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2 WIND POWER SYSTEMS

2.1 Introduction

Wind is the movement of air caused by the irregular heating of the Earth's surface. It happens at all scales, from local breezes created by heating of land surfaces that lasts some minutes, to global winds caused from solar heating of the Earth. Wind power is the transformation of wind energy into more utile forms, typically electricity using wind turbines [Gipe, 2004].

2.2 History

The first use of wind power was to make possible the sailing of ships in the Nile River some 5000 years ago. Many civilizations used wind power for transportation and other applications. The Europeans used it to crush grains and pump water in the 1700s and 1800s. The first wind mill to generated electricity in the rural U.S. was installed in 1890 [Patel 2006]. However, for much of the twentieth century there was small interest in using wind energy other than for battery charging for distant dwellings. These low-power systems were quickly replaced once the electricity grid became available. The sudden increases in the price of oil in 1973 stimulated a number of substantial

Government-funded programs for research, development and demonstrations of wind turbines and other alternative energy technologies.

In the United States this led to the construction of a series of prototype turbines starting with the 38 diameter 100kW Mod-0 in 1975 and culminating in the 97.5m diameter 2.5MW Mod-5B in 1987. Similar programs were pursued in the UK, Germany and Sweden [Burton et al. 2001]. Today, even larger wind turbines are being constructed such as 5MW units. Wind generated electricity is the fastest renewable growing energy business sector [Gipe, 2004].

Growth in the use of larger wind turbines, has made small wind turbines increasingly attractive for small applications such as, powering homes and farms. Wind power has become a very attractive renewable energy source because it is cheaper than other technologies and is also compatible with environmental preservation. To provide the reader with an idea of how has been the growth in wind energy, the installed capacity of wind has increased by a factor of 4.2 during the last five years [Mathew 2006]. The total global installed capacity of wind power systems in 2006 is approximately 73,904MW. Figure 2.1 [World Wind Energy 2007] shows the total installed in the last few years and provide a prediction for 2010. Figure 2.2 [The wind indicator 2005] shows the total wind power installed in different parts of the world.

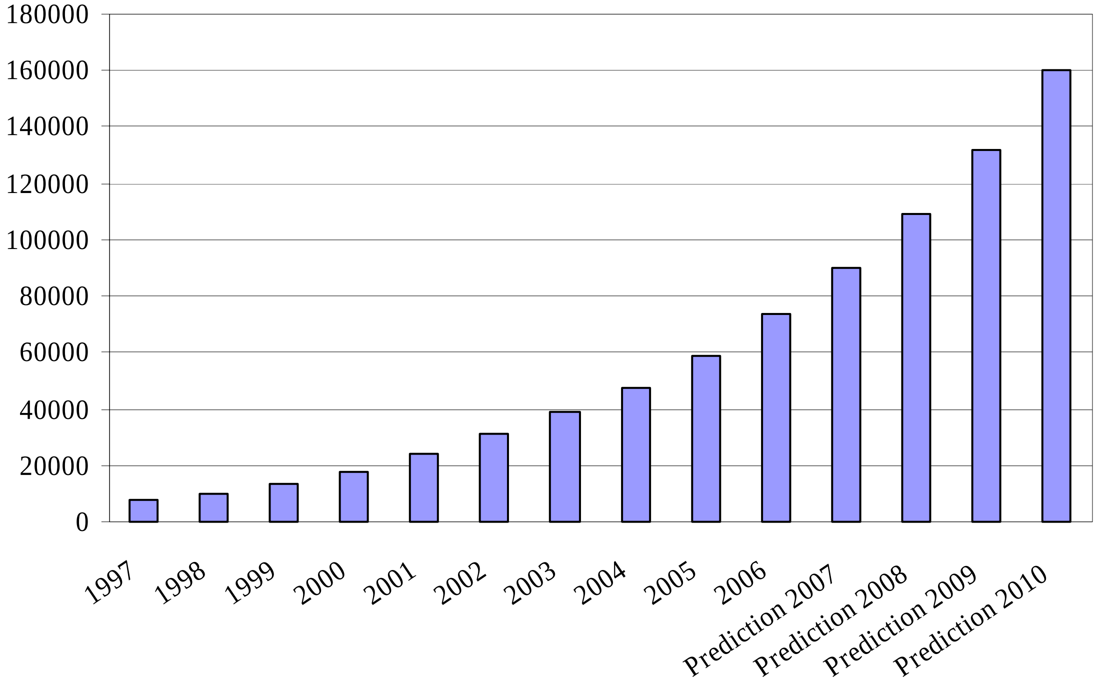


Figure 2-1 World Wind Energy – Total Installed Capacity (MW) (Adapted from [World Wind Energy])

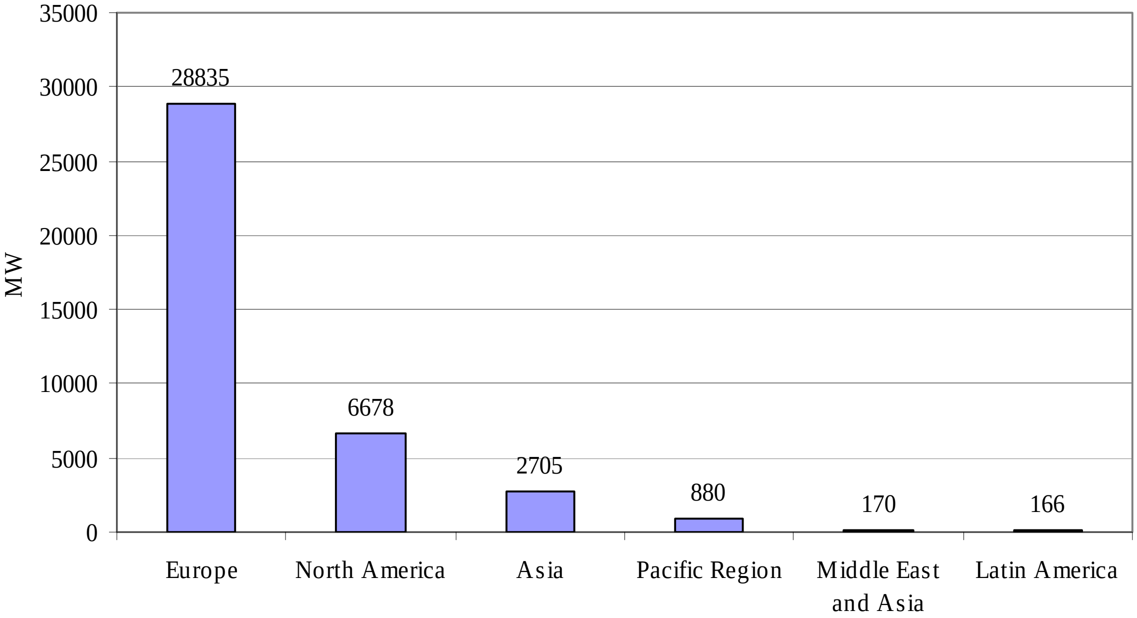


Figure 2-1 Installed Wind Energy Capacity (MW) in Different Regions (Adapted from [The Wind Indicator 2005])

2.3 Wind Turbines

A wind turbine is a machine that converts the kinetic energy from the wind into mechanical energy. If the mechanical energy is used directly by machinery, such as a pump or grinding stones, the machine is usually called a windmill. If the mechanical energy is then converted to electricity, the machine is called a wind generator [Gipe, 2004].

The modern wind turbine is a sophisticated piece of machinery with aerodynamically designed rotor and efficient power generation, transmission and regulation components. The size of these turbines ranges from a few Watts (Small Wind Turbines) to several Million Watts (Large Wind Turbines).

The modern trend in the wind industry is to go for bigger units of several MW capacity in places where the wind is favorable, as the system scaling up can reduce the unit cost of wind-generated electricity. Most of today's commercial machines are horizontal axis wind turbines (HAWT) with three bladed rotors.

While research and development activities on vertical axis wind turbines (VAWT) were intense during the end of the last century, VAWT could not evolve as a reliable alternative to the horizontal axis machines [Mathew 2006]. Figure 2.3 shows the typical vertical and horizontal wind turbines.

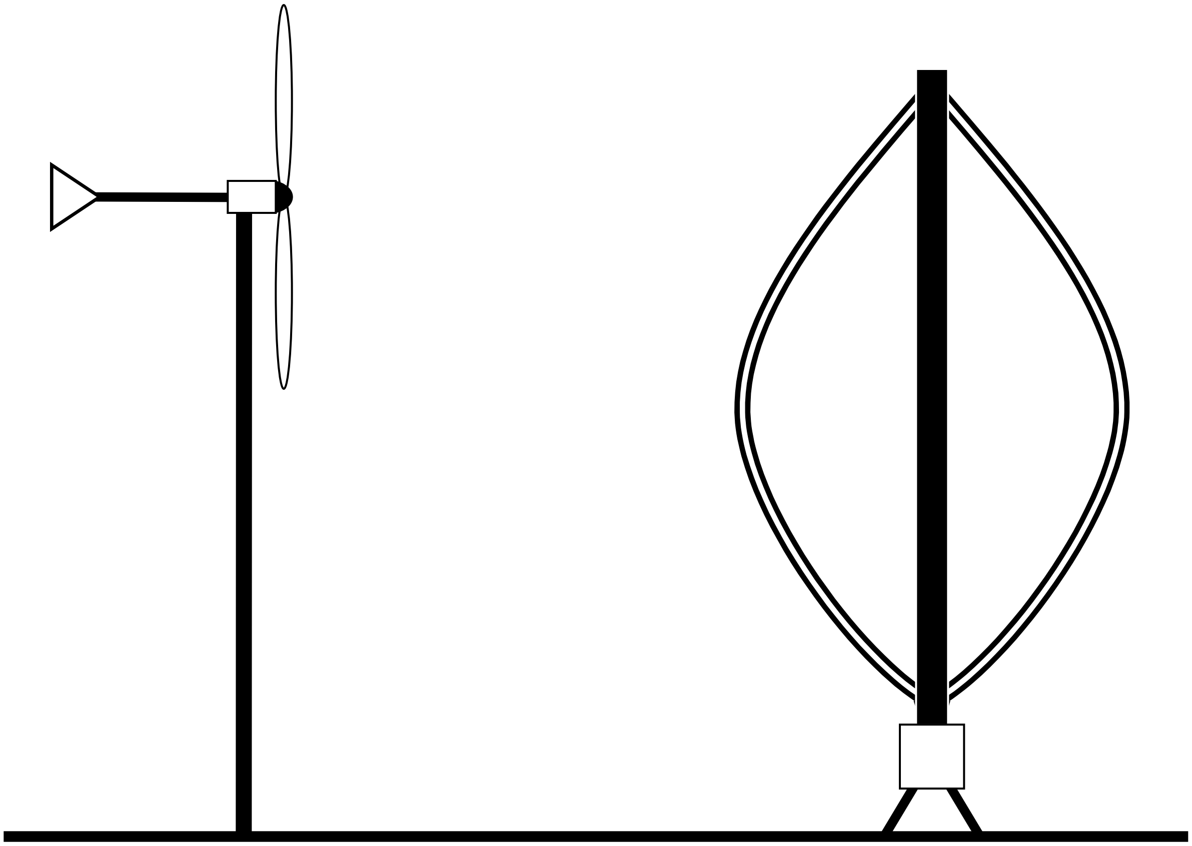


Figure 2-2 Horizontal Axis Wind Turbine (HAWT) and Vertical Axis Wind Turbine (VAWT)

2.3.1 Wind Turbines Components

The basic components for horizontal axis wind turbine are shown on **Figure 2-3 Components of a Wind Turbine.**

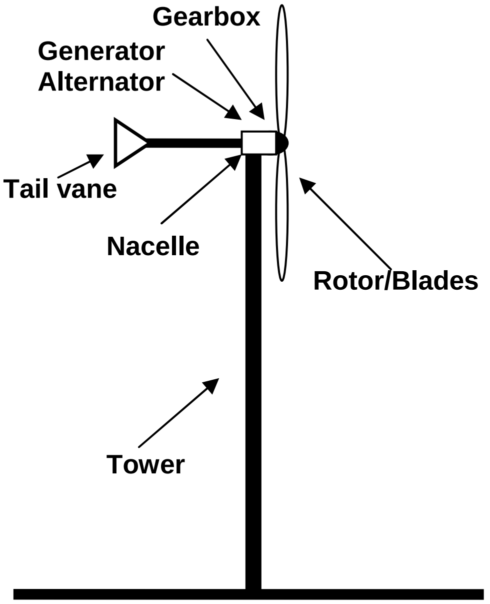


Figure 2-3 Components of a Wind Turbine

- Rotor/blades – The blades together with the hub are called the rotor. The rotor drives the generator by harnessing the kinetic energy in the wind. The blades are aerodynamically shaped to best capture the wind. The amount of energy a turbine can capture is proportional to the rotor sweep area. The blades are usually made of fiberglass, metal, reinforced plastic or wood.
- Generator/Alternator – Is the part of the turbine that produces electricity from the kinetic energy captured by the rotor. A generator produces Direct Current (DC)

power or, if in use, an alternator produces Alternating Current (AC) power, depending on the application for the turbine.

- Gearbox – Most turbines above 10 kW use a gearbox to match the rotor speed to the generator speed.
- Nacelle – Is the housing that protects the essential motorized parts of a turbine.
- Tail vane (Yaw system) – A yaw system aligns a HAWT with the wind. Most micro and mini systems use a simple tail vane that directs the rotor into the wind. In some systems, the rotor is downwind of the generator, so it naturally aligns with the wind. Some yaw systems can be offset from the vertical axis to regulate rotor power and speed by tilting the turbine slightly upward.

The following components are also usually supplied as part of a small wind turbine package:

- Control & Protection System – Control systems vary from simple switches, fuses and battery charge regulators to computerized systems for control of yaw systems and brakes. The sophistication of the control and protection system varies depending on the application of the wind turbine and the energy system it supports.
- Tower – Is the support of the small wind turbine. The wind speed increases at higher heights, meaning the higher the tower the greater the power. There are several types of towers.
    - Guyed lattice towers, where the tower is permanently supported by guy wires. These towers tend to be the least expensive, but take up a lot of space on a yard. A radio broadcast tower is a good example of a guyed lattice tower.

- Guyed tilt-up towers, which can be raised and lowered for easy maintenance and repair.
- Self-supporting towers, which do not have any guy wires. These towers tend to be the heaviest and most expensive, but because they do not require guy wires, they do not take up as much space on a yard.

2.4 Small Wind Turbines

Small wind turbines are typically used for powering houses, farms and remote locations that usually consume less than 50 kW of total capacity. For use these small turbines there must be enough wind, tall towers are allowed in the neighborhood or rural area, there enough space, the noise level of the turbine is approved and know how much electricity want to produce.

2.4.1 Small Wind Turbines Manufacturers

Today there are more than fifty manufactures of small wind turbines worldwide, and they produce more than one hundred different models [Gipe, 2004]. TABLE 2-1 and TABLE 2-2 present examples of small wind turbines available in the market today. These turbines are the most used in the United States and Europe for small wind power applications. Looking at the table we see that while larger turbine rotor area translates into more power that can be extracted from the wind and it also make the turbine more expensive. We selected a 25m tower to be used with all turbines. The prices were obtained from different manufactures in the internet during January 2008.

