 meters

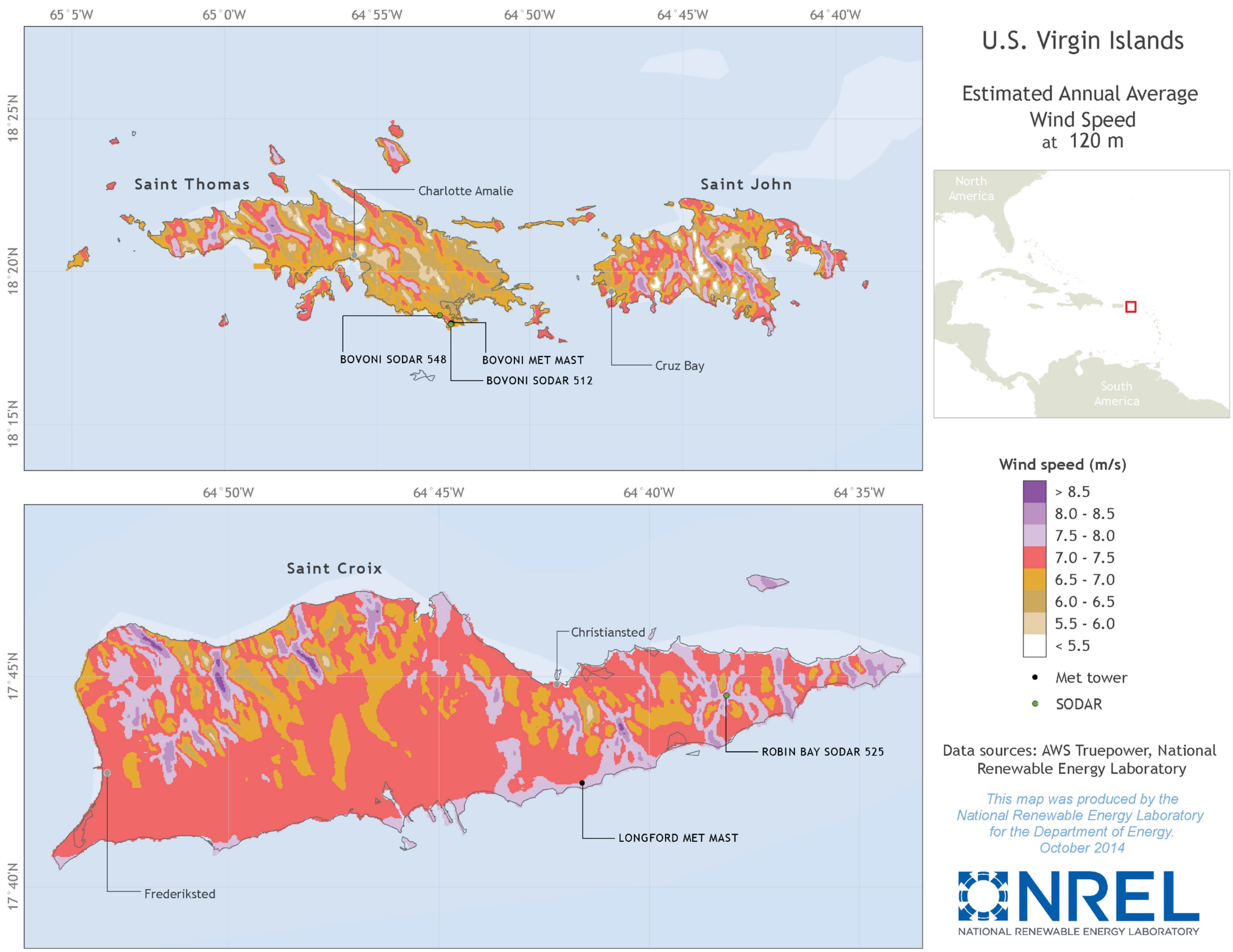

Figure B-5. Estimated annual average wind speed at 120 meters