TABLE 2-1 Small wind turbines cost information, in US dollars

Product	Watts @ 28 mph	Turbine price	25m tower price	Turbine and tower	$/W	$/rotor area, m^2	W/m^2
SouthWest (Air X)	400	$600	$805	$1,405	$3.51	1376	392
SouthWest (Whisper 100)	900	$2,085	$805	$2,890	$3.21	834	260
SouthWest (Whisper 200)	1000	$2,400	$805	$3,205	$3.20	453	141
SouthWest (Whisper 500)	3000	$7,095	$1,157	$8,252	$2.75	497	181
SouthWest (Skystream 3.7)	1800	$5,400	$1,157	$6,557	$3.64	603	166
Aeromax Engineering (Lakota S, SC)	800	$1,591	$804	$2,395	$2.99	698	233
Bergey (BWC 1500)	1500	$4,700	$1,968	$6,668	$4.45	943	212
Bergey (BWC XL.1)	1000	$2,590	$1,968	$4,558	$4.56	929	204
Bergey (BWC Excel-R)	8100	$23,000	$2,396	$25,396	$3.14	720	230
Bornay (Inclin 250)	250	$2,151	$1,157	$3,308	$13.23	2149	162
Bornay (Inclin 600)	600	$2,726	$1,157	$3,883	$6.47	1236	191
Bornay (Inclin 1500)	1500	$3,973	$1,157	$5,130	$3.42	896	262
Bornay (Inclin 3000)	3000	$6,028	$1,968	$7,996	$2.67	744	279
Bornay (Inclin 6000)	6000	$10,070	$1,968	$12,038	$2.01	1120	558
Abundant Renewable Energy (ARE110)	2500	$11,500	$1,968	$13,468	$5.39	1323	246
Abundant Renewable Energy (ARE442)	10000	$36,000	$2,396	$38,396	$3.84	943	246
Kestrel Wind (600)	600	$1,296	$804	$2,100	$3.50	1188	340
Kestrel Wind (800)	800	$1,995	$804	$2,799	$3.50	808	231
Kestrel Wind (1000)	1000	$2,950	$1,157	$4,107	$4.11	581	141
Kestrel Wind (3000)	3000	$8,400	$1,968	$10,368	$3.46	914	265
Solacity (Eoltec)	6000	$25,200	$1,968	$27,168	$4.53	1103	244

TABLE 2-2 Small wind turbines physical data and seller

Product	**Rotor Diameter (m)**	**Rotor Area (m^2)**	**Weigh lb**	**Voltage V**	**Seller**
SouthWest (Air X)	1.14	1.02	13	12, 24, 48 Vdc	Alt En Store
SouthWest (Whisper 100)	2.1	3.46	47	12, 24, 48 Vdc	Infinigy
SouthWest (Whisper 200)	3	7.07	65	12, 24, 48 Vdc 230 Vac	Gaiam
SouthWest (Whisper 500)	4.6	16.62	155	12, 24, 48 Vdc 230 Vac	Alt En Store
SouthWest (Skystream 3.7)	3.72	10.87	154	120/240 AC	Southwest
Aeromax Engineering (Lakota S, SC)	2.09	3.43	35	12, 24, 48 Vdc	Aeromax Engineering
Bergey (BWC 1500)	3	7.07	168	12, 24, 36, 48, 120 Vdc	Alter System
Bergey (BWC XL.1)	2.5	4.91	75	24, 48 Vdc	Alter System
Bergey (BWC Excel-R)	6.7	35.26	1050	48 Vdc 120Ac 240Ac	Alt En Store
Bornay (Inclin 250)	1.4	1.54	93	12, 24, 48, 220 Vdc	Bornay
Bornay (Inclin 600)	2	3.14	93	12, 24, 48, 220 Vdc	Bornay
Bornay (Inclin 1500)	2.7	5.73	93	12, 24, 48, 220 Vdc	Bornay
Bornay (Inclin 3000)	3.7	10.75	276	12, 24, 48, 220 Vdc	Bornay
Bornay (Inclin 6000)	3.7	10.75	342	12, 24, 48, 220 Vdc	Bornay
Abundant Renewable Energy (ARE110)	3.6	10.18	315	48Vdc	ARE
Abundant Renewable Energy (ARE442)	7.2	40.72	1350	48Vdc	ARE
Kestrel Wind (600)	1.5	1.77	44	12, 24, 48, 220 Vdc	www.kestrelwind.co.za
Kestrel Wind (800)	2.1	3.46	66.1	12, 24, 48, 220 Vdc	www.kestrelwind.co.za
Kestrel Wind (1000)	3	7.07	88	12, 24, 48, 220 Vdc	www.kestrelwind.co.za
Kestrel Wind (3000)	3.8	11.34	397	24, 48, 220 Vdc	www.kestrelwind.co.za
Solacity (Eoltec)	5.6	24.63	450	3 phase AC	Solacity.com

2.5 Large Wind Turbines

Large wind turbines are typically used to sell power to electric utilities. Their power ranges from 100 kW up to 5 MW. For use these large turbines there must be enough wind, tall towers are allowed in the neighborhood or rural area, there enough space, the noise level of the turbine is approved and know how much electricity want to produce.

2.5.1 Large Wind Turbines Manufactures

TABLE 2-3 presents examples of large wind turbines available in the market today. These turbines are the most used in the United States and Europe for large wind power applications. From TABLE 2-3 see that while larger turbine rotor area translates into more power that can be extracted from the wind and it also make the turbine more expensive. Installed cost of these turbines ranges between 1 and 1.4 dollars per installed W. Typical costs of operation and maintenance are in the $0.01 per kWh generated.

TABLE 2-3 Examples of large wind turbines and basic data

Manufacturer	**Product**	**kW @ 28 mph**	**Watt/m^2**	**Rotor diameter (m)**	**Rotor area (m^2)**	**Output voltage (V)**
Distributed Energy System	NorthWind 100	100	289	21	346.36	480
AAER Wind	A-1000	1000	378	58	2642.08	690
GE	1.5xle	1500	281	82.5	5345.62	
GE	2.5xl	2500	318	100	7853.98	
GE	3.6sl	3600	372	111	9676.89	
ACSA	A27/225	225	393	27	572.56	400
Enercon	E-33	330	377	33.4	876.16	
Enercon	E-44	900	592	44	1520.53	
Enercon	E-48	800	442	48	1809.56	
Enercon	E-53	800	364	52.9	2197.87	
Enercon	E-70	2300	581	71	3959.19	
Enercon	E-82	2000	379	82	5281.02	
Vesta Wind Systems	V52-850kw	850	400	52	2123.72	690
Vestas Wind Systems	V82-1.65MW	1650	312	82	5281.02	690
Vestas Wind Systems	V80-1.8 MW	1800	358	80	5026.55	690
Vesta Wind System	V90-1.8 & 2.0	2000	314	90	6361.73	690
Vesta Wind Systems	V80-2.0MW	2000	398	80	5026.55	690
Vesta Wins Systems	V90-3.0MW	3000	472	90	6361.73	690
Fuhrlander	FL 1500	1500	322	77	4656.63	690
Fuhrlander	FL 2500	2500	318	100	7853.98	690
Gamesa	G58-850KW	850	322	58	2642.08	690
Gamesa	G90-2.0MW	2000	314	90	6361.73	690
Nordex	N60/1300	1300	460	60	2827.43	690
Nordex	S77/1500 KW	1500	322	77	4656.63	690
Nordex	N90/2300	2300	362	90	6361.73	660
Nordex	N100/2500 KW	2500	320	99.8	7822.60	600
Suzlon	Serie 600	600	283	52	2123.72	690
Suzlon	S66-1250	1250	365	66	3421.19	600
Suzlon	S.82-1.5MW	1500	284	82	5281.02	690
Suzlon	S.88	2000	329	88	6082.12	690

2.6 Wind Turbines Efficiency and Power Curve

The theoretical limit of power extraction from wind, or any other fluid was derived by the German aerodynamicist Albert Betz. Betz law, [Betz, 1966], states that 59% or less of the kinetic energy in the wind can be transformed to mechanical energy using a wind turbine.

In practice, wind turbines rotors deliver much less than Betz limit. The factors that affect the efficiency of a turbine are the turbine rotor, transmission and the generator. Normally the turbine rotors have efficiencies between 40 to 50%. Gearbox and generator efficiencies can be estimated to be around 80% to 90%. Also efficiency of a turbine is not constant. It varies with wind speeds. Many companies do not provide their wind turbine efficiencies. Instead they provide a power curve.

A power curve is a graph that represents the turbine power output at different wind speeds values. The advantage of using a power curve is that it includes the wind turbines efficiency for all wind speeds of operation. The power curve is normally provided by the turbine's manufacture. **Figure 2-4** presents an example of a wind turbine power curve. Note that at speeds from 0 to 3.5 m/s the power output is zero. This occurs because there is not sufficient kinetic energy in the wind to move the wind turbine rotor. Normally the manufactures provide a technical data sheet where the start up wind speed of the turbine is given. In general lower start up wind speeds result in higher energy coming from the turbine.

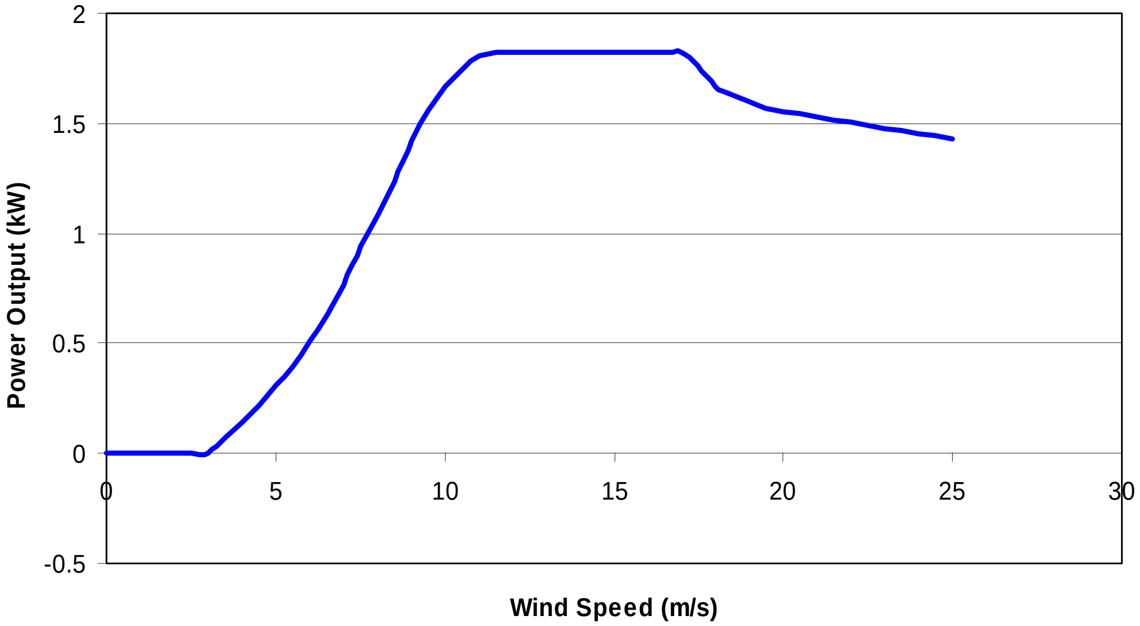


Figure 2-4 Power Curve for Wind Turbine "Sky Stream 3.7" of South West Company (Source: Data from manufacturer, plot by author)

A manufacturer may also show the power curve information in table format. The table provides the exact value of power at different wind speed. The power curve is then obtained by plotting the table values. TABLE 2-4 and TABLE 2-5 present the power curve data for different small turbines. TABLE 2-6 and TABLE 2-7 present the power curve data for different large turbines.

TABLE 2-4 Power curve values, in kW, for small wind turbines

Wind Speed m/s	**SouthWest**					**AeroMax Engineering**	**Bergey**		
	Air X	**Whisper 100**	**Whisper 200**	**Whisper 500**	**Skystream 3.7**	**Lakota S, SC**	**BWC 1500**	**BWC XL.1**	**BWC Excel-R**
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.01	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.05
4	0.02	0.02	0.05	0.27	0.14	0.03	0.08	0.06	0.25
5	0.03	0.06	0.15	0.55	0.31	0.07	0.15	0.12	0.70
6	0.04	0.12	0.28	0.88	0.51	0.11	0.30	0.23	1.38
7	0.07	0.19	0.44	1.26	0.77	0.28	0.45	0.38	2.18
8	0.09	0.28	0.63	1.70	1.08	0.34	0.60	0.54	3.11
9	0.13	0.39	0.78	2.18	1.42	0.41	0.80	0.70	4.26
10	0.16	0.52	0.89	2.67	1.67	0.53	1.15	0.89	5.37
11	0.20	0.66	0.96	3.07	1.80	0.64	1.30	1.06	6.63
12	0.28	0.80	0.99	3.28	1.82	0.75	1.50	1.21	7.45
13	0.35	0.90	1.00	3.33	1.82	0.90	1.60	1.24	8.09
14	0.41	0.92	1.00	3.26	1.82	1.16	1.70	1.20	8.05
15	0.44	0.91	0.99	3.13	1.82	1.28	1.60	1.15	7.92
16	0.45	0.88	0.96	2.96	1.82	1.30	0.35	1.10	7.75
17	0.35	0.85	0.93	2.77	1.82	1.25	0.35	1.05	7.51
18	0.15	0.81	0.90	2.56	1.67	1.20	0.40	0.99	7.28
19	0.15	0.77	0.85	2.33	1.60	1.10	0.40	0.94	7.11
20	0.15	0.73	0.81	2.08	1.55	1.00	0.40	0.90	6.96
21	0.15	0.69	0.77	1.76	1.53	0.98	0.40	0.85	6.73
22	0.15	0.64	0.72	1.45	1.50	0.93	0.40	0.85	6.49
23	0.15	0.60	0.68	1.13	1.48	0.90	0.40	0.85	6.26
24	0.15	0.56	0.63	0.82	1.45	0.90	0.40	0.85	6.03

TABLE 2-5 Power curve values, in kW, for small wind turbines (cont)

Wind Speed m/s	**Bornay**					**Abundant Renewable Energy**		**Kestrel Wind**				**Solacity**
	Inclin 250	**Inclin 600**	**Inclin 1500**	**Inclin 3000**	**Inclin 6000**	**ARE110**	**ARE442**	**Kestrel 600**	**Kestrel 800**	**Kestrel 1000**	**Kestrel 3000**	**Eoltec**
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.02	0.03	0.11	0.25	0.68	0.14	0.30	0.01	0.02	0.01	0.05	0.14
4	0.03	0.06	0.22	0.50	1.10	0.20	0.64	0.03	0.04	0.08	0.15	0.34
5	0.05	0.11	0.41	0.75	1.60	0.25	1.40	0.05	0.10	0.17	0.26	0.67
6	0.08	0.15	0.59	1.00	2.10	0.50	2.13	0.09	0.19	0.34	0.50	1.16
7	0.12	0.24	0.80	1.50	3.10	0.70	3.57	0.14	0.27	0.53	0.79	1.81
8	0.17	0.32	1.00	1.80	3.90	1.32	5.62	0.21	0.36	0.74	1.17	2.71
9	0.21	0.41	1.12	2.15	4.50	1.65	7.75	0.30	0.47	1.00	1.59	3.82
10	0.24	0.50	1.24	2.50	5.00	2.25	9.55	0.39	0.58	1.29	2.00	5.00
11	0.27	0.55	1.40	2.80	5.50	2.55	10.38	0.48	0.69	1.64	2.50	5.70
12	0.30	0.60	1.55	3.10	6.00	2.55	10.50	0.55	0.79	1.20	2.90	6.00
13	0.33	0.60	1.67	3.30	6.25	2.55	10.50	0.63	0.86	1.21	3.45	6.00
14	0.35	0.60	1.78	3.50	6.50	2.55	10.50	0.65	0.86	1.22	3.40	6.00
15	0.30	0.56	1.64	3.25	6.00	2.55	10.50	0.66	0.85	1.23	3.40	6.00
16	0.25	0.52	1.50	3.00	5.80	2.55	10.50	0.65	0.85	1.23	3.40	6.00
17	0.26	0.53	1.53	3.03	5.90	2.55	10.50	0.65	0.85	1.23	3.40	6.00
18	0.26	0.54	1.55	3.05	6.00	2.55	10.50	0.65	0.85	1.23	3.40	6.00
19	0.26	0.54	1.60	3.20	6.00	2.55	10.50	0.65	0.85	1.23	3.40	6.00
20	0.26	0.54	1.64	3.35	6.00	2.55	10.50	0.65	0.85	1.23	3.40	6.00
21	0.26	0.54	1.65	3.38	6.00	2.55	10.50	0.65	0.85	1.23	3.40	6.00
22	0.26	0.54	1.66	3.39	6.00	2.55	10.50	0.65	0.85	1.23	3.40	6.00
23	0.26	0.54	1.66	3.40	6.00	2.55	10.50	0.65	0.85	1.23	3.40	6.00
24	0.26	0.54	1.66	3.40	6.00	2.55	10.50	0.65	0.85	1.23	3.40	6.00

TABLE 2-6 Power curve values, in MW, for large wind turbines

Wind Speed m/s	**Suzlon**				**Nordex**				**Gamesa**		**Fuhrlander**		**Vestas Wind Systems**			
	S.88 - 2.1MW	**S.82 -1.5MW**	**S66 -1.2MW**	**Serie 600KW**	**N100/2.5MW**	**N90/2.3MW**	**S77/1.500MW**	**N60/1.3MW**	**G90-2.0MW**	**G58-850KW**	**FL 2500**	**FL 1500**	**V90-3.0MW**	**V90-2.0MW**	**V82-1.65MW**	**V52-850KW**
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00
4	0.01	0.00	0.04	0.00	0.05	0.04	0.04	0.03	0.08	0.08	0.10	0.03	0.05	0.05	0.03	0.04
5	0.14	0.10	0.09	0.04	0.21	0.18	0.13	0.07	0.20	0.15	0.20	0.10	0.24	0.16	0.14	0.08
6	0.31	0.26	0.15	0.10	0.43	0.35	0.24	0.13	0.36	0.24	0.48	0.24	0.40	0.33	0.31	0.12
7	0.55	0.47	0.29	0.18	0.73	0.58	0.40	0.24	0.59	0.37	0.73	0.40	0.65	0.60	0.51	0.20
8	0.84	0.71	0.45	0.25	1.11	0.87	0.60	0.38	0.90	0.53	1.08	0.60	0.95	0.88	0.76	0.30
9	1.18	0.97	0.64	0.40	1.58	1.24	0.85	0.54	1.27	0.70	1.50	0.90	1.28	1.20	1.02	0.41
10	1.54	1.22	0.83	0.47	2.02	1.62	1.11	0.70	1.63	0.80	2.08	1.16	1.65	1.63	1.29	0.55
11	1.86	1.38	1.01	0.55	2.31	2.01	1.33	0.87	1.86	0.84	2.50	1.34	2.04	1.90	1.50	0.65
12	2.04	1.44	1.15	0.59	2.46	2.23	1.48	1.02	1.96	0.85	2.50	1.45	2.45	1.98	1.64	0.76
13	2.09	1.47	1.24	0.61	2.50	2.30	1.50	1.12	1.99	0.85	2.50	1.50	2.75	2.00	1.65	0.83
14	2.10	1.50	1.25	0.61	2.50	2.30	1.50	1.25	2.00	0.85	2.50	1.50	2.90	2.00	1.65	0.85
15	2.10	1.50	1.25	0.61	2.50	2.30	1.50	1.30	2.00	0.85	2.50	1.50	3.00	2.00	1.65	0.85
16	2.10	1.50	1.25	0.61	2.50	2.30	1.50	1.34	2.00	0.85	2.50	1.50	3.00	2.00	1.65	0.85
17	2.00	1.50	1.25	0.60	2.50	2.30	1.50	1.36	2.00	0.85	2.50	1.50	3.00	2.00	1.65	0.85
18	2.00	1.50	1.25	0.60	2.50	2.30	1.50	1.32	2.00	0.85	2.50	1.50	3.00	2.00	1.65	0.85
19	2.00	1.50	1.25	0.60	2.50	2.30	1.50	1.32	2.00	0.85	2.50	1.50	3.00	2.00	1.65	0.85
20	2.00	1.50	1.25	0.60	2.50	2.30	1.50	1.31	2.00	0.85	2.50	1.50	3.00	2.00	1.65	0.85
21	2.00	1.50	1.25	0.60	2.50	2.30	1.50	1.31	2.00	0.85	2.50	1.50	3.00	2.00	1.65	0.85
22	2.00	1.50	1.25	0.60	2.50	2.30	1.50	1.31	2.00	0.85	2.50	1.50	3.00	2.00	1.65	0.85
23	2.00	1.50	1.25	0.60	2.50	2.30	1.50	1.30	2.00	0.85	2.50	1.50	3.00	2.00	1.65	0.85
24	2.00	1.50	1.25	0.60	2.50	2.30	1.50	1.29	2.00	0.85	2.50	1.50	3.00	2.00	1.65	0.85

TABLE 2-7 Power curve values, in MW, for large wind turbines (cont)

Wind Speed m/s	**Enercon**						**AAER Wind**	**ACSA**	**GE**			**Distributed Energy Systems**
	E-82	**E-70**	**E-53**	**E-48**	**E-44**	**E-33**	**A-1000**	**A27/225**	**3.6sl**	**2.5xl**	**1.5xle**	**NorthWind 100**
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.03	0.02	0.04	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00
4	0.08	0.06	0.08	0.03	0.02	0.01	0.03	0.01	0.10	0.05	0.08	0.01
5	0.17	0.13	0.14	0.07	0.05	0.03	0.07	0.02	0.25	0.15	0.16	0.01
6	0.32	0.24	0.23	0.12	0.10	0.06	0.14	0.03	0.45	0.39	0.30	0.02
7	0.53	0.40	0.34	0.19	0.16	0.09	0.24	0.05	0.73	0.64	0.50	0.03
8	0.82	0.63	0.48	0.28	0.24	0.14	0.36	0.08	1.10	0.99	0.73	0.04
9	1.18	0.89	0.65	0.41	0.34	0.20	0.51	0.11	1.70	1.35	1.00	0.05
10	1.66	1.22	0.74	0.56	0.47	0.25	0.67	0.15	2.18	1.90	1.25	0.06
11	1.89	1.59	0.78	0.67	0.60	0.29	0.86	0.17	2.70	2.25	1.46	0.08
12	2.00	1.90	0.81	0.75	0.71	0.32	1.00	0.21	3.18	2.42	1.50	0.09
13	2.05	2.08	0.81	0.79	0.79	0.34	1.00	0.22	3.40	2.50	1.50	0.09
14	2.05	2.23	0.81	0.81	0.85	0.34	1.00	0.23	3.55	2.50	1.50	0.10
15	2.05	2.30	0.81	0.81	0.88	0.34	1.00	0.23	3.60	2.50	1.50	0.10
16	2.05	2.31	0.81	0.81	0.91	0.34	1.00	0.23	3.60	2.50	1.50	0.10
17	2.05	2.31	0.81	0.81	0.91	0.34	1.00	0.23	3.60	2.50	1.50	0.10
18	2.05	2.31	0.81	0.81	0.91	0.34	1.00	0.23	3.60	2.50	1.50	0.10
19	2.05	2.31	0.81	0.81	0.91	0.34	1.00	0.23	3.60	2.50	1.50	0.10
20	2.05	2.31	0.81	0.81	0.91	0.34	1.00	0.23	3.60	2.50	1.50	0.10
21	2.05	2.31	0.81	0.81	0.91	0.34	1.00	0.23	3.60	2.50	1.50	0.10
22	2.05	2.31	0.81	0.81	0.91	0.34	1.00	0.23	3.60	2.50	1.50	0.10
23	2.05	2.31	0.81	0.81	0.91	0.34	1.00	0.23	3.60	2.50	1.50	0.10
24	2.05	2.31	0.81	0.81	0.91	0.34	1.00	0.23	3.60	2.50	1.50	0.10

2.7 Wind Turbine Power

To estimate the average power generated by a wind turbine at a given site you may use the average wind speed for the site and the wind turbine power curve to estimate the average power output. The power available for a wind turbine at a specific site is:

$$P = P_c(v) * n \tag{2-1}$$

Where P is an estimate of the expected power production at the site, $P_c(v)$ is the turbine power output from the power curve at wind speed v, and n is the number of wind turbines to be installed. The generated energy, for a given wind speed, is obtained multiplying the power produced at such speed by the time the wind blows at such speed. Total generated energy is obtained adding the energy produced at each wind speed the turbine is capable of producing electricity.

2.8 Wind Resources

Wind resource is the most important element in projecting turbine performance at a given place. The energy that can be extracted from a wind stream is proportional to the cube of its velocity, meaning that doubling the wind velocity increases the available energy by a factor of eight. Also, the wind resource itself rarely is a constant or has a steady flow. It varies with year, season, and time of day, elevation above ground, and form of terrain. Proper location of windy sites, away from large obstructions, improves wind turbine's performance.

2.8.1 Anemometer

Wind speed is measured with an instrument called an anemometer. These come in several types. The most common type has three or four cups attached to a rotating shaft. When the wind hits the anemometer, the cups and the shaft rotate. The angular speed of the spinning shaft is calibrated in terms of the linear speed of the wind. In the U.S., wind speed is reported in miles per hour or in nautical miles per hours (knots). In other countries, it is reported in kilometers per hours or meters per second. No matter what measurement system is installed, the user needs to be sure it is properly calibrated. Make note that the energy that can be extracted from the wind is proportional to the cube of its velocity, meaning bad wind speed measurements will cause an even worse estimate of power available, [Gipe, 2004].

For a small wind turbine a minimum of one year of data should be recorded and compared with another source of wind data. It is very important that the measuring equipment is set high enough to avoid turbulence created by trees, buildings or other obstructions. Readings would be most useful if they have been taken at hub height, or the elevation at the top of the tower where the wind turbine is going to be installed, [Gipe, 2004].

2.8.2 Wind Speed Height Correction

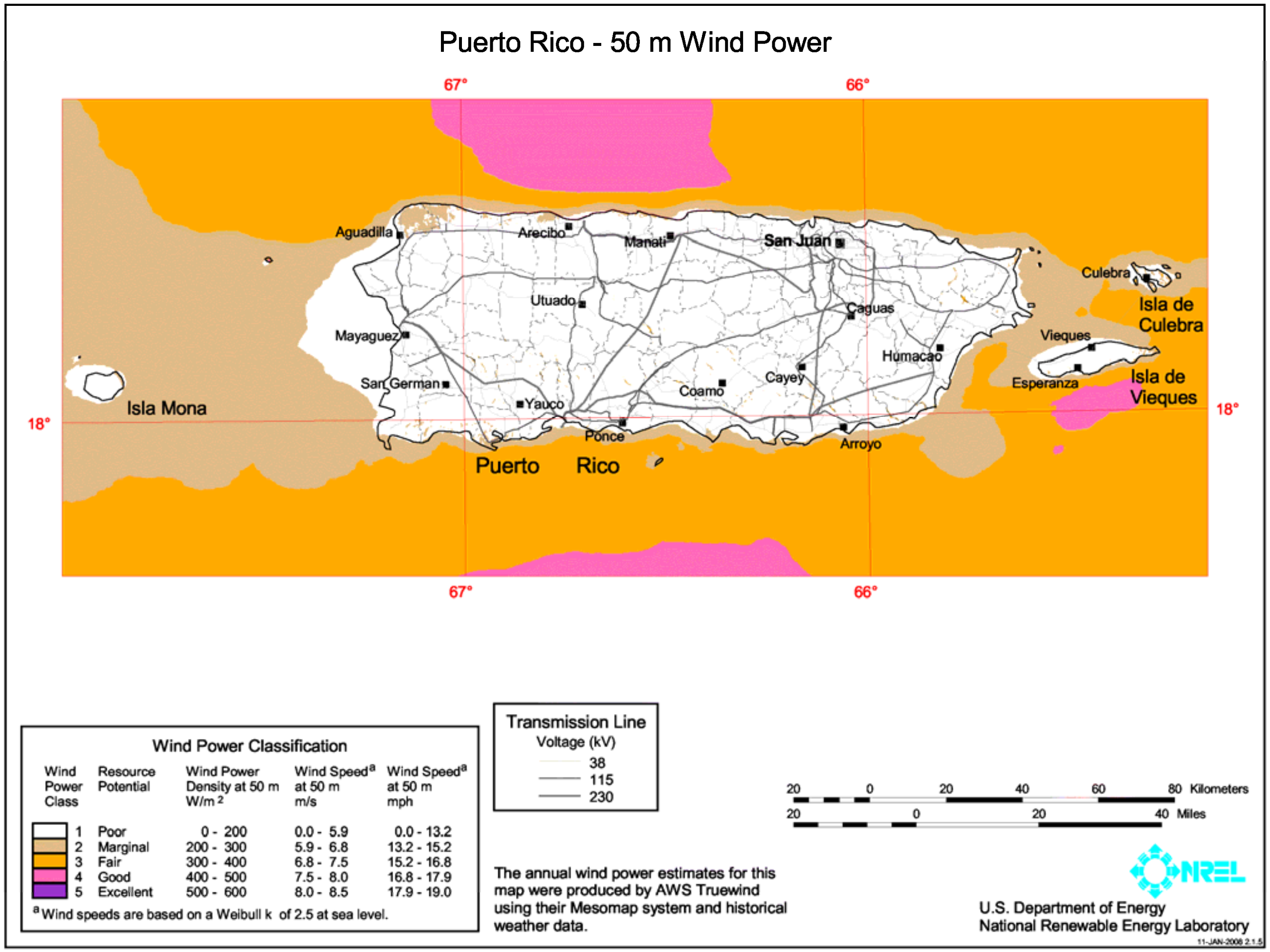
If the measurement of wind speed was not made at the wind turbine hub height it is important to adjust the measured wind speed to the hub height. This can be done using the one-seventh power law as shown in Equation 2.2, [Burton et al. 2001].

$$\frac{v(z_2)}{v(z_1)} = \left(\frac{z_2}{z_1}\right)^{\alpha} \qquad \textbf{2-2}$$

Where $v(z_2)$ is the wind speed at the desired height z_2, $v(z_1)$ is the wind speed measured at a known height z_1. α is a coefficient known as the wind shear exponent. The wind shear exponent varies with pressure, temperature and time of day. A commonly use value for α is one-seventh (1/7), approximately 0.1429.

2.8.3 Wind Resources in Puerto Rico

Puerto Rico is a mountainous, oceanic island situated between the Atlantic Ocean and the Caribbean Sea, at approximately 18º N latitude and 66º longitude. The island is approximately rectangular, 177 kilometers east to west and about 57 kilometers maximum north to south. The prevailing wind of the island comes from the northeast trade winds [Burton et al. 2001]. A collaborative effort between the US Department of Energy (DOE), the National Renewable Energy Laboratory (the Wind Powering America program and the Wind Resource Group), AWS Truewind and the Puerto Rico Energy Affairs Administration has produced a high resolution wind maps for Puerto Rico. Figure 2-5 shows the annual average wind power at 50 m for Puerto Rico [NREL 2008].



Wind Power Classification

	Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m ^{2}	Wind Speed[a] at 50 m m/s	Wind Speed[a] at 50 m mph
☐	1	Poor	0 - 200	0.0 - 5.9	0.0 - 13.2
■	2	Marginal	200 - 300	5.9 - 6.8	13.2 - 15.2
■	3	Fair	300 - 400	6.8 - 7.5	15.2 - 16.8
■	4	Good	400 - 500	7.5 - 8.0	16.8 - 17.9
■	5	Excellent	500 - 600	8.0 - 8.5	17.9 - 19.0

[a] Wind speeds are based on a Weibull k of 2.5 at sea level.

The annual wind power estimates for this map were produced by AWS Truewind using their Mesomap system and historical weather data.

U.S. Department of Energy
National Renewable Energy Laboratory

Figure 2-5 Puerto Rico annual average wind map at 50 m height [Source: NREL 2008]

The maps show estimates of wind speed. The only way to make sure the wind speed presented in the maps is correct for a given location is to use an anemometer to measure wind speed at the site. Several studies have measure wind speed in Puerto Rico. TABLE 2-8 and TABLE 2-9 present a diurnal distribution of mean wind velocity in (m/s) for several sites in Puerto Rico. TABLE 2-10 and TABLE 2-11 present monthly distribution of mean wind velocity in (m/s) for the sites shown in TABLE 2-8 and TABLE 2-9. All the data has been adjusted to a height of 25 meters from the ground.

TABLE 2-8 Diurnal distribution of mean wind velocity, m/s at 25 m above ground [Briscoe, 1966]

hour	Cape San Juan	Yunque	Gurabo Town	Viejo San Juan	Buchanan	Rio Blanco	Roosevelt Roads	Fajardo City	Catalina
1	6.35	6.25	1.21	2.42	1.45	0.68	4.70	0.63	1.02
2	6.11	6.20	1.26	2.18	1.36	0.68	4.60	0.63	1.07
3	6.45	6.20	0.92	2.13	1.45	0.63	3.97	0.63	0.97
4	6.11	6.30	1.11	2.08	1.45	0.63	4.02	0.58	1.02
5	6.06	6.25	0.97	1.99	1.41	0.68	4.07	0.58	1.02
6	6.11	6.25	1.16	2.04	1.31	0.63	4.02	0.63	1.11
7	6.25	6.45	1.07	1.94	1.16	0.63	4.02	0.63	1.31
8	6.06	6.35	1.02	2.52	1.31	0.68	4.85	0.78	1.41
9	6.11	6.06	1.11	3.64	1.70	0.78	5.62	1.16	1.45
10	6.20	5.87	1.89	4.99	2.38	1.07	6.16	1.60	1.55
11	6.11	5.82	2.62	5.87	3.01	1.21	6.45	1.74	1.60
12	6.20	5.72	3.20	6.30	3.30	1.31	6.69	1.89	1.89
13	6.35	5.67	3.34	6.69	3.49	1.41	6.59	2.18	1.89
14	6.35	5.77	3.44	6.64	3.59	1.45	6.79	2.13	1.89
15	6.50	5.87	3.44	6.30	3.49	1.26	6.59	2.08	1.94
16	6.59	5.91	3.10	6.11	3.20	1.16	6.45	2.13	1.79
17	6.59	5.77	2.67	5.67	3.10	1.02	6.01	1.70	1.50
18	6.45	6.01	2.08	5.04	2.76	0.73	5.14	1.41	1.31
19	6.54	6.11	1.41	4.17	2.28	0.63	4.65	0.78	1.11
20	6.50	6.25	1.21	3.88	1.79	0.63	4.41	0.63	1.02
21	6.54	6.30	1.31	3.10	1.41	0.58	4.31	0.68	0.97
22	6.35	6.35	0.97	3.01	1.36	0.63	4.22	0.63	1.02
23	6.59	6.30	1.11	2.62	1.26	0.58	4.27	0.78	0.97
24	6.54	5.91	0.87	2.47	1.21	0.58	4.17	0.68	1.02

TABLE 2-9 Diurnal distribution of mean wind velocity, m/s at 25 m above ground

hour/place	Aguirre [a]	Cuyón [a]	CROEM [a]	Cape San Juan [a]	Tallaboa [b]
1	2.28	5.97	4.61	6.68	2.24
2	2.18	5.86	4.51	6.52	2.27
3	2.29	5.79	4.28	6.47	2.30
4	2.28	5.59	4.43	6.43	2.34
5	2.13	5.61	4.14	6.35	2.39
6	2.16	5.59	4.09	6.20	2.42
7	2.19	5.61	3.98	6.17	2.42
8	2.29	5.61	3.83	6.27	2.37
9	3.00	5.42	3.55	6.26	3.12
10	4.37	5.10	3.70	6.26	4.15
11	5.47	4.83	4.18	6.33	4.93
12	6.06	4.61	4.44	6.39	5.51
13	6.53	4.58	4.83	6.47	5.82
14	6.69	4.67	4.99	6.49	5.82
15	6.63	4.69	4.89	6.56	5.57
16	6.38	4.72	4.75	6.53	5.18
17	5.89	4.62	4.43	6.56	4.67
18	5.30	4.70	4.21	6.49	4.03
19	4.38	4.94	4.25	6.81	3.24
20	3.32	5.23	4.30	6.95	2.62
21	2.80	5.66	4.51	6.93	2.37
22	2.58	5.94	4.41	6.96	2.22
23	2.52	6.15	4.55	6.93	2.18
24	2.46	6.11	4.59	6.71	2.20

[a] [Soderstrom, 1989]

[b] [PREPA, 1997] (original measurements at 10 m, adjusted to 25 m using 1/7 power law)

TABLE 2-10 Monthly average distribution of wind velocity, m/s at 25 m above ground [Briscoe, 1966]

Place\ Month	Cape San Juan	Yunque	Gurabo	Viejo San Juan	Buchanan	Rio Blanco	Roosevelt Roads	Fajardo	Catalina
Jan	5.50	6.16	1.43	3.20	2.40	1.07	4.85	1.45	1.04
Feb	5.40	5.21	1.70	4.44	2.52	1.04	5.65	1.41	1.91
Mar	6.30	2.13	1.94	4.70	1.74	0.99	5.74	1.53	1.96
Apr	8.36	5.43	2.04	3.95	2.59	0.92	5.91	1.43	1.58
May	7.76	7.05	1.94	1.94	0.87	0.58	5.60	0.95	1.19
Jun	6.83	8.97	2.40	4.58	2.62	0.80	5.87	0.58	0.97
Jul	8.85	7.66	2.11	4.85	2.64	0.80	6.45	0.90	1.87
Aug	7.59	6.45	2.01	5.26	1.62	0.92	5.94	1.26	1.41
Sep	4.19	6.52	1.09	3.73	2.18	0.70	3.71	0.63	1.38
Oct	6.08	7.13	1.77	3.20	2.11	0.70	4.00	1.38	0.92
Nov	3.13	5.19	1.16	3.05	1.87	0.70	3.64	1.07	0.92
Dec	6.01	5.09	1.67	4.00	1.94	0.90	4.05	1.07	0.78

TABLE 2-11 Monthly average distribution of wind velocity, m/s at 25 m above ground [Soderstrom, 1989]

Place\ Month	Aguirre	Cuyón	CROEM	Cape San Juan
Jan	3.72	5.42	3.65	6.40
Feb	3.76	4.76	5.04	6.11
Mar	3.86	5.50	4.89	6.13
Apr	3.29	4.06	4.89	6.34
May	3.81	5.05	4.38	5.68
Jun	2.95	5.40	3.57	4.90
Jul	4.69	6.72	3.16	7.11
Aug	4.72	6.35	4.20	5.76
Sep	4.37	4.76	3.54	6.76
Oct	4.45	4.33	3.42	6.76
Nov	3.36	5.61	5.74	7.76
Dec	3.11	5.84	5.74	7.01

2.9 Weather Effects

The sun causes most weather effects changes. When the sun strikes the earth, it heats the soil near the surface. In turn, the soil warms the air lying above it. Warm air is less dense than cool air, and, like a helium-filled balloon, it rises. Cool air flows in to take its place and is itself heated. The rising warm air eventually cools and falls back to the earth completing the convection cell. This cycle is repeated over and over again every day. This is how wind is created on Earth. While the sun keeps shinning the earth wind will keep flowing.

In islands, winds are stronger and more frequent along the coast because of differential heating between the land and the water. During the day, the sun warms the land much quicker than it does the surface of water. Water has higher specific heat and can store more energy without a change in temperature than can soil. The air above the land is once again warmed and rises. Cool air flows landward, replacing the warm air, creating a large convection cell. At night the flows reverse as the land cools more quickly than the water. [*Gipe* 2006]

2.9.1 Monthly Wind Variations in Puerto Rico

The average wind speeds in Puerto Rico vary by season and by month. In summer the island is windier in comparison to winter. This happens because summer is warmer than winter. Sun's rays hit the Earth at a more direct angle during summer than during winter and also because the days are much longer than the nights during the summer. During the winter, the Sun's rays hit the Earth at an extreme angle, and the days are short. These effects are due to the tilt of the Earth's axis. **Figure 2-6** shows the average monthly distribution of mean wind velocity in (m/s).

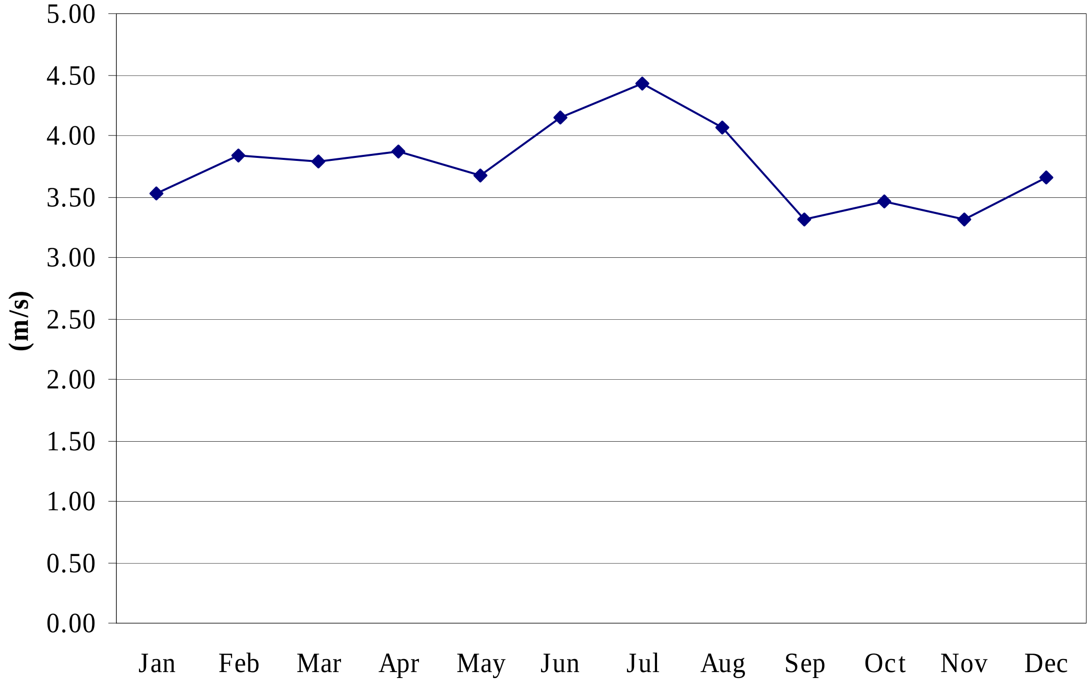


Figure 2-6 Puerto Rico Average Monthly Wind Speed

2.9.2 Diurnal Wind Effects in Puerto Rico

The diurnal effect is the change in wind speed from the night to the day. Puerto Rico presents this effect very clearly in inland areas. Figure 2-7 shows the average diurnal wind speed change. The graph shows that as the sun heats the ground in the morning hours the wind speed increases. At sunset the wind returns to the speed it had during the morning hours. Figure 2-8 presents the diurnal effect at different sites in Puerto Rico.

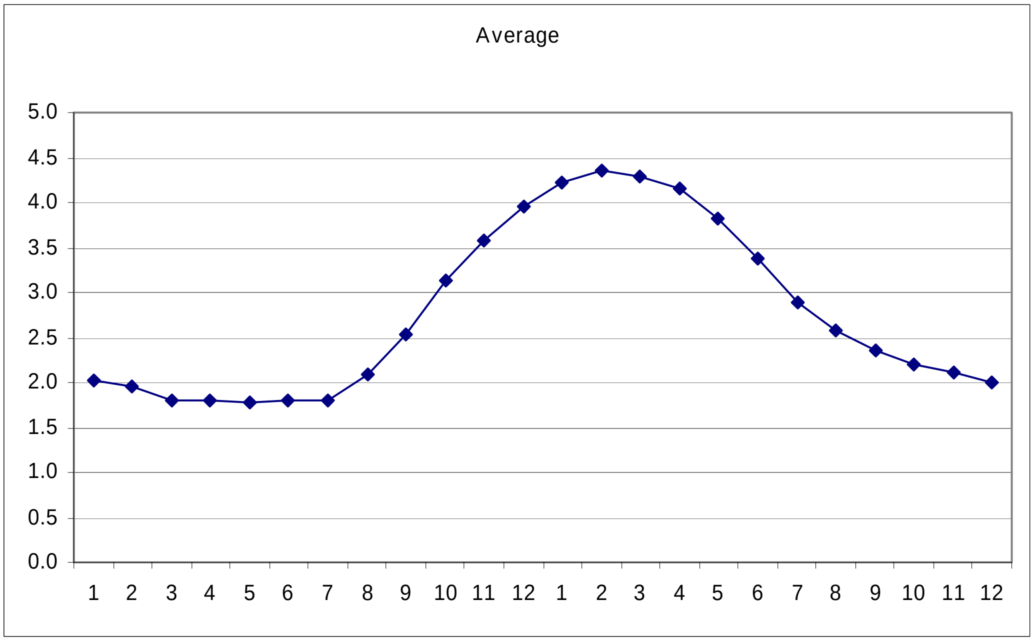


Figure 2-7 Puerto Rico Average Diurnal Wind Speed Effect

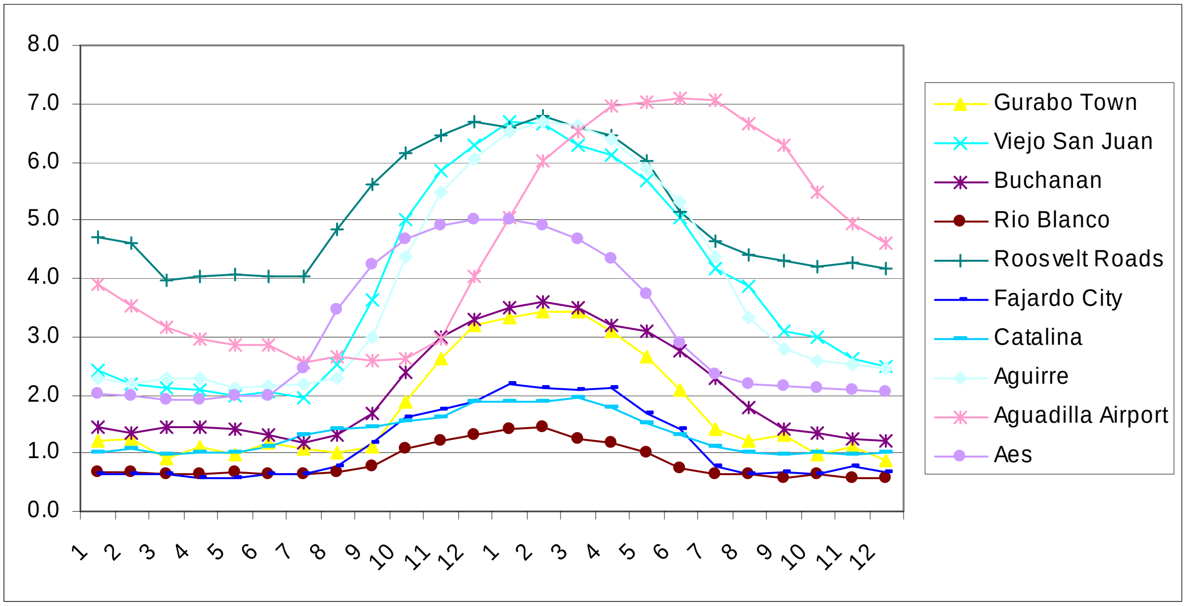


Figure 2-8 Hourly Average Wind Speed in Places with Diurnal Wind Effect Change

But not all places present this effect. For example places in Puerto Rico like Fajardo "Cape San Juan" and the Peak of Yunque Mountain that has no obtrusion to the northeast trade winds, do not present a significant diurnal change. The northeast trade winds have average speed around 6.5 m/s. Figure 2-9 presents the hourly average wind speed in places where there is no diurnal change effects.

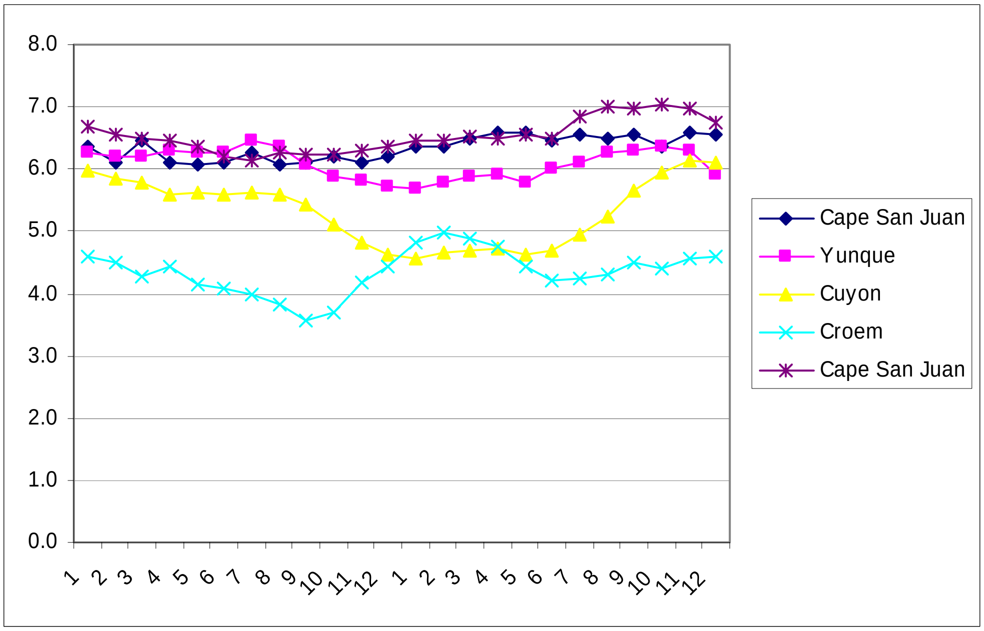


Figure 2-9 Hourly average wind speed with no diurnal change

2.10 Estimated Inland Required Surface or "Foot Print", for Wind Turbines

2.10.1 Estimated Inland Surface Area

The island of Puerto Rico has an area of approximately 160 km x 56 km = 8,960 km², or approximately 2.24 million cuerdas.[1] From wind maps we identify the best wind to be in a 3 km wide band along the north, east, and south coast, as shown in Figure 2-10. This 3 km band also has the best access to infrastructure; wide roads, proximity to the electric grid, ports etc. We estimate this 3 km wide band along the north, east, and south coast to has an area of approximately 960 km² (240,000 cuerdas). This is 10.7% of Puerto Rico's total area.

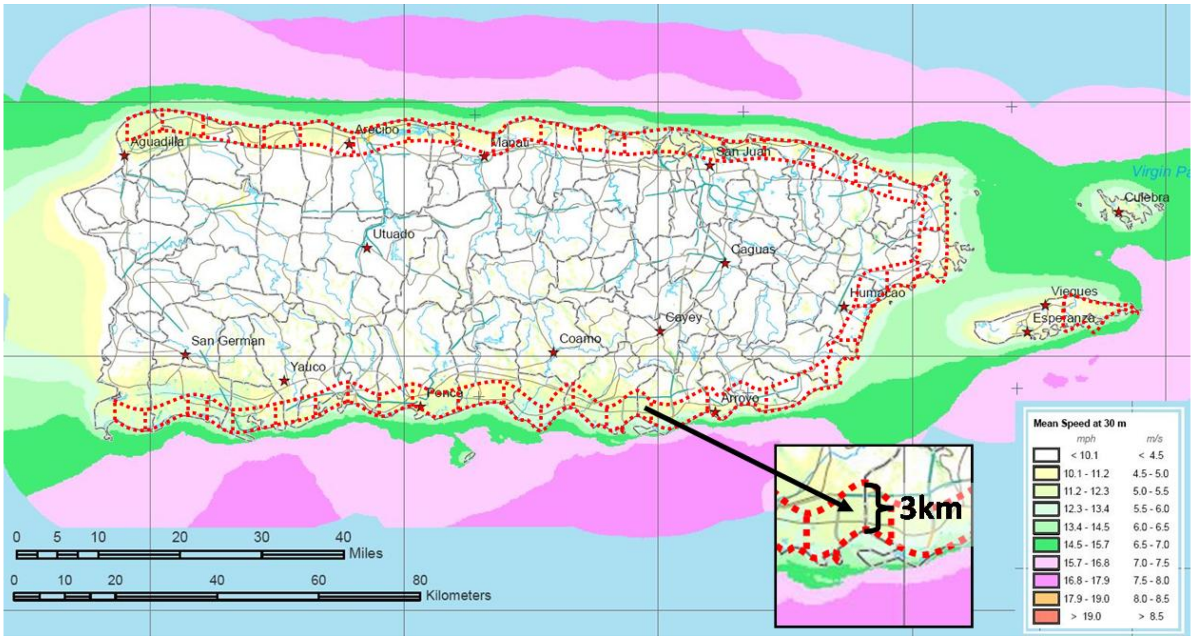


Figure 2-10 Selected Area with High Wind Speed Resources [Background map from AWS Truewind]

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[1] One cuerda is an unit of area equal to approximately 4,000 m^2. 1 km equals 1,000 m, 1 km^2 = 1,000,000 m^2, thus 1 km^2 is approximately 250 cuerdas.

Not all of this land is available since a portion of it is being used. Thus, an assessment is needed to identify fallow and used land. Since determining if land is being used can become a philosophical debate we simplify the analysis dividing the area into populated areas, where structures are built, and unpopulated areas. We use satellite photography (using Google Earth) to perform this task and the results are shown in **Figure 2-11.** Areas marked with red dots represent unpopulated areas and areas marked with lines represent populated areas.

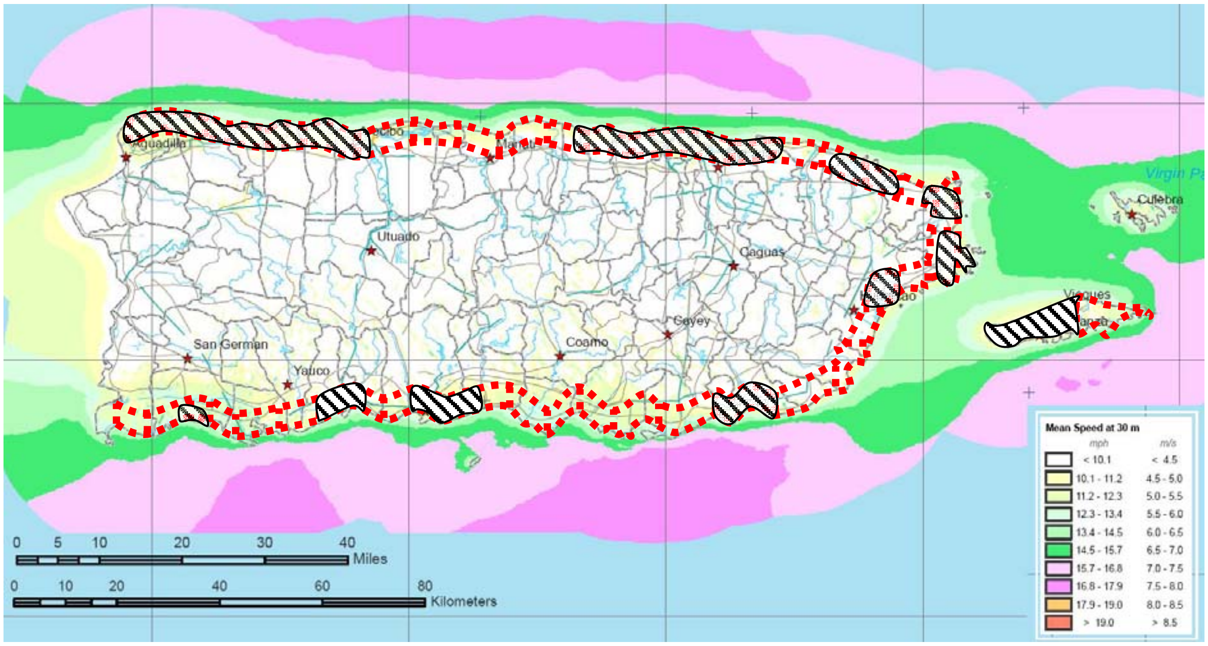

Figure 2-11 Populated Area and Unpopulated Area in Puerto Rico [Background map from AWS Truewind]

Further geometric analysis, using the map and a ruler, shows that approximately 50% of the total area in the 3 km band corresponds to populated areas, 480 km² or 120,000 cuerdas. We assume that populated areas may not be used to develop wind farms using large wind turbines but it can be used to install small wind turbines, residential and commercial type turbines. The remaining 50% of the 3 km wide band along the north, east, and south coast is not heavily populated and we assume it can be used to develop wind farms using large wind turbines.

2.10.2 Large Wind Turbine Spacing

A wind turbine is designed to extract energy from the wind as it passes thru its blades. Since the wind mass is the same before and after the turbine but the wind has less energy the wind speed decreases. If we wish to install a second wind turbine behind the first one we must separate the turbines enough for the wind to recover its original speed thus allowing the second wind turbine to produce as much electricity as the first one.

Optimum separation will vary with type of terrain, wind speed, wind turbines being used and other factors. In this work we use as general rule, assuming flat land, that large turbines will be placed apart a distance of 6 to 10 rotor diameters in the direction of prevailing wind and half of that separation, 3 to 5 rotor diameters, in the direction perpendicular to the prevailing winds, see Figure 2-12. Note that this separation is a function of the wind turbine rotor diameter, thus turbines with larger rotor will be placed farther apart than turbines with smaller rotor.

Thus assuming a desired separation factor, k, the area required by each turbine as a function of its rotor diameter can be easily calculated as shown in Figure 2-13.

Table 2-12 shows an estimate of required area per turbine and installed capacity per unit area, as a function of wind turbines separation, for several wind turbines.

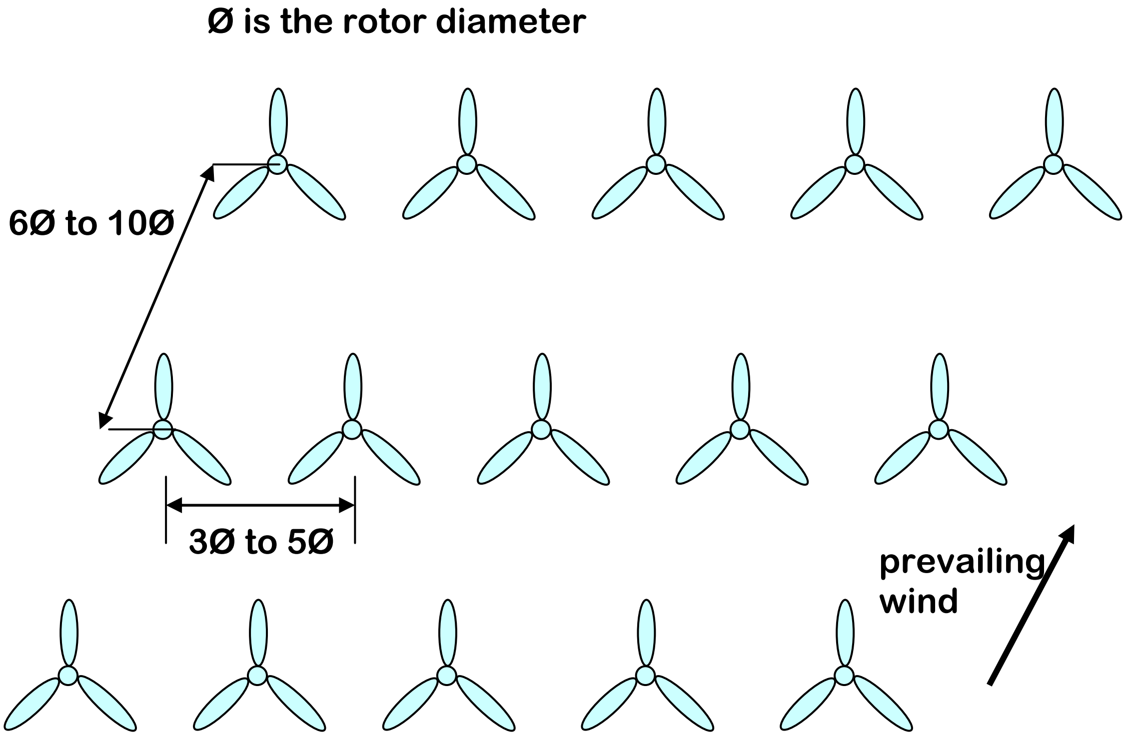

Figure 2-12 Large wind turbine spacing

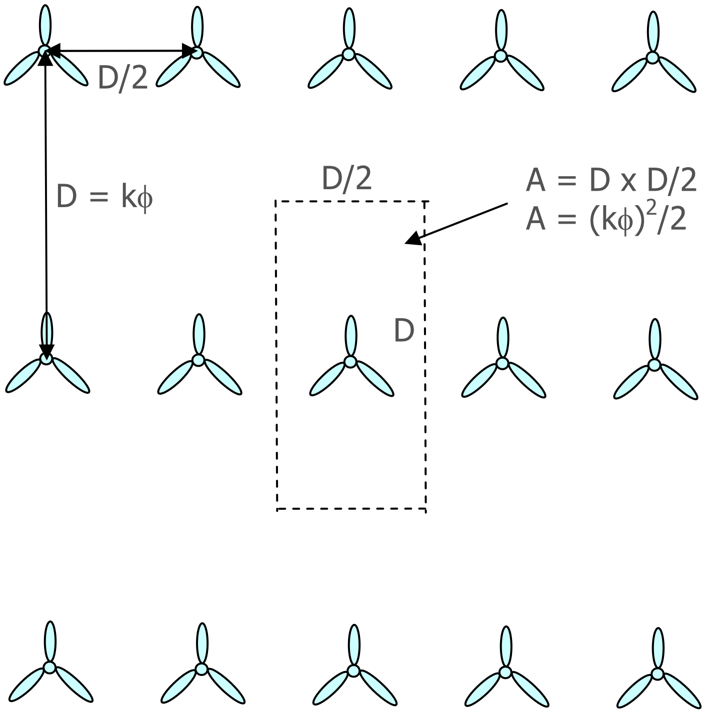

Figure 2-13 Area required by each large wind turbine

Table 2-12 Required area per turbine and installed capacity per unit area as a function of wind turbines separation for several wind turbines.

Turbine	Power capacity [MW]	Rotor diameter [m]	k=10	k=8	k=6	k=10	k=8	k=6
			Area per turbine [km^2]			Installed capacity per unit area [MW/km^2]		
Enercon E53	0.81	53	0.140	0.090	0.051	5.8	9.0	16.0
Vestas V52	0.85	52	0.135	0.087	0.049	6.3	9.8	17.5
Gamesa G58	0.85	58	0.168	0.108	0.061	**5.1**	7.9	14.0
AAER A1000	1.00	58	0.168	0.108	0.061	5.9	9.3	16.5
Enercon E 70	2.30	70	0.245	0.157	0.088	9.4	14.7	26.1
GE 2.5xl	2.50	100	0.500	0.320	0.180	**5.0**	7.8	13.9

Note that a commonly used "power density" of 5 MW/km^2 corresponds to a conservative separation of 10 rotor diameters in the direction of prevailing wind for these large turbines, k = 10.

2.10.3 Estimate number of large wind turbines and installed capacity

An estimate of the number of large wind turbines, per square kilometer, that could be installed in the unpopulated half of the 3 km wide band along the north, east, and south coast of Puerto Rico is shown in Table 2-13. If we were to use all available land, 480 km^2, and turbines with rotor diameter of 52 m, such as the Vestas V52, with a spacing factor k=8 then 5,547 turbines could be installed. In the other hand, if we were to use only 10% of the available land, 48 km^2, and larger turbines with rotor diameter of 100 m, such as the GE 2.5xl, with a spacing factor k=10 then only 96 turbines could be installed.

Table 2-13 Estimate of large wind turbines that could be installed

Turbine	Power capacity [MW]	Rotor diameter [m]	k=10	k=8	k=10	k=8	k=10	k=8
			Turbines in 480 km^2		Turbines in 240 km^2		Turbines in 48 km^2	
Enercon E53	0.81	53	3418	5340	1709	2670	342	534
Vestas V52	0.85	52	3550	5547	1775	2774	355	555
Gamesa G58	0.85	58	2854	4459	1427	2229	285	446
AAER A1000	1.00	58	2854	4459	1427	2229	285	446
Enercon E70	2.30	70	1959	3061	980	1531	196	306
GE 2.5xl	2.50	100	960	1500	480	750	96	150

Finally, an estimate of installed capacity in MW is shown in Table 2-14. If we were to use all available land, 480 km^2, and turbines with rotor diameter of 52 m, such as the Vestas V52, with a spacing factor k=8 then 4,715 MW could be installed. In the other hand, if we were to use only 10% of the available land, 48 km^2, and larger turbines with rotor diameter of 100 m, such as the GE 2.5xl, with a spacing factor k=10 then only 375 MW could be installed.

Table 2-14 Estimate of installed capacity in MW

Turbine	Power capacity [MW]	Rotor diameter [m]	k=10	k=8	k=10	k=8	k=10	k=8
			MW in 480 km^2		MW in 240 km^2		MW in 48 km^2	
Enercon E53	0.81	53	2768	4325	1384	2163	277	433
Vestas V52	0.85	52	3018	4715	1509	2358	302	472
Gamesa G58	0.85	58	2426	3790	1213	1895	243	379
AAER A1000	1.00	58	2854	4459	1427	2229	285	446
Enercon E70	2.30	70	4506	7041	2253	3520	451	704
GE 2.5xl	2.50	100	2400	3750	1200	1875	240	375

Is it better to install less very large turbines or smaller turbines? Wind turbines are not power producers, they are energy producers. The answer is install turbines that produce the most amount of energy, turbines that match the wind regime.

2.10.4 Estimate energy production using large wind turbines

To estimate the energy production per turbine we use the turbine power curve, as provided by the manufacturer, and the wind distribution. We offer an example for wind turbines that can be installed at similar height, 50 m in this case. Power curves for the wind turbines with rotor diameter of approximately 50 m; Enercon E53, Vestas V52, Gamesa G58, AAER A1000 and Suzlon Series 600 are shown in Figure 2-14.

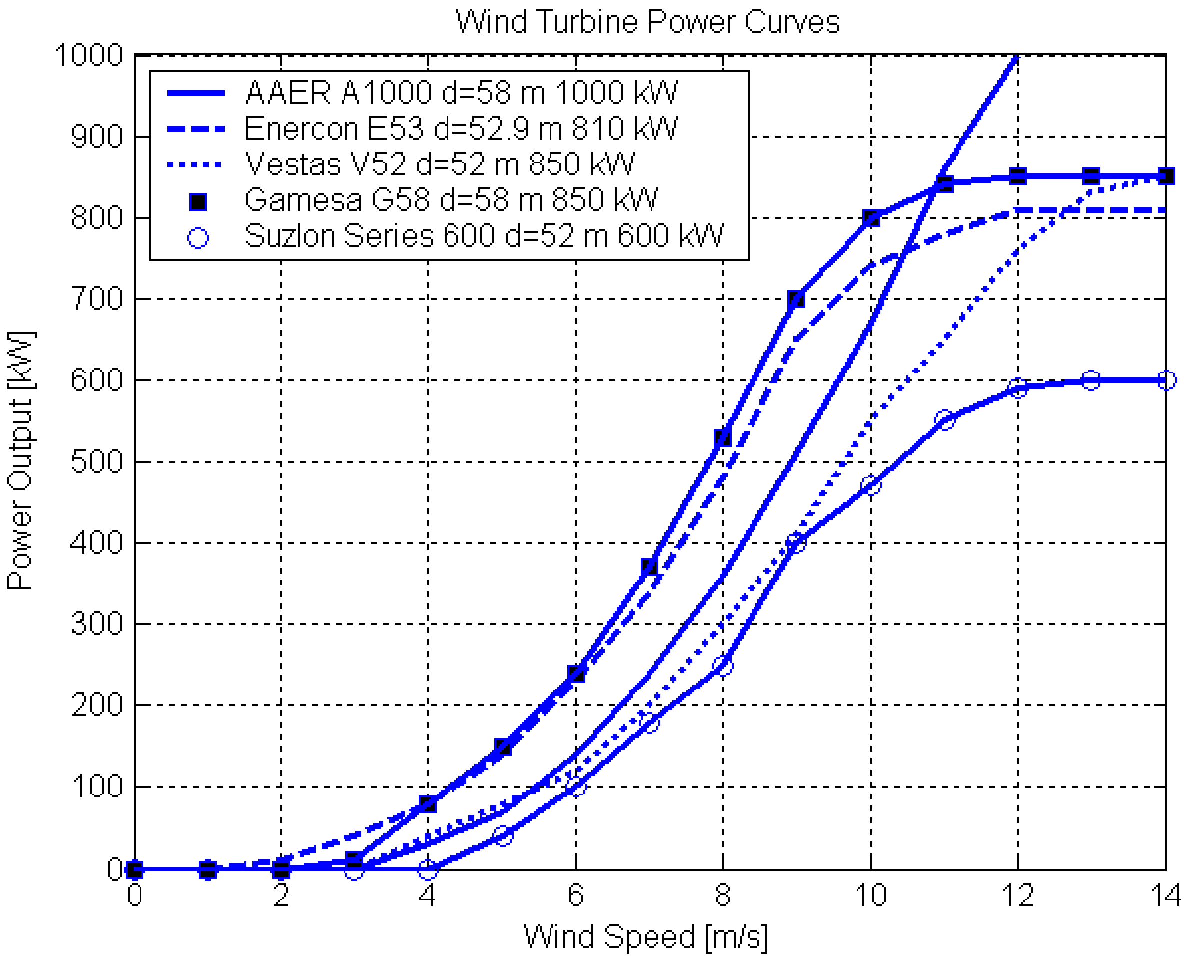

Figure 2-14 Power curves for turbines than can be installed at 50 m height; Enercon E53, Vestas V52, Gamesa G58 and AAER A1000.

Note that even thought they are rated at the same power, 850 kW, the Gamesa G58 generates greater or equal power than the Vestas V52 at all wind speeds. This is so because the Gamesa G58 has a larger rotor and will produce more energy than the Vestas V52.

Also note that even though the AAER A1000 is rated at 1,000 kW and has a rotor diameter of 58 m, equal to the Gamesa G58 rotor diameter, the Gamesa G58 will produce more energy because it generates greater or equal power than the AAER A1000 at wind speeds under 11 m/s.

Wind speed varies with wind site and, at most sites in Puerto Rico, the wind speed is less than 11 m/s during most of the hours of the year as shown in Figure 2-15.

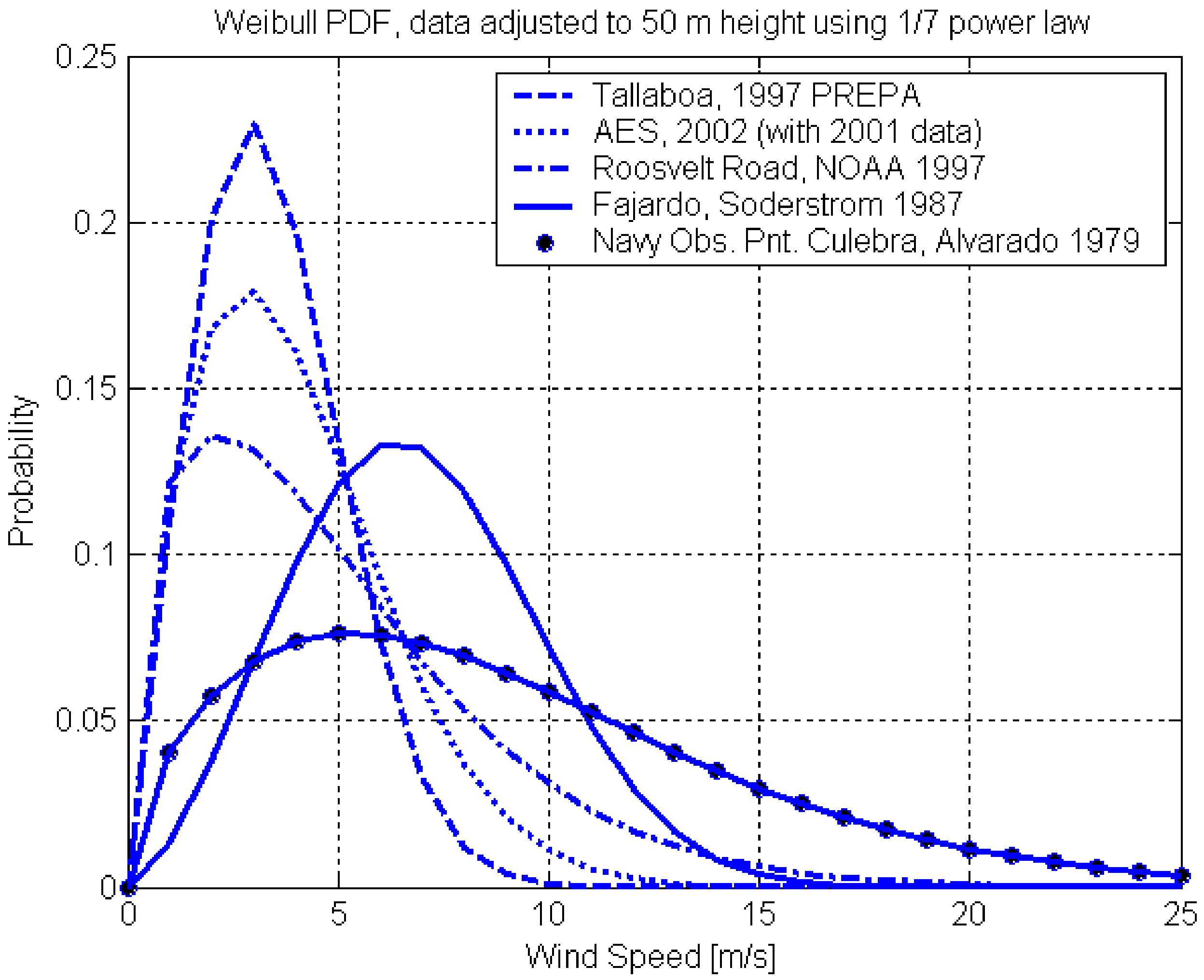

Figure 2-15 Weibull probability density functions at five sites in Puerto Rico.

A probability density function (pdf), in this case a Weibul pdf, summarizes the probability of the wind blowing at a given speed. The probability axis, the vertical axis, can be easily converted to hours in a year by simply multiplying it by the number of hours in a standard year, 8760 hours. Then the plot will indicate the number of hours the wind was blowing at a given speed.

Figure 2-16 shows the location of the sites with wind speed (Weibull) pdf shown in Figure 2-15**.** Note how the probability of higher wind speeds increases as we move from west to east and from south east to north east.

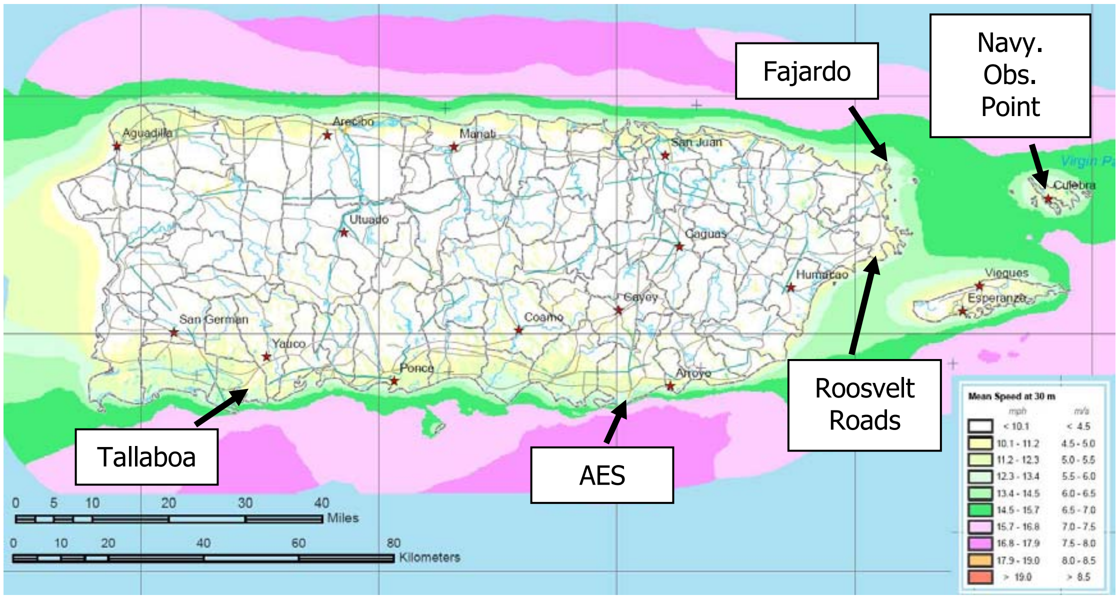

Figure 2-16 Sites with wind speed (Weibull) pdf shown in Figure 2-15 [Background map from AWS Truewind]

To obtain the energy production for a given wind turbine we combine its power curve and the probability density function of wind speed at a given site. Figure 2-17 shows the Weibull pdf (in hours/year) at AES and the Gamesa G58 power curve. The point by point product of hours per year and power produced at each wind speed produces the energy density function shown in Figure 2-18.

The area under the energy density function, or alternatively the sum of all products of hours per year and power produced at each wind speed, provide an estimate of the annual energy production of the wind turbine at the specific site.

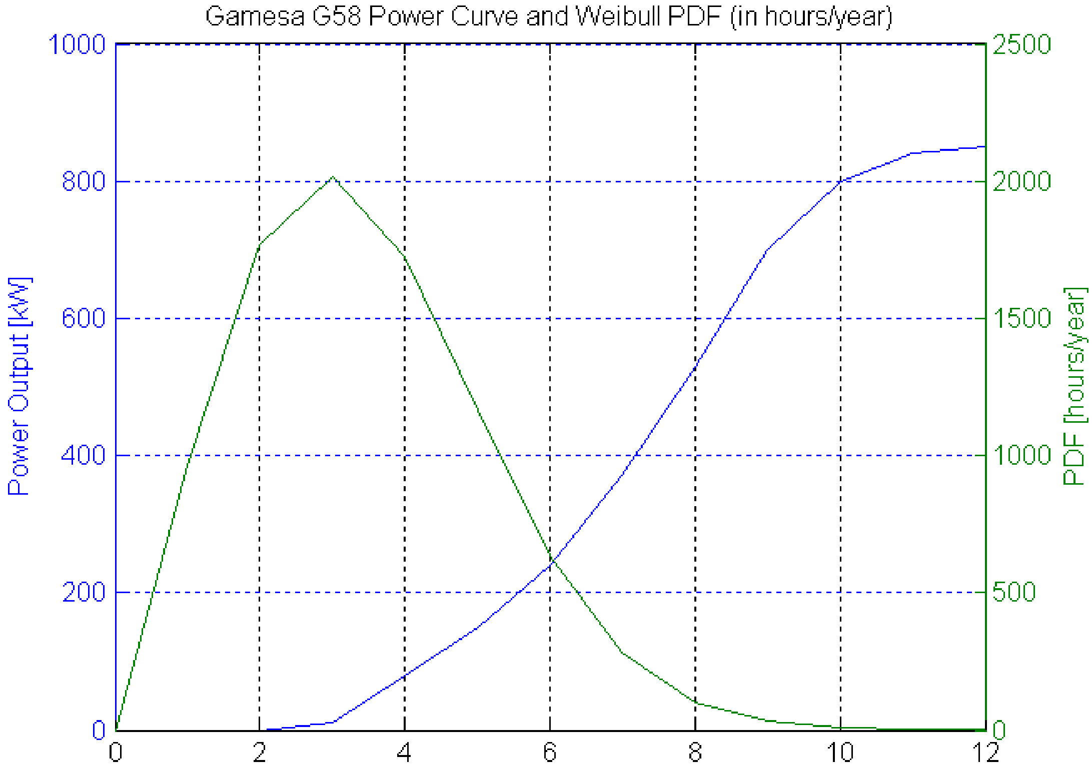

Figure 2-17 Wind speed Weibull pdf (in hours/year) at AES and Gamesa G58 power curve.

Table 2-15 shows the annual energy production, in MWh, per turbine @ 50 m height and different sites in Puerto Rico. Note that the Gamesa G58 produces more energy than the AAER A1000 at all sites. Also note that the Enercon E53 produces more energy than the Gamesa G58 in Tallaboa where the wind blows at lower speed.

Table 2-15 Annual energy production, in MWh, per turbine @ 50 m height

Turbine	Power capacity [MW]	Rotor diameter [m]	Tallaboa	AES	Roosvelt Roads	Fajardo
Enercon E53	0.81	53	**725**	**1127**	**1722**	**3142**
Vestas V52	0.85	52	**348**	**637**	**1154**	**2153**
Gamesa G58	**0.85**	58	**681**	**1136**	**1793**	**3355**
AAER A1000	**1.00**	58	**354**	**714**	**1378**	**2614**

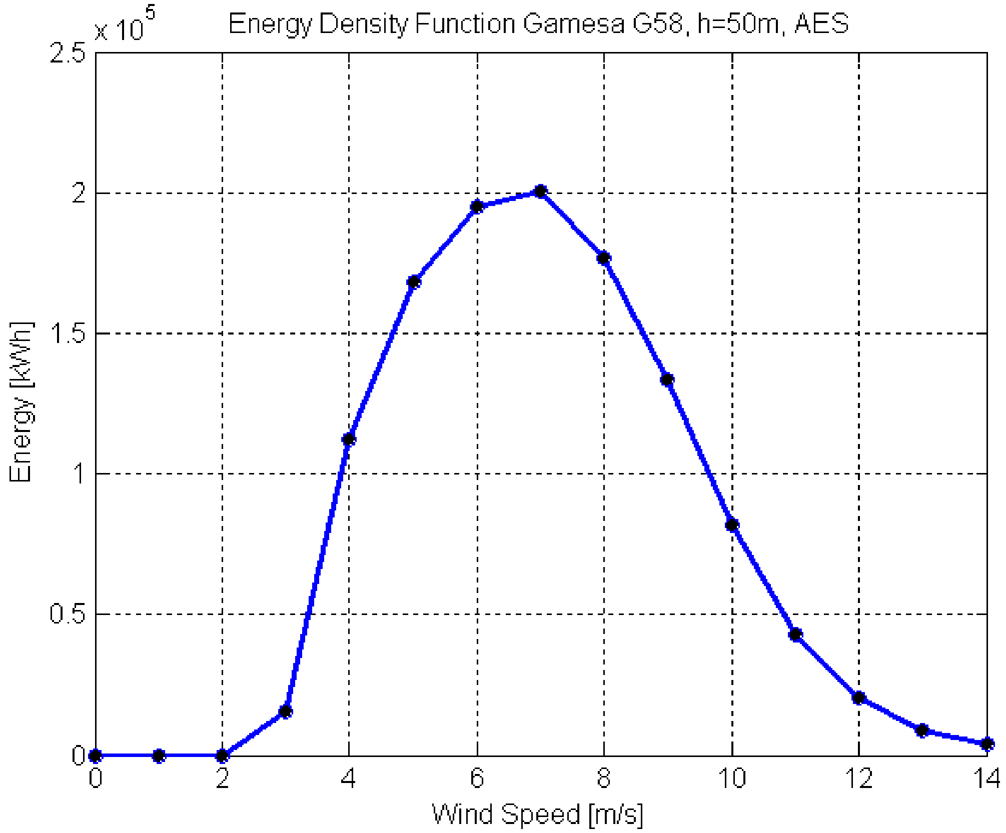

Figure 2-18 Estimate of the energy density function for a Gamesa G58 wind turbine installed at 50 m in the vicinity of AES, Guayama Puerto Rico.

Assuming we were to use only 10% of the available land, 48 km^2, and Gamesa G58 turbines with spacing factor k=10, then 285 turbines could be installed. Assuming an annual 1136 MWh per turbine the 285 turbines will generate approximately 323,760 MWh per year.

According to the Puerto Rico Electric Power Authority in Puerto Rico the average residential costumer demands 800 kWh per month or 9,600 kWh per year (9.6 MWh per year). These 285 turbines could produce the annual energy required by 33,725 residential customers. On the other hand, according to the "Banco de Desarrollo Económico de Puerto Rico" in 2006 Puerto Rico demanded 20,600,000 MWh, thus these 285 turbines could only produce 1.57% of the energy required in 2006. If we were to use 50% of the unpopulated land in the 3 km wide band along the north, east, and south coast to install this type of turbines we will be able to produce approximately 7.86% of the energy demanded in Puerto Rico in 2006.

2.10.5 Estimate number of small wind turbines

For small wind turbines we use a very conservative estimate that each wind turbine will occupy approximately 20,000 m², or 5 cuerdas. Even with this assumption the total number of small wind turbines that can be installed in the populated zones of the 3 km band is, 531000000m²/20000m² = 26,550 turbines. Half of these, or 13,275, will still be a significant market for small wind turbines.

2.10.6 Estimate energy production using small wind turbines

Analysis of TABLE 2-1 shows that the Bornay Inclin 3000 and Inclin 6000 are the small turbines with lowest installation cost per unit of capacity, 2.67 $/W for the Inclin 3000 and 2.01 $/W for the Inclin 6000. Further analysis of TABLE 2-4 shows that these two small turbines produce the most amount of energy for the wind regimen we find in Puerto Rico.

We assume that small wind turbines will be installed at a height of 25 m.
Figure 2-22 shows the Weibull pdf adjusted to 25 m height, for several sites in Puerto Rico.

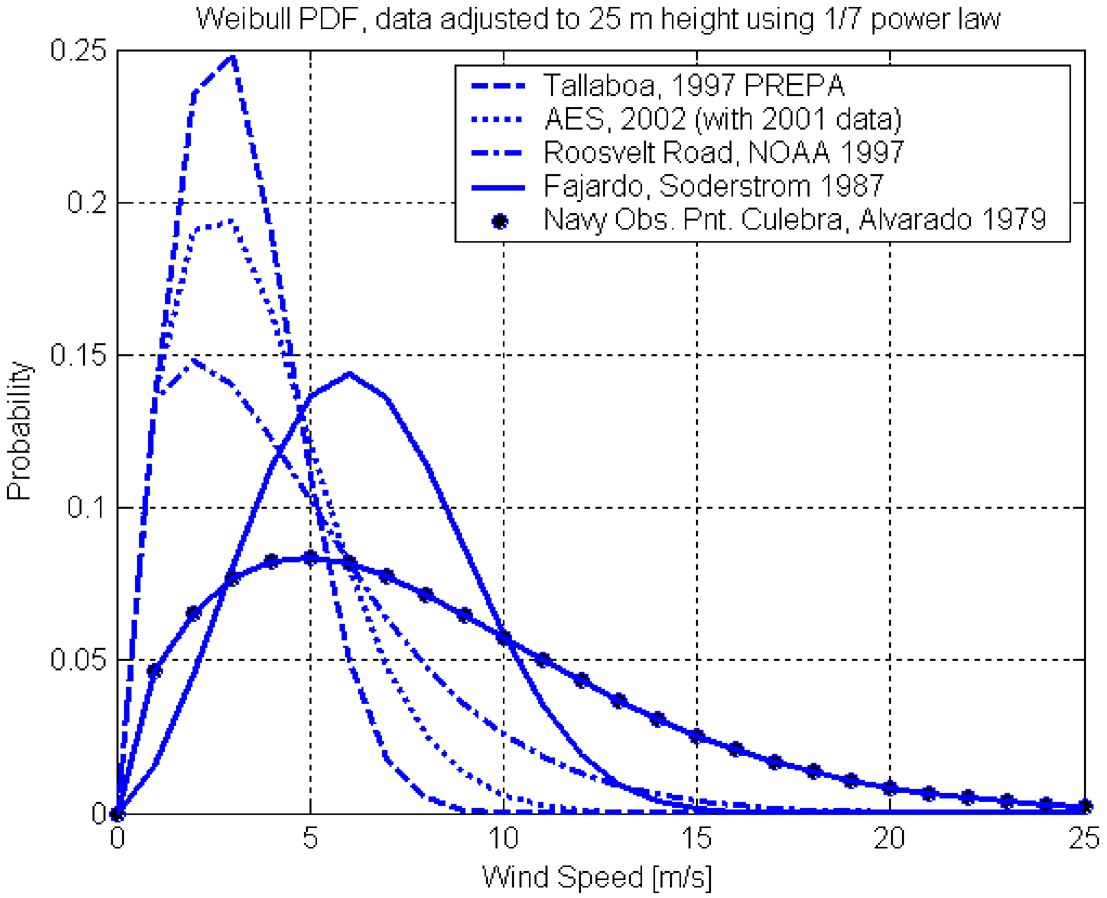

Figure 2-19 Weibull pdf, adjusted to 25 m height, for several sites in Puerto Rico.

Figure 2-20 shows the power curves for the Bornay Inclin 3000 and Inclin 6000 small turbines. Using these power curves and Weibull pdf we estimate the annual energy production, in kWh, per turbine at 25 m height. Figure 2-16 shows the estimated energy production.

Table 2-16 Annual energy production, in kWh, per turbine @ 25 m height

Turbine	Power capacity [kW]	Rotor diameter [m]	Tallaboa	AES	Roosvelt Roads	Fajardo
Bornay Inclin 3000	3	3.7	2870	4148	6334	11,104
Bornay Inclin 6000	6	3.7	6777	9298	13,505	23,200

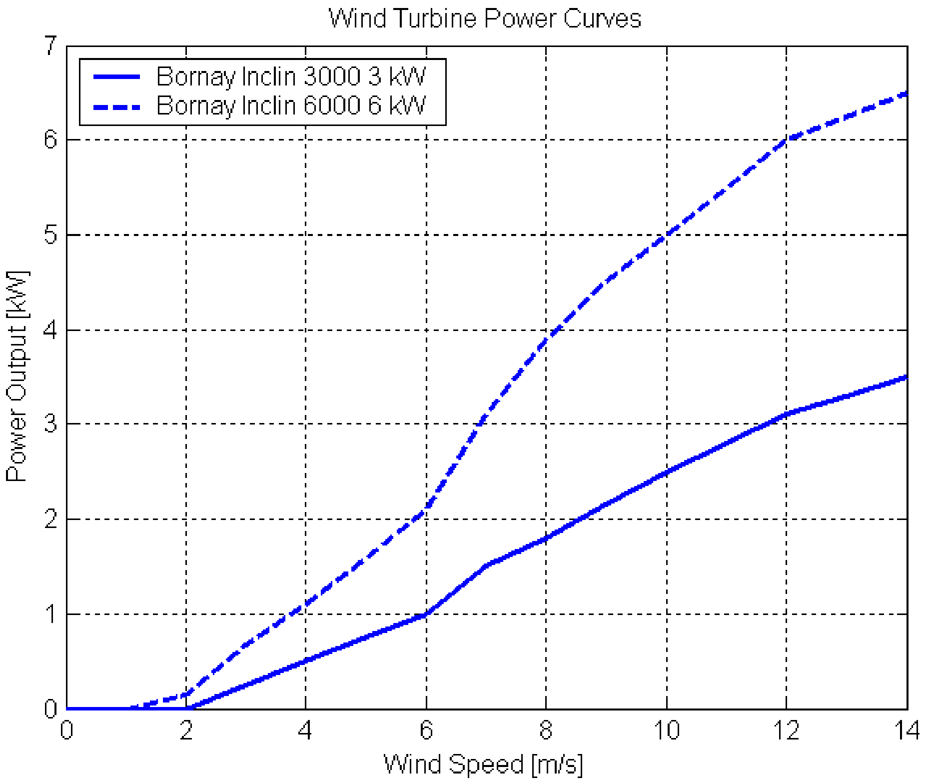

Figure 2-20 Power curves for Bornay Inclin 3000 and Inclin 6000.

Recall that the average residential costumer in Puerto Rico demands 800 kWh per month or 9,600 kWh per year (9.6 MWh per year). The Bornay Inclin 3000 exceeds the annual energy required a residential customer in Fajardo. The Bornay Inclin 6000 exceeds the annual energy required a residential customer in Roosvelt Roads and Fajardo and almost supply the energy demand at AES.

Is it worth to install a small wind turbine? Table 2-17 shows the annual dollar value of the energy produced by each small turbine, and at each site, assuming a residential rate of 27.5 ¢/kWh and net metering program that allows the residential customer to sale all excess energy at the residential rate of 27.5 ¢/kWh.

Table 2-17 Dollar value of annual energy production per turbine @ 25 m height

Turbine	$/kWh	Tallaboa	AES	Roosvelt Roads	Fajardo
Bornay Inclin 3000	0.275	$789	$1,141	$1,742	$3,054
Bornay Inclin 6000	0.275	$1,864	$2,557	$3,714	$6,380

Table 2-18 shows the present value of the energy produced by these small wind turbines assuming an annual interest rate of 2.5% (a conservative inflation adjustment for the cost of money), a fixed and unlikely electricity rate of 27.5 ¢/kWh and 20 years of operation.

Table 2-18 Present worth of the energy produced by small wind turbines

Turbine	Estimated cost of installed turbine	Tallaboa	AES	Roosvelt Roads	Fajardo
Bornay Inclin 3000	$12,000	$12,412	$17,939	$27,393	$48,021
Bornay Inclin 6000	$16,000	$29,308	$40,211	$58,405	$100,333

In all cases an investment in a small turbine returns a profit.

2.11 Offshore Wind Generation

2.11.1 Estimate of offshore area suitable for wind turbine installation

To estimate the area available for off shore wind turbines we use the map provided by NOAA [NOOA 2003] and shown in Figure 2-21. This map allows locating areas with ocean floor 0 to 30 m deep, the standard depth use to install offshore wind turbines.

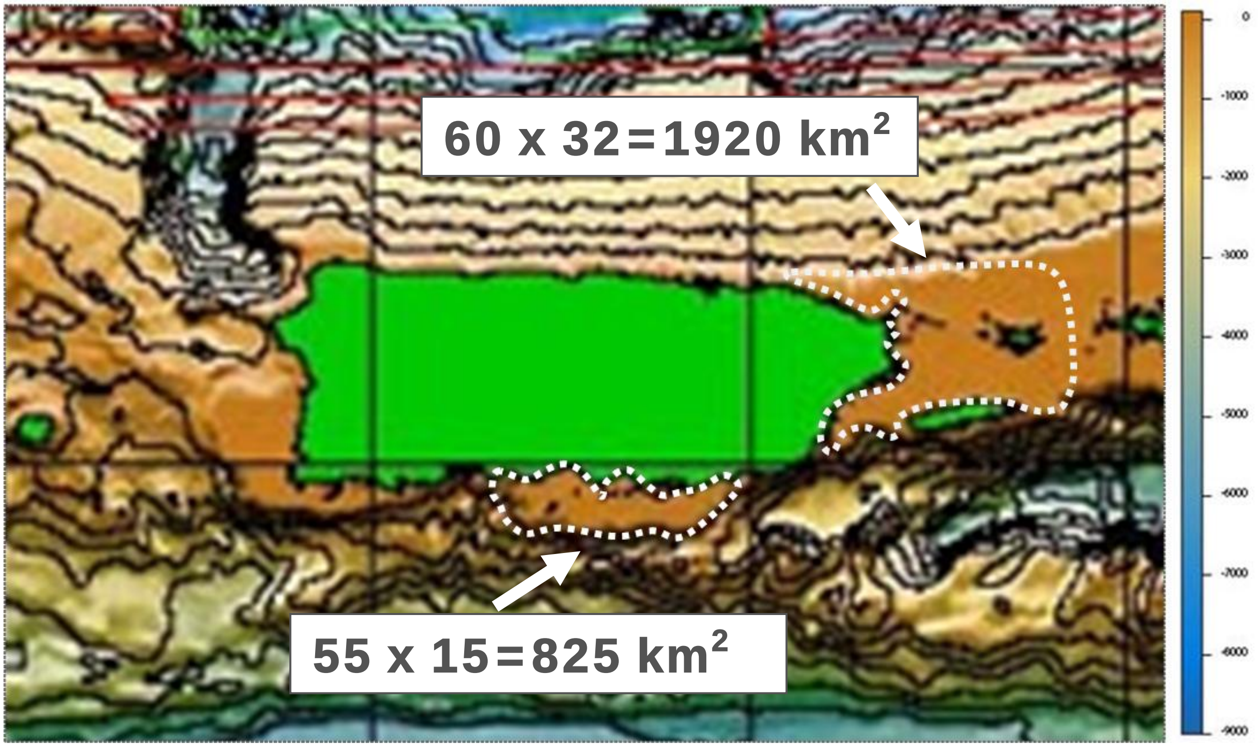

Figure 2-21 Areas of suitable depth for offshore wind turbines [NOOA, 2003]

From this analysis the total suitable are for off-shore wind turbines installation is approximately 2,745 km^2.

2.11.2 Estimate of offshore wind power capacity

Assuming a power density of 5 MW/km^2 the 2,745 km^2 can accommodate 13,725 MW of installed wind capacity. If only 10% is used we still have 1,372 MW.

2.11.3 Estimate of offshore wind energy production

We assume that off-shore wind turbines will be installed at a height of 100 m and that the off-shore wind regime has a Weibull pdf, adjusted to a height of 100 m, similar to wind regime in Roosvelt Roads or Fajardo.

Figure 2-22 shows the Weibull pdf adjusted to 100 m height, for Roosvelt Roads and Fajardo.

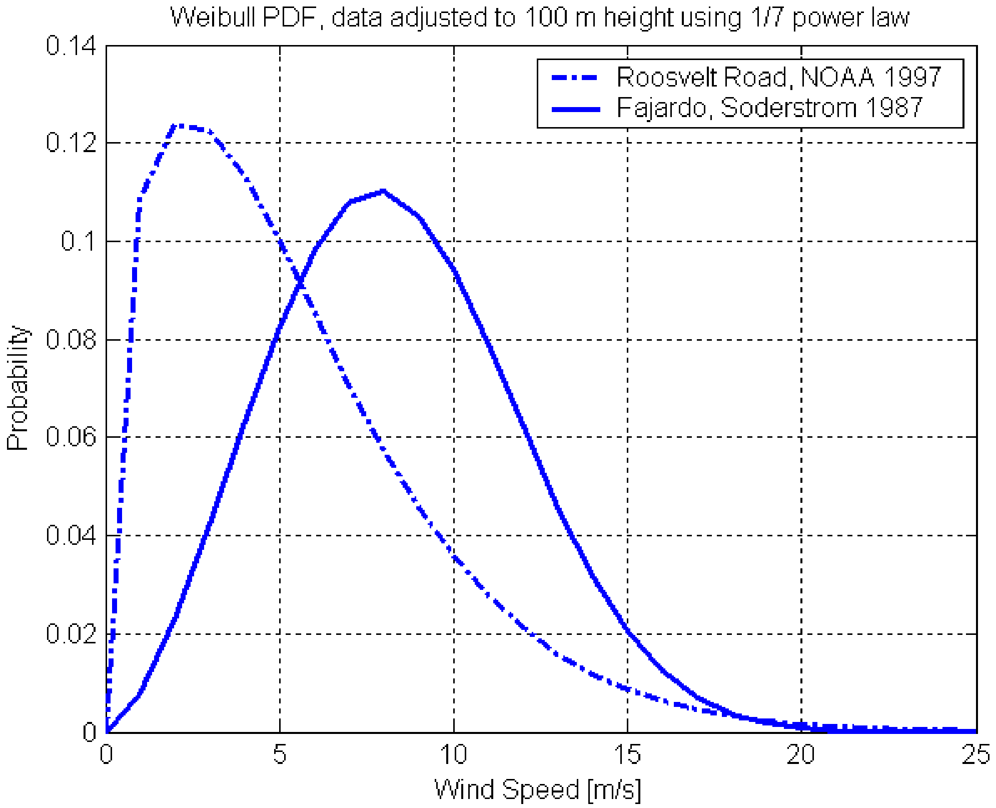

Figure 2-22 Weibull pdf, adjusted to 100 m height, for Roosvelt Roads and Fajardo.

In our analysis we consider four wind turbines that can be installed at 100 m height; Enercon E 70, GE 2.5xl, Vestas V90 and Fuhrlander FL 2500. Figure 2-23 shows the power curves for these large turbines.

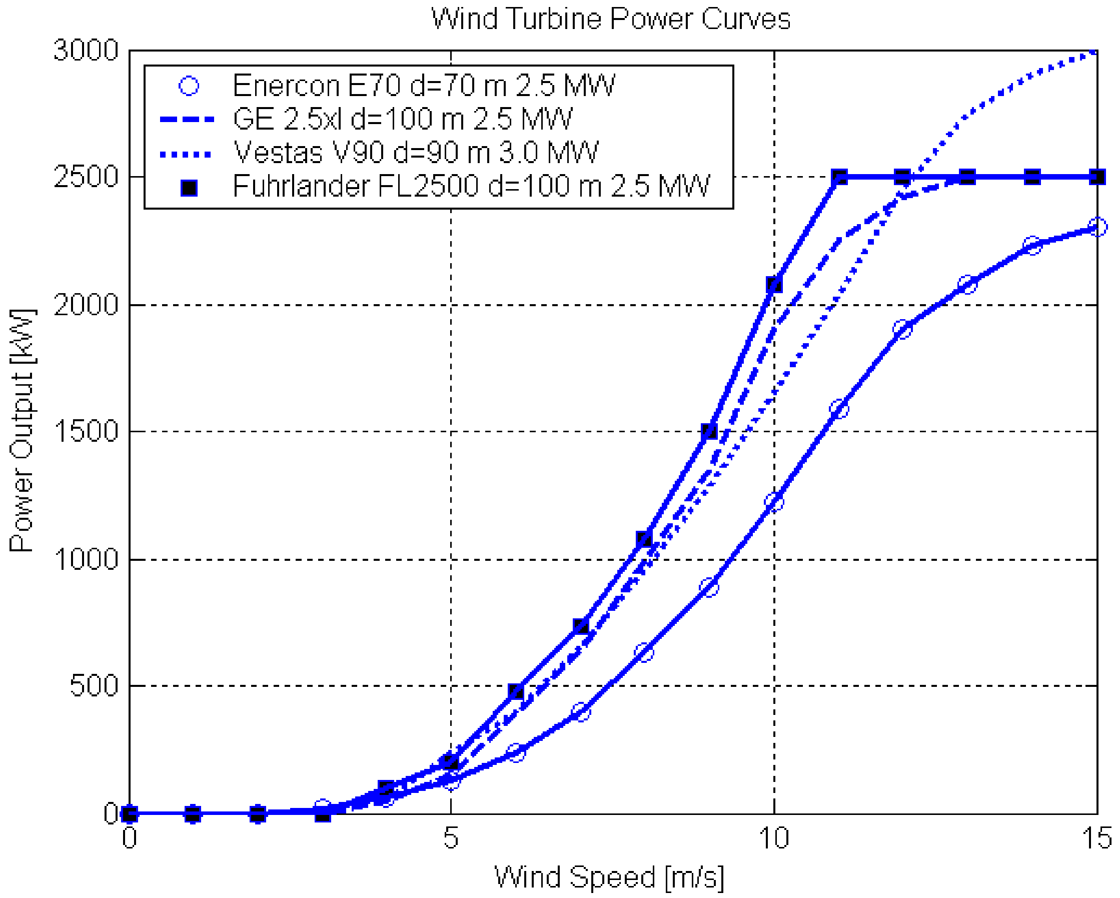

Figure 2-23 Power curves for large wind turbines to be installed at 100 m.

Using these power curves and Weibull pdf we estimate the annual energy production, in MWh, per turbine at 100 m height. Table 2-19 shows these values assuming an off-shore wind regime with a Weibull pdf similar to the specified site.

Table 2-19 Annual energy production, in MWh, per turbine @ 100 m height

Turbine	Power capacity [MW]	Rotor diameter [m]	Roosvelt Roads*	Fajardo*
Enercon E70	2.3	70	3118	7155
GE 2.5xl	2.5	100	4305	9864
Vestas V90	3.0	90	4339	9810
Fuhrlander FL2500	2.5	100	4759	10,680

* The off-shore wind regime is assumed to have a Weibull pdf, adjusted to 100 m height, and similar to the specified site.

Note that the Fuhrlander FL2500 produces more energy than any of the other wind turbines even though its rated capacity of 2.5 MW is less than the 3.0 MW rated capacity of the Vestas V90.

Assuming we were to use only 10% of the available off-shore area, 275 km^2, and Fuhrlander FL2500 turbines with spacing factor k=10, then 550 turbines could be installed. Assuming an annual 4759 MWh per turbine the 550 turbines will generate approximately 2,617,450 MWh per year.

Recall that the average residential costumer in Puerto Rico demands 800 kWh per month or 9,600 kWh per year (9.6 MWh per year). These 550 off-shore turbines could produce the annual energy required by 272,651 residential customers.

According to the "Banco de Desarrollo Económico de Puerto Rico" in 2006 Puerto Rico demanded 20,600,000 MWh, thus these 550 off-shore turbines could produce 12.7% of the energy required in 2006. If we were to use 50% of the available off-shore area to install this type of turbines we will be able to produce approximately 63.5% of the energy demanded in Puerto Rico in 2006. The latter case will require a new approach to the operation of the electric grid.

2.12 Interconnection Issues

High penetration of intermittent wind power (greater than 20% of generation meeting load) in the system faces fundamental technical and financial constraints with regards to the connection of wind farms to the electrical network. These challenges include power quality, active and reactive power flow, infrastructure, network stability, cost recovery and profitability. Technically, it affects the network in the following ways and has to be studied in detail [Zhenyu et al. 2006]:

1) Power flow - Ensure that the interconnecting transmission or distribution lines will not be over-loaded. This type of analysis is needed to ensure that the introduction of additional generation will not overload the thermal limit of the lines and other electrical equipment. Both active and reactive power requirements should be investigated. Reactive power should be generated not only at the interconnection point (PCC), but also throughout the network, and should be compensated locally.

2) Short circuit - Determine the impact of additional generation sources to the short circuit current ratings of existing electrical equipment on the network.

3) Transient stability - dynamic behavior of the system during contingencies, sudden load changes and disturbances. Voltage and angular stability during these system disturbances are important. In most cases, fast acting reactive-power compensation equipment, including SVCs and STATCOMs, should be included for improving the transient stability of the network.

4) Electromagnetic transients – Ensure these fast operational switching transients have a detailed representation of the connected equipment, wind turbines, their controls and protections, the converters, and DC links.

5) Protection – Investigate how unintentional islanding and reverse power flow may have a large impact on existing protection schemes, philosophy, and settings.

6) Power leveling and energy balancing - Due to the fluctuating and uncontrollable nature of wind power as well as the uncorrelated generation from wind and load, wind power generation has to be balanced with other fast controllable generation sources. These include gas, hydro, or renewable power generating sources, as well as short and long-term energy storage, to smooth out fluctuating power from wind generators and increase the overall reliability and efficiency of the system. The costs associated with capital, operations, maintenance and generator stop-start cycles have to be taken into account as well.

7) Power Quality - Fluctuations in the wind power and the associated power transport (AC or DC), have direct consequences to the power quality. As a result, large voltage fluctuations may result in voltage variations outside the regulation limits, as well as violations on flicker and other power quality standards.

